RIGA TECHNICAL UNIVERSITY

Ansis Avotiņš

RESEARCH AND DEVELOPMENT OF SMART LED LIGHTING SYSTEM

Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY

Faculty of Electrical and Environmental Engineering
Institute of Industrial Electronics and Electrical Engineering

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"Computerised Control of Electrical Technologies"

RESEARCH AND DEVELOPMENT OF SMART LED LIGHTING SYSTEM

The Doctoral Thesis

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EIROPAS SOCIĀLAIS FONDS

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph.D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on April 11, 2022 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12 Āzenes Street, room 212.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph.D.) is my own.

I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Ansis Avotiņš ______________________________ (signature)

Date: ______________________________________

The Doctoral Thesis has been prepared as a thematically united collection of scientific publications. It consists of summary and 27 publications and 1 WIPO patent. Publications have been written in English. The total number of publication pages is 290.

Acknowledgements

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Contents

General Overview of the Thesis

Topicality of the research

During the spring summit of the European Council in 2007, EU 20-20-20 Directive 2012/27/EU was passed [1]. From 1990 to 2018, the greenhouse gas emissions decreased by 23 % [2], according to the information in Eurostat database, the total air pollution and CO_2 emissions of 27 EU Member States from 2010 to 2019 decreased on average by 1.57 % annually. The key challenge of the EU Green Deal, that was passed in 2019 [2], is to provide that the EU greenhouse gas emissions decrease by 50–55 % by 2030, compared to the level of 1990. Since 2012, Latvia has used resources of the Emission Allowance Auction Instrument (EKII) to co-finance street lighting modernisation projects (23), and smart urban solutions are introduced that are based on a more comprehensive use of information and communication technologies (ICT), which increase the energy efficiency significantly, reduce emissions and improve traffic safety. Based on Eurostat data, the death toll of street accidents in Latvia per 100,000 inhabitants has decreased from 26.8 (in 2000) to 7.7 (in 2018) that indirectly correlates with the improved availability of street lighting in towns. In 2012, Latvia spent 79 GWh/per year for street lighting that, as a result of increased electricity tariff, amounted to EUR 11.34 million (26).

Due to the European energy market liberalisation increase in the number of local energy networks, integration of renewable energy resources, spread of cogeneration and micro production (micro networks, virtual electricity facilities) and demand from new users, more modern monitoring, control and electronic electricity trade technologies are necessary that would impact the existing street lighting systems, if implemented.

Based on the European Construction Technology Platform (ECTP) data, 80 % of Europeans live in cities [3] that are the end users of public lighting systems. Infrastructure in the city centres, especially in Eastern Europe, is outdated, therefore, when rebuilding these areas, the cities should focus on more efficient use of energy and possible integration of alternative energy sources [4]. To ensure street lighting in a city in Europe, the total electricity consumption expenditure on average is 6–7 %, but in some cases it can reach even 60 % of the total budget of local municipality [5]. Improvement of the energy efficiency of the end user, in this case in the street lighting system and LED luminaries, creates additional savings for the producers, as it is known that significant losses in the electricity production are common in transmission (2 %) and distribution (8 %) processes. LED luminaries currently are the key solution aimed at increasing the efficiency of street lighting systems, and with implementation of movement sensors and efficient light regulating algorithms, the smart street lighting systems have high future potential, creating new functions and opportunities for smart cities that would consequently create significant economic benefits.

Main hypotheses and aims

Hypotheses

1. It is possible to save up to 50 % on electricity with smart street lighting systems equipped with LED luminaires.
2. It is possible to save additional 10 % on electricity with smart street lighting systems equipped with LED luminaires and motion sensors.
3. Smart lighting control system with dynamic control algorithm can improve lighting quality and traffic safety on streets.

Aims

1. Perform analysis of lighting systems and develop their architecture comparison.
2. Develop a new smart LED lighting system.
3. Experimentally prove advantages of smart LED lighting systems.
4. Optimise new smart LED lighting system control methods.

Research tools and methods

MatLab and MS-Excel computer programs were used to simplify the theoretical calculations and graphically represent the obtained results. In addition to modelling and development of electrical circuits, OrCAD and LTspice software were used. DiaLux lighting calculation software was used to simulate and determine the optical quality of the lighting. For ZigBee protocol tests, Microchip ZENA 3.0 Network Analyzer software and transceivers were used.

The verification of the obtained theoretical results in laboratory conditions was performed with the help of experiments in a laboratory specially adapted for this purpose and in a specially built laboratory stand. The stand is designed with dimensions of 2.2 m × 2.2 m × 3 m, and the LED luminaires under study were placed in it. The stand was covered with black curtain material, thus providing optical measurements that are not affected by external lighting. Measurements were performed using Hagner digital lux meter EC1, LMK MobileAir lighting photo camera able to take luminance photography, and Avantes VIS-NIR spectrometer. An adjustable DC power supply or autotransformer, function generator (for control signals), power analyser, oscilloscopes, thermal imager Fluke Ti10 and laser temperature meter were used to test the electrical parameters both indoors and outdoors.

Scientific novelty

1. New wireless data transmission communication modules, based on ZigBee and radio signals, integrated in each controlled LED luminaire to determine real-time power consumption, have been integrated and tested in real conditions of the existing street lighting system.
2. A new decentralized street intelligent lighting system with dimmable LED luminaires, motion sensors and real-time wireless data transmission has been developed and integrated into the real urban street lighting system.
3. A new method for real-time monitoring of street lighting electricity consumption has been developed.
4. Novel traffic intensity adaptive control algorithm for lighting system and LED luminaries has been developed.

Practical novelties

1. A new ZigBee protocol wireless communication control module has been developed for the regulation of LED luminaires, which has been installed at the testing Pilot-Site in the RTU parking lot (*Meža Street*), replacing the existing sodium high-pressure lamp luminaires and thus increasing energy efficiency.
2. A new intelligent LED lighting system has been installed for pedestrians in the RTU campus territory in *Ķīpsala* and for vehicle traffic on *Zunda krastmala* Street, which has resulted in a significant reduction in electricity consumption.
3. A new system and method for real-time monitoring of electricity consumption (WIPO patent) was developed and adapted to measure the electricity consumption of LED luminaires.

Practical significance of the work

In the course of the work, in-depth knowledge of intelligent street lighting systems with LED luminaires was acquired, which allowed to provide expertise services to several Latvian municipalities and institutions of Ministry of Environmental Protection and Regional Development of the Republic of Latvia.

New product has been developed – dimmable LED luminary with power of 56 W.

A novel adaptive control algorithm for maximum energy efficiency increase has been developed which has the necessary lighting quality and traffic safety in terms of lighting parameters.

In the course of the work, experimental tests of LED lighting systems were carried out in several Pilot Sites, which allowed to evaluate the reduction of power consumption of large number of lighting luminary in real lighting systems and compliance of lighting quality parameters to regulatory norms and initial results of Dialux modelling programs and overall efficiency of the control system.

Approbation of the Thesis

74 publications and 2 patents were created in total. The summary of the Thesis consists of 27 publications and 1 WIPO patent. List of publications and patent:

1. **A. Avotins**, L. R. Adrian, R. Porins, P. Apse-Apsitis, L. Ribickis. Smart City Street Lighting System Quality and Control Issues to Increase Energy Efficiency and Safety. Baltic Journal of Road and Bridge Engineering, 2021, Volume 16, Issue 4, pp. 28–57.
2. L.R. Adrian, **A. Avotins**, D. Repole, O. Tetervenoks. Development of New Radar and Pyroelectric Sensors for Road Safety Increase in Cloud-Based Multi-Agent Control Application. Baltic Journal of Road and Bridge Engineering, 2021, Volume 16, Issue 4, pp. 76–107.
3. **A. Avotins**, O. Tetervenoks, L. R. Adrian and A. Severdaks, "Traffic Intensity Adaptive Street Lighting Control," IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society, 2021, pp. 1–6.
4. K. Kviesis, L. R. Adrian, **A. Avotins**, O. Tetervenoks and D. Repole, "MAS Concept for PIR Sensor-Based Lighting System Control Applications," 2020 IEEE 8th Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), 2021, pp. 1–5.
5. R. Porins, P. Apse-Apsitis and **A. Avotins**, "PIR-Sensor Based Street Lighting System Control," 2020 IEEE 8th Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), 2021.
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7. Tetervenoks, O., **Avotins, A.**, Fedorjana, N., Kluga, A., Krasts, V. Potential Role of Street Lighting System for Safety Enhancement on the Roads in Future. In: 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2019): Conference Proceedings, Latvia, Riga, 7–9 October 2019, pp. 349–353. e-ISBN 978-1-7281-3942-5.
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e-ISBN 978-90-75815-27-6.

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12. Apse-Apsitis, P., Šenfelds, A., **Avotins, A.**, Paugurs, A., Priedītis, M. Power Measurement and Data Logger with High-Resolution for Industrial DC-Grid Application. Power Electronics and Applications (EPE'17 ECCE Europe), 2017 19th European Conference, Vol. 9, pp. 36–42. ISSN 2255-9140. e-ISSN 2255-9159.
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Introduction

In the course of evolution, humans have invented different artificial lighting technologies, however, as artificial lighting requires different energy resources, energy saving [1]–[4] is the key driver for the evolvement of lighting technologies [5], [6]. Currently, in the area of artificial lighting, a completely new light emitting technology, LED (Light-Emitting Diode), is in the spotlight in the world. Due to the rapid development of LED technologies in the recent years, it is called the “light of the 21st century”, and the topicality of this technology was proved by the Nobel Prize in physics awarded in 2014 to Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura for inventing the energy efficient and environmentally friendly light source – blue light emitting diode (LED) [7], [8]. It served as an impulse to manufacture the power LED that is a combination of several small LEDs (in series, parallel or in a matrix) in one integrated casing (hereinafter – in a chip) that is now widely used in the street lighting system luminaries.

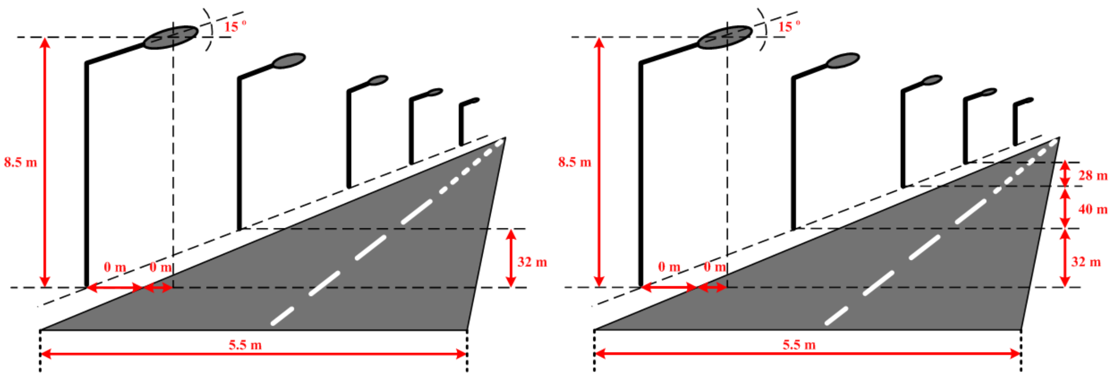
In the recent years, the key LED feature is used more often – by regulating current with different power supply blocks (20) or dimmers it is possible to regulate (to dim) the amount of emitted light from 0 to 100 %, and consequently it is possible to regulate the energy consumption of the LED luminary that was not possible fully for the gas discharge bulb luminaries. Therefore, with the help of LED dimming, lighting management systems are used more often (14), allowing to save 30–50 % of energy, compared to high pressure gas discharge bulb luminaries. In future, along with the development of the LED technology, power converters, communication and management systems (14), the electricity consumption might decrease even more, providing new opportunities in the development of quality and functional development of lighting systems (21), moreover, the future electricity supply might be decentralised and more equipped with ICT on several levels, therefore the term “smart grids” has been introduced. This serves as basis for the research that would allow to assess the possibility to use the smart grid approach in lighting systems.

Street lighting was introduced to increase the safety on roads and reduce road accidents, according to accident analysis in different USA cities [9], where the number of people who have died during the night is 3–4 times higher than during the natural light conditions, even if the traffic intensity decreases. Several quality standards were developed [10] for measurements and photometric parameter limits to be maintained that are accepted in many countries in the world and are continuously updated considering the developments in the area of lighting technologies.

1. Analysis of Lighting Quality Assessment Parameters

To create energy efficient street lighting system that complies with the laws and regulations [10], it is necessary to select appropriate luminary for every situation, therefore the characteristic parameters of each street have to be assessed that are of **geographic character**, namely, the width of street, number of lanes, distance between posts, height of posts, angle of luminary placement, distance from the road, reflection coefficient of road surface, etc. Generally, city streets can be divided in two groups (see Fig. 1.1):

a) streets with constant distance between poles (usually new/reconstructed streets);
b) streets with random distance between poles (non-reconstructed streets).



a) constant pole distance;

b) random pole distance.

Fig. 1.1. Street profile and necessary data for Dialux calculations.

The next parameter that provides requirements for the street lighting level is types of traffic participants and traffic intensity. The selection of street lighting determines the parameter of lighting quality: minimum values of L_{av} (cd/m^2), U_0, U_l, f_{TI}, R_{EI} are described in the first section of the Technical Report of LVS [10] that is effective in the European Union (EU) Member States and prescribes 4 time zones during which dimming is allowed to maintain different lighting levels.

The key parameter to compare different types of lighting sources and luminaries is the total efficacy of the luminary (K, lm/W) [11], which is referred to as hL in other sources and is expressed as a proportion between the total amount of emitted light (lm, cd×sr) and total power spent (P, W). Monochromatic radiation at the frequency 540 × 10^{12} Hz, spectral light efficiency is 683 lm/W, $K(\lambda_{555})$ = 683 lm/W that is equal with 683 cd×sr/W (radiated wave length λ at this frequency is approximately 555 nm).

To measure the amount of light, radiometric and photometric measurements are used (16). Radiometric measurements show the actual optical power that is determined by the consumed energy in entire lighting source spectrum. However, as human eye does not react to all wave lengths equally, a division is implemented with bell-shaped curve that is called the luminous efficiency function ($V(\lambda)$) given in Fig. 1.2.

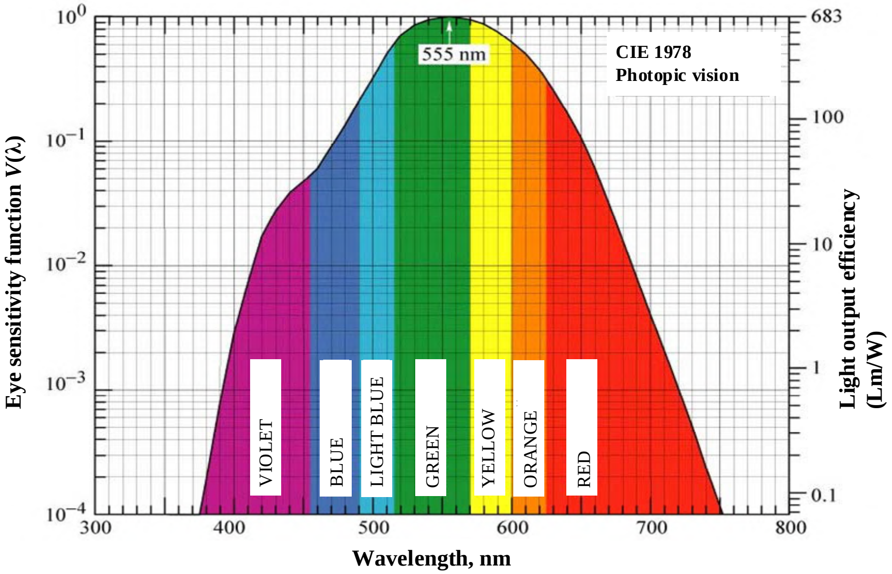


Fig. 1.2. Photopic colour vision and their maximum efficiency values.

Light return efficiency η_L can be expressed as a multiplication of spectral and electrical efficiency:

$$\eta_L = \eta_S \eta_E, \tag{1.1}$$

where η_S is spectral efficiency in the visible spectrum, lm/W,

η_E is electrical efficiency (without a measuring unit) expressed as the power of emitted light vs. consumed electrical power.

Considering the eye sensitivity function $\bar{y}(\lambda)$ spectral efficiency can be expressed as follows:

$$\eta_S = 683 \int_0^{\infty} \bar{y}(\lambda) B_\lambda \, d\lambda. \tag{1.2}$$

Considering that the Sun is the source of white light with surface temperature of 5800 K and it is described by normalised spectral function,

$$B_\lambda = 15 \left(\frac{hc}{\pi k T} \right)^4 \lambda^{-5} \left[e^{hc/\lambda k T} - 1 \right]^{-1} m^{-1}, \tag{1.3}$$

where λ is wave length, nm;

h is Planck constant;

c is speed of light;

k is Boltzmann constant;

T is absolutely black body temperature in Kelvins.

However, if the spectral efficiency has to be expressed in a specific wave length range, for example, in the ideal white light zone where $\lambda_{blue} = 400$ nm, but $\lambda_{red} = 700$ nm, the spectrum efficiency is calculated as follows:

$$\eta_S = 683 \frac{\int_{\lambda_{blue}}^{\lambda_{red}} \bar{y}(\lambda) B_\lambda \, d\lambda}{\int_{\lambda_{blue}}^{\lambda_{red}} B_\lambda \, d\lambda}, \tag{1.4}$$

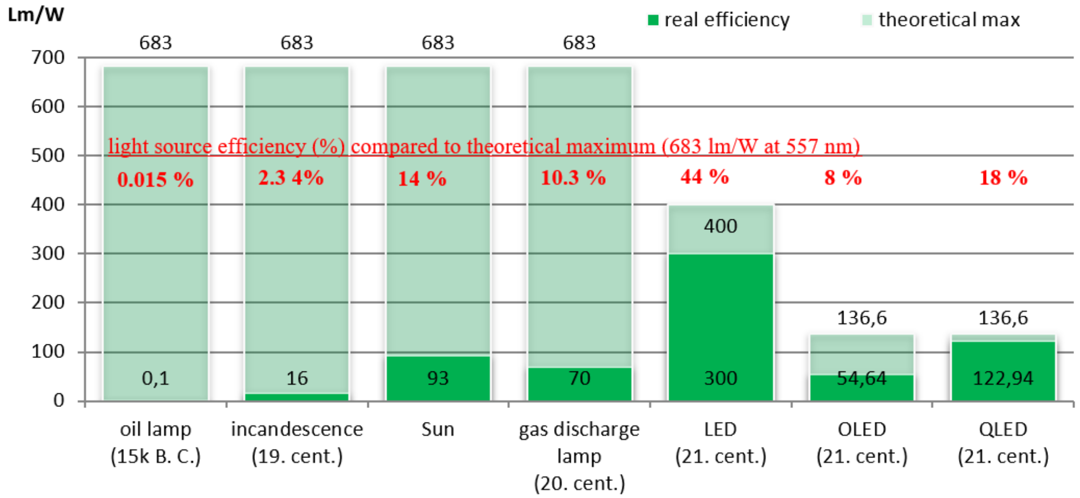


Fig. 1.3. Different light source efficiency comparison.

There are several LED chip manufacturers with different products and quality parameters (service life, efficiency, etc.), but the largest in terms of sales in 2018 are [12] given in Table 1.1; Nichia and Samsung are more focused on indoor luminaries and multimedia household appliances, however, in the area of street luminaries Osram and CREE manufactured LED chips are used most often.

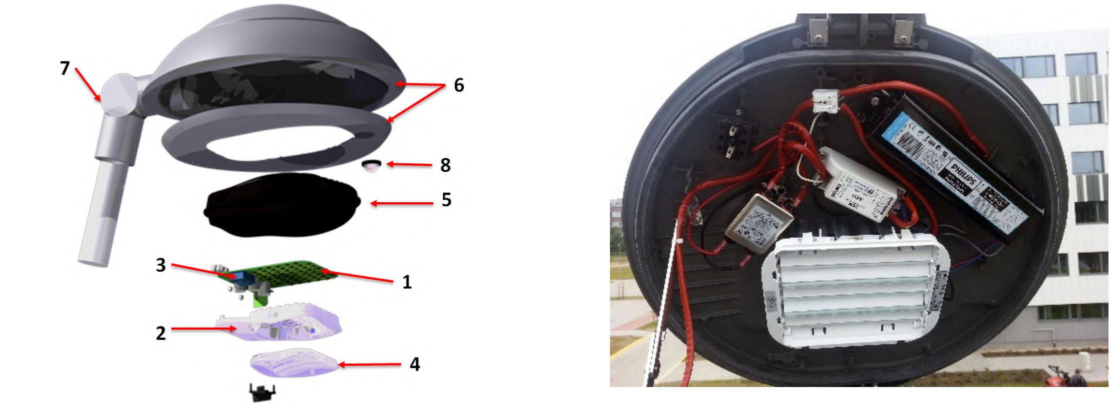
Table 1.1

TOP 10 LED manufacturers by sold quantities in year 2018

No.	Manufacturer	No.	Manufacturer
1	Nichia	6	Samsung LED
2	Osram Opto Semiconductors	7	Everlight
3	Lumileds	8	CREE
4	Seoul Semiconductor	9	NationStar
5	MLS	10	Lite-On

2. LED Street Luminary Research and Development

LED luminary consists of three main elements – luminary housing, ballast, and light source. But if looking in more detail, then smart LED luminary (see Fig. 2.1) consists of light source (LED crystal/ PCB) (1); reflector (2); driver/power supply (3); lens (4); heat sink/cooling system (5); housing (6); fixture to the lighting pole (7); and different sensors (8).



a) LED luminary base elements; b) installed LED luminary in real environment.

Fig. 2.1. LED luminary and main elements [15].

The casing of the luminary determines the parameters of temperature conductivity (including the service life of LED), as well as such mechanical parameters as IP class (protection against dust and humidity) and IK class (impact resistance). L70 and L90 tests help to determine the theoretical LED luminary service life. LED luminary cooling system can be passive or active (the use of ventilators causes additional power consumption). In the case of passive cooling, the parameters of temperature conductivity of aluminium or similar material have to be evaluated. Additionally, a luminary can include a temperature control node that reduces the current of LED luminary automatically, to ensure that the maximum temperature of p-n junction would not be exceeded, for example, if the external temperature is over 37 °C.

To compare street LED luminaries of different manufacturers, considering their performance, the total emitted luminous flux of a luminary (Φ_L, lm) and the power of luminary (P_L, W) have to be considered, therefore the ratio of these values is the total light output efficacy – the characteristic measure is emitted lumens vs. the consumed watt (lm/W).

$$\eta_L = \frac{\Phi_L}{P_L}, \quad (2.1)$$

$$\Phi_L = \Phi_{LED} - \Phi_1 - \Phi_2 - \Phi_3 - \Phi_4, \quad (2.2)$$

where Φ_{LED} – LED chip (light source) emitted light flow that includes losses in primary optics (according to the manufacturers of diodes, on average approximately 6 %);

Φ_1 – light losses incurred at the moment of manufacturing of luminary, when the LED chip is soldered on the PCB plate and the soldering appliance damages the primary lens of the LED chip (in case when wrong nozzle is used);

Φ_2 – light losses in the secondary optics (luminary lenses, reflectors, diffusers);

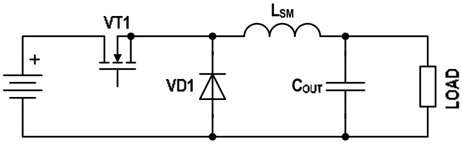
Φ_3 – light losses on the inner sides of luminary casing (up to 2 %);

Φ_4 – light losses in the protective casing of luminary (acrylic, glass, polycarbonate or borosilicate), where the losses depending on the material cause loss of 2–15 %;

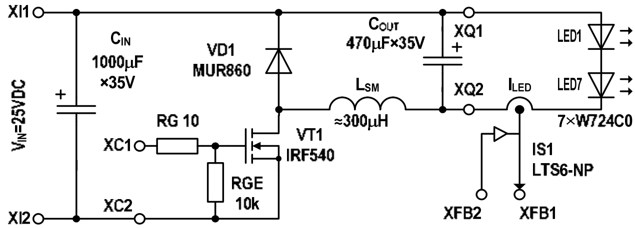
$$P_L = \left(P_{\mathrm{LED\,chip}} \times n_{\mathrm{number\,of\,chips}}\right) + P_{\mathrm{driver}}. \tag{2.3}$$

The total power of a luminary (P_L, W) is determined by the sum of consumed energy of n-number of LED chips and ballast power losses that is determined by the efficiency of ballast at the respective LED chip working current.

As the light emitted by LED is proportional to its consumed current (DC), then the level of emitted light can be controlled by means of constant current regulation in every LED string, which is also the most efficient way (28). It is possible to use the power pulse width modulation (PWM), however, as LED is very sensitive towards the changes in current, it can cause blinking and stroboscopic effect.

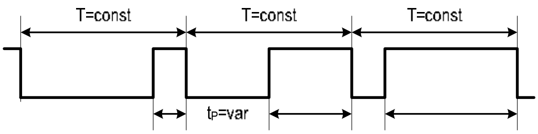


a) basic topology;

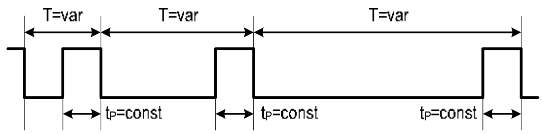


b) buck converter of the test bench.

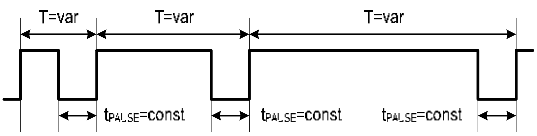
Fig. 2.2. Buck (step-down) converter in dimming application.



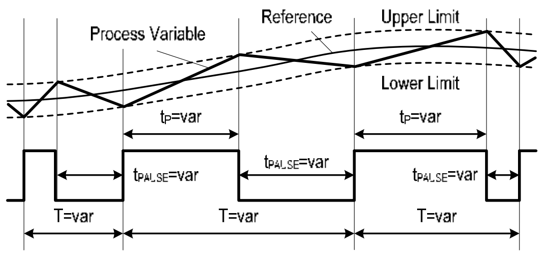
a) pulse width modulation (PWM);



b) constant pulse frequency modulation;



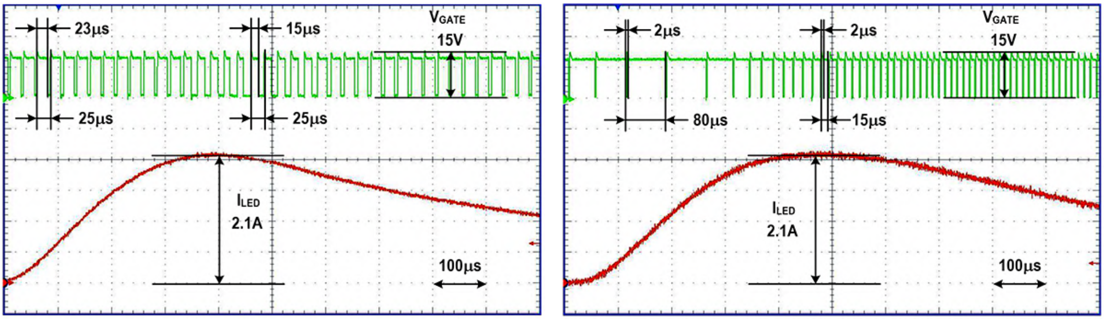
c) constant pause frequency modulation;



d) hysteresis control.

Fig. 2.3. Approaches to generation of the control signals (24).

As LED itself is a low direct voltage element, it should be powered with constant and continuous current. Therefore, DC/DC section is mainly necessary because LED luminary is powered by the alternating voltage (hereinafter – 230 V AC) line. Due to this, different direct voltage convertor circuits are used as current regulators: for example, Buck, Boost, Buck-Boost, and Buck-Boost with zero pulsation (Chook) type convertors. To determine the most efficient solution for generating command signals, there are several methods (see Fig. 2.3) and circuit in Fig. 2.2 b) can be used to create a testing device for light regulation.



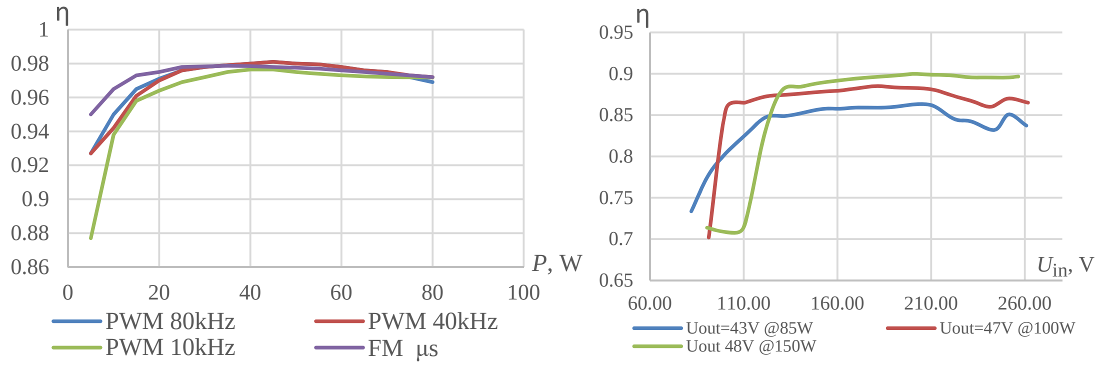
a) PWM ($f_{PWM} = 40$ kHz); b) FM ($t_{PAUSE} = 2$ µs).

Fig. 2.4. Dynamic performance of modulation methods (developed by I. Galkins).

During experiments, incoming/outgoing voltage (U_{IN} and U_{LED}) and current (I_{IN} and I_{LED}) were determined. Then, input and output power were calculated (P_{IN} and P_{LED}). Considering the power, the efficiency coefficient of convertor is calculated:

$$\eta(\%) = 100\frac{P_{LED}}{P_{IN}} = 100\frac{U_{LED}I_{LED}}{U_{IN}I_{IN}}. \quad (2.4)$$

The light regulator efficiency coefficient calculated using this method is shown in Fig. 2.5; in the case of PWM management, these curves look traditionally – with clear losses in the ends of the curve. The data obtained analytically and experimentally prove that the efficiency described above is high with all the verified management methods. The efficiency determined with FM (2µs) is steadier over all the power range, moreover, with 7 % less losses at the minimum power (5 W) in dimmed mode.



a) b)

Fig. 2.5. a) – Efficiency of step-down LED dimmer; b) – resonant converter (DER212) with PFC circuit.

Luminaries often contain one or several LED strings that have to be controlled separately. The ballasts of street luminaries require rectifier and power factor corrector (PFC) for a higher input current quality. Therefore, to join smaller size, mass and expenses with equal functionality, it is advised to use one rectifier and PFC for all LED current regulators (Fig. 2.6). The actual efficiency of the AC/DC boost resonant half-bridge convertor (25) (implemented on "Power Integrations" integral micro-scheme PL-C810PG standard circuit (DER212)) is provided in Fig. 2.5 b).

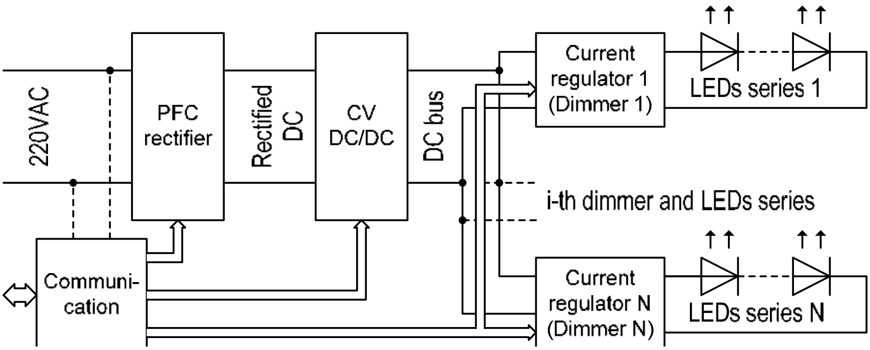


Fig. 2.6. Luminary power supply for multiple parallel LED series.

Several LED luminaries were developed within the framework of the Doctoral Thesis. **LED1 luminary** (Fig. 2.7) is constructed based on the matrix type LED (Fig. 2.8) circuit that is composed of 4 parallel strings with 14 LED diodes in each string. Diode power is 1 W (colour: warm white), therefore the planned maximum power of luminary is 56 W.

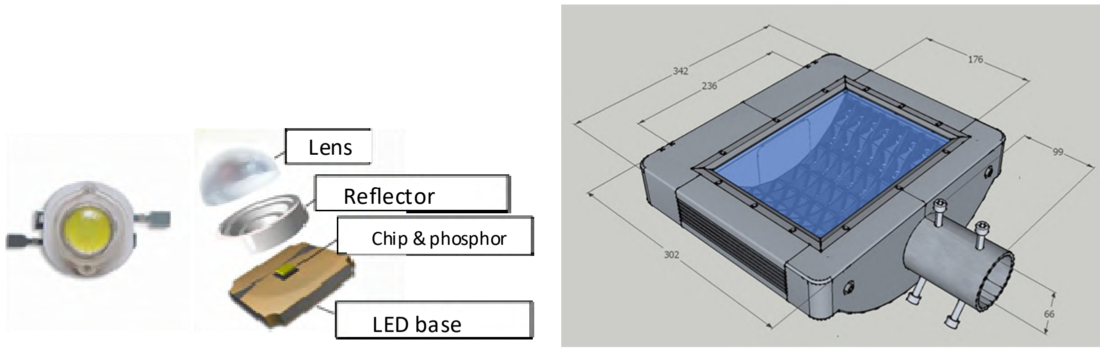


Fig. 2.7. LED luminary 1: a) light source (1 W) sample and b) LED1 luminary housing.

The main internal structural construction layout of LED luminary is shown in Fig. 2.8; and it consists of 4 key blocks.

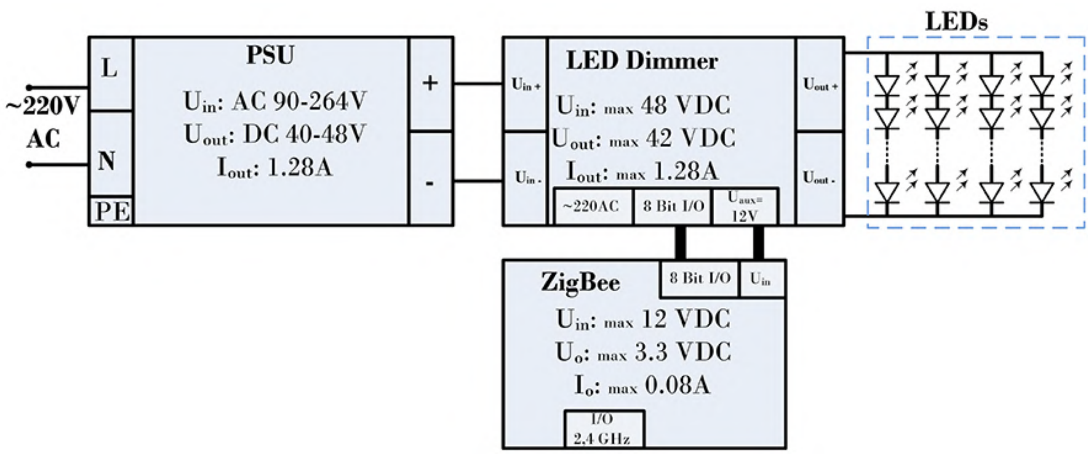
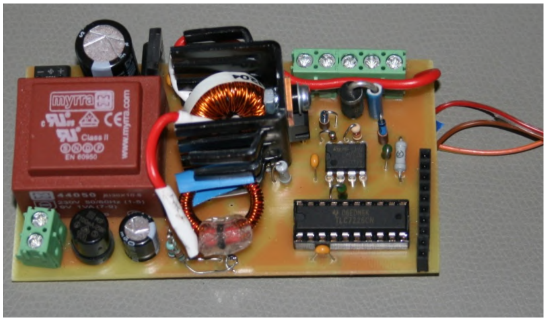


Fig. 2.8. Internal structure of the LED1 luminary.

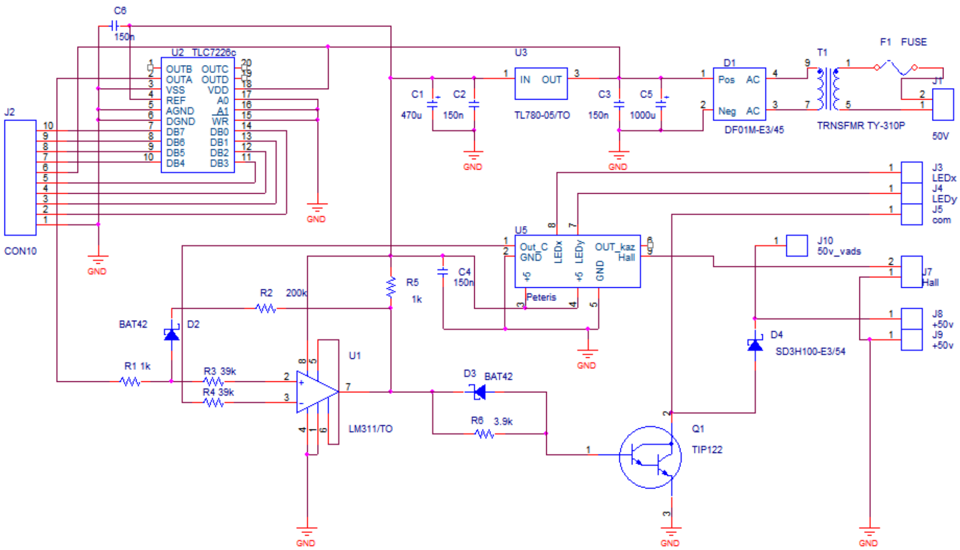
PSU is a standard, non-regulating constant current supply block that changes 220 V alternating voltage to 40–48 V direct voltage. In this case, the experimentally determined (Fig. 2.9 a)) maximum output power is 61.5 W, and maximum constant output current is 1.28A.

a) luminary testing stand;

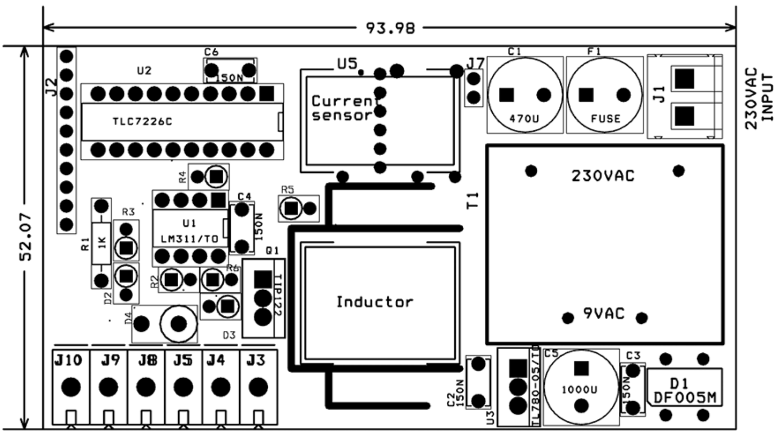


b) dimmer with integrated control module.

Fig. 2.9. Testing of LED1 luminary housing and integration of dimmer and control unit.



a) principal electrical scheme;

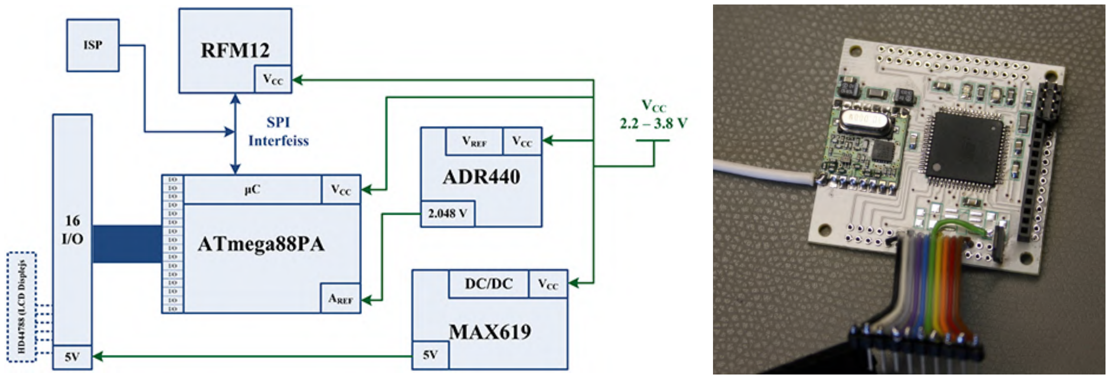


b) PCB plate design and electronic component placement.

Fig. 2.10. LED1 luminary current regulation (dimmer) scheme.

LED dimmer is the power circuit (Figs. 2.9 b) and 2.10) of smart luminary control unit that receives digital signal (for example, from FPGA (22)) and can regulate output power. Current is regulated in the range of 0–100 % considering the level and amount of light output that is not directly proportional to the current (it has rather exponential character).

ZigBee is a wireless communication and control unit transceiver part that detects external command signal and sends it to LED Dimmer that regulates the current provided to LED diodes.



a) communication module block diagram; b) developed PCB prototype.

Fig. 2.11. LED1 luminary ZigBee communication module block diagram and device.

Wireless communication module (Fig. 2.11) is provided for transmission of small data packages with low data transmission speed (up to 115.2 kBps) in half-duplex mode, i.e., it cannot transmit and receive information at the same time. As the phase modulation used in the transceiver and communication synchronisation (Fig. 2.12) is performed considering the change of phase, the length of transferred data packages depends significantly from the change of data binary form "0" and "1", i.e., changes in the carrier frequency phase by 180˚. LED1 luminary testing results are displayed in Fig. 2.13, where the total efficiency at nominal power is 80 % (electrical energy maximum efficiency is 86 %) and regulating light at 40–45 W, lag in the form of hysteresis by 18 % is caused.

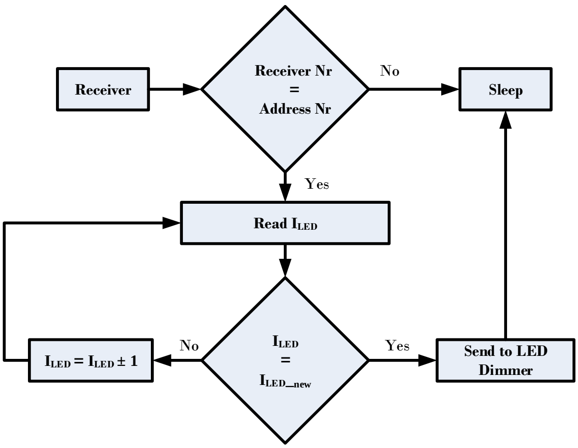
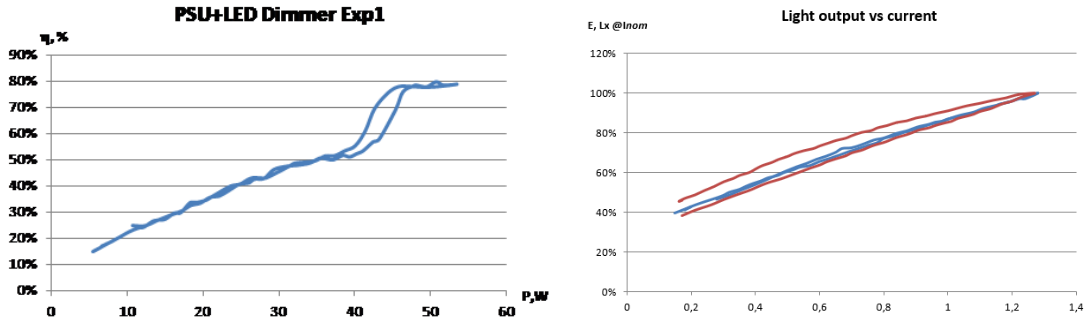


Fig. 2.12. Simplified control algorithm.



(a) total efficiency characteristics; (b) relation of current and light output.

Fig. 2.13. Total efficiency characteristics (a) and relation of current and light output (b) for LED1 luminary.

LED2 luminary (power is regulated up to max. 112 W) main circuit is given in Fig. 2.14. Its operation is based on 3 LED groups each of which contains 3 parallel LED diode (Cree XPG 3 W, 4000 K) strings with 6 LED diodes in each string, every group (18 diodes) are powered by separate supply block that increases the security of operations, because if one supply block fails, the other two continue operating and street lighting will be intact and the system operator will receive a notification that the respective luminary is damaged. Damaged luminary is identified by the power measurement node whose value is changed in the digital signal and with the help of micro controller and transceiver information is transferred to the control unit and vice versa – commands are received from it. Power supply block [17] is created on the TOP204 based (SMPS) circuit for regulation of outgoing voltage with PWM, current stabilisation, micro controller management (0 – max. power, 255 – min. power) and small distance data transmission wireless communication.

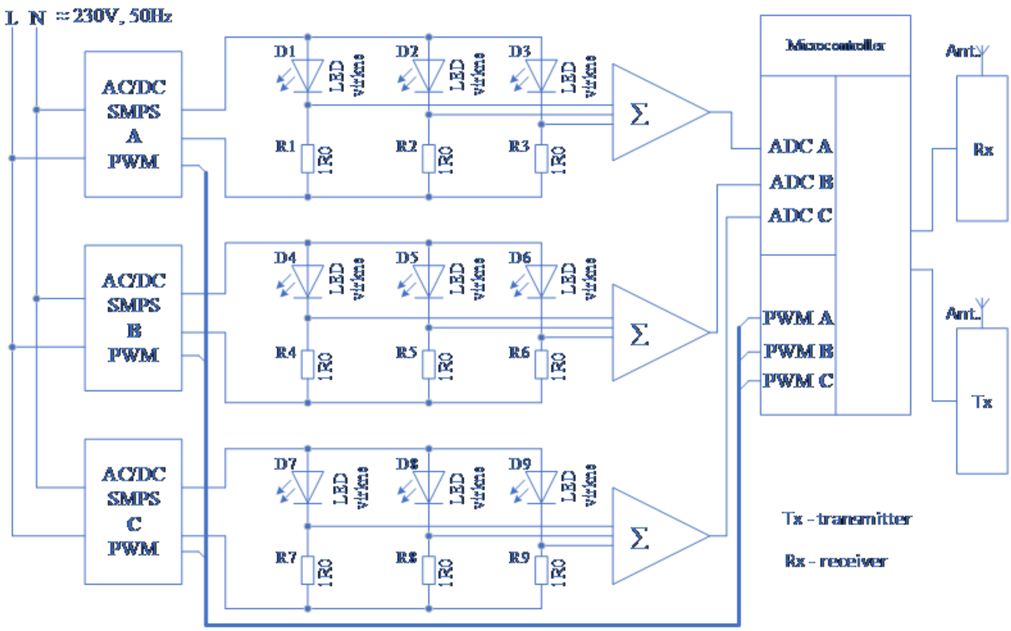
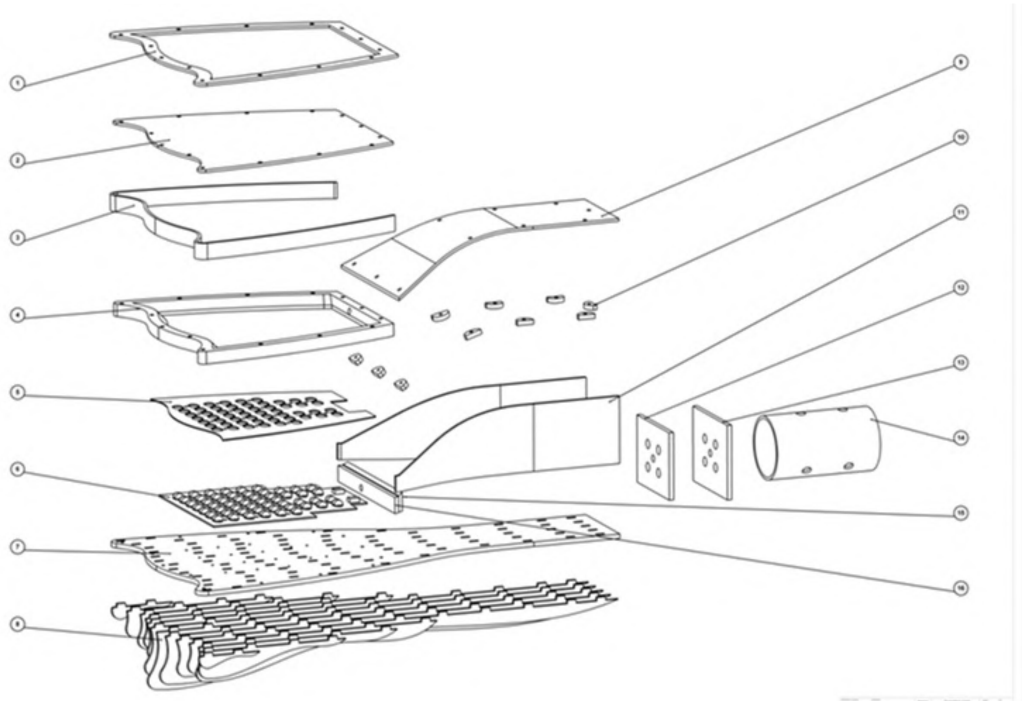


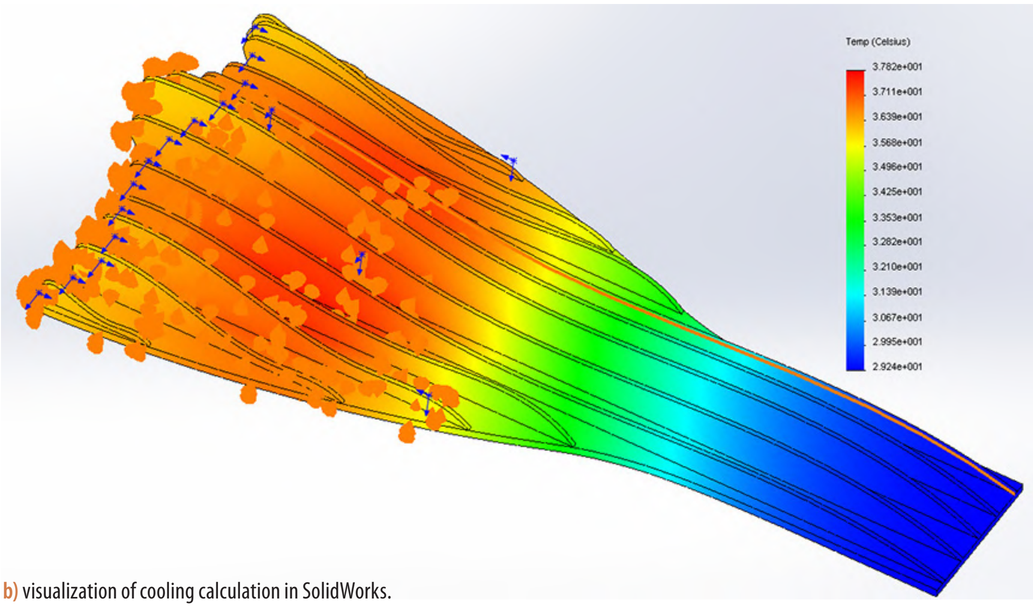
Fig. 2.14. Integration of LED2 series power supply into one luminary – functional diagram.

Figure 2.16 shows data received from wireless communication, where the efficiency of LED2 luminary is approximately 85 %. Figure 2.15 a) provides constructive/assembly solution of LED2 luminary, but Fig. 2.15 b) provides temperature change calculation results that show maximum 37 °C at 100 %

load. The developed form is unique because luminary cools down similarly in different wind directions. LED2 luminary regulating range (0–100 %) efficiency values at nominal power are given in Fig. 2.16. Figure 2.17 provides the prototype of LED2 luminary and the created aluminum PCB plate with two types of LEDIL lenses to expand the radiation of lighting that complies with the street profile and to obtain uniformity.



a) exploded view of construction;



b) visualization of cooling calculation in SolidWorks.

Fig. 2.15. LED2 luminary housing.

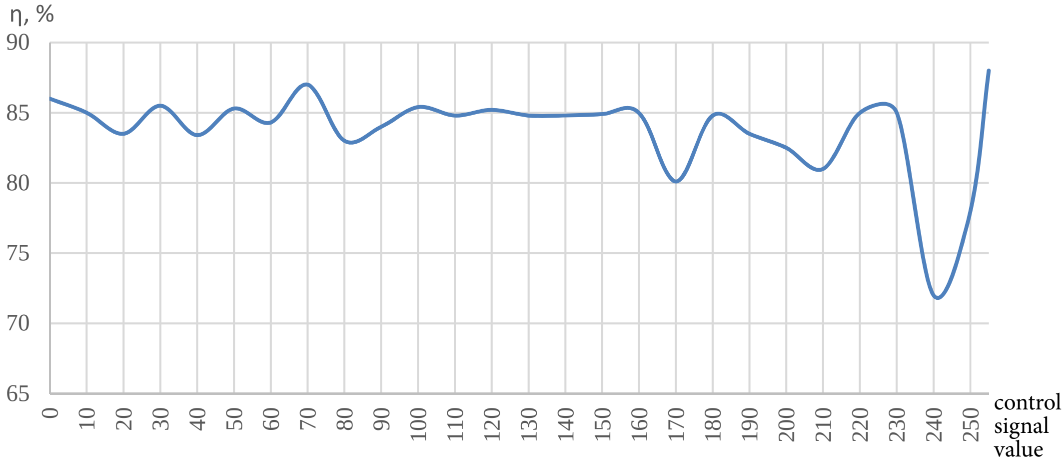
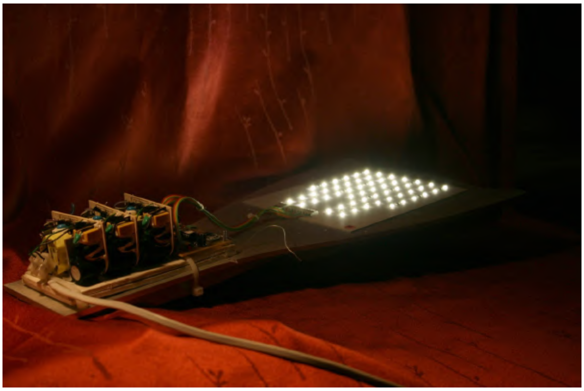
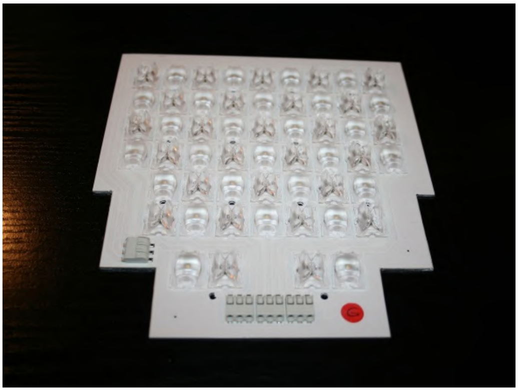


Fig. 2.16. LED2 lumianry efficiency at nominal power (56 W).



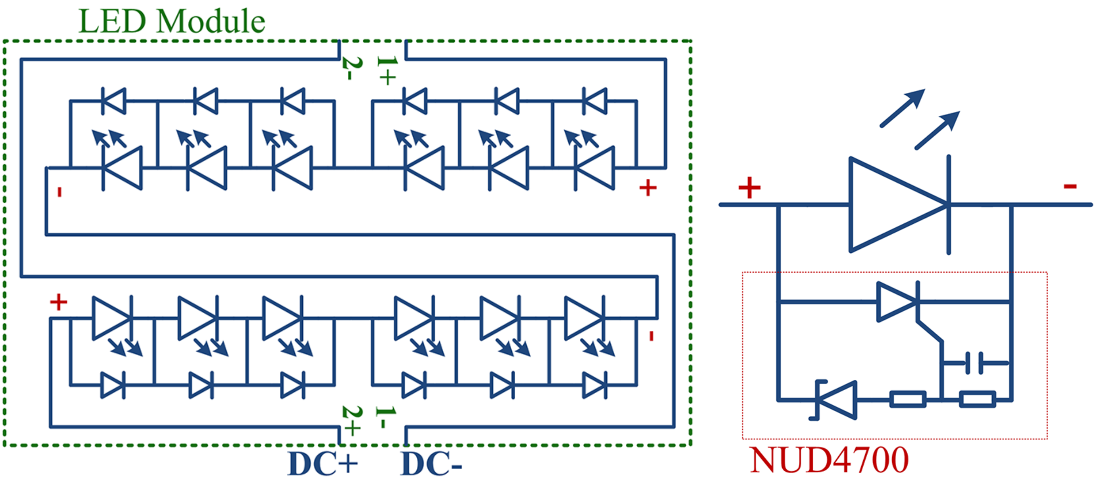
a) prototype;



b) PCB plate with two LEDIL lens types.

Fig. 2.17. LED2 luminary and its testing.

LED3 luminary was developed using the only series connection and constant current control for LED diodes. PCB module-type approach of 12 LED diodes allows to optimise manufacturing expenses and reduce the variations of types of PCB plates and rated power. PCB modules can be connected in series and parallel connection, and in the event of damage to LED diode, a parallelly connected energy efficient active shunt NUD4700 (Fig. 2.18) is provided. It is nominally provided for 1 W (350 mA at 3 V) LED diodes, however, if appropriate cooling is ensured, it can maintain current up to 1 A.



a) LED PCB schematic of one module; b) active shunt.

Fig. 2.18. LED PCB schematic of one module (a) and active shunt (b).

Power is supplied by module LPi80CS70F20 (Fig. 2.19) with rectifier, PFC chain and DC/DC buck converter with one output, which ensures regulated constant current control for LED diodes (Fig. 2.20).

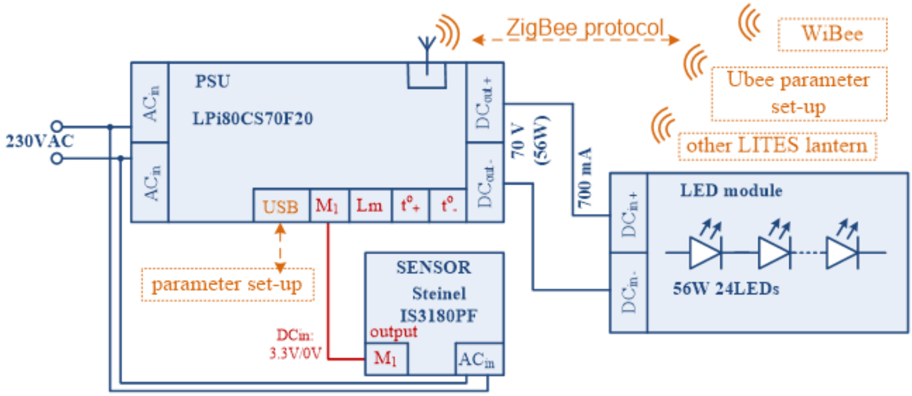
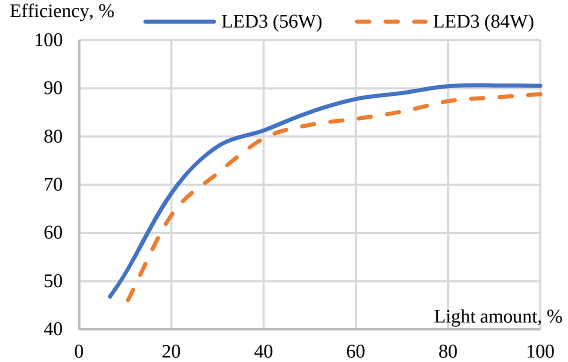


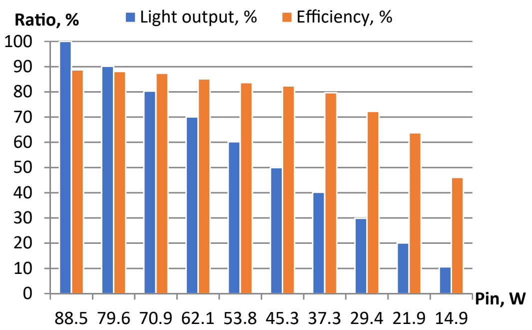
Fig. 2.19. LED3 (56 W) luminary block diagramm.

Fig. 2.20. LED3 luminary 28 W PCB plate module, voltage is 40 V_{DC}, and current is 700 mA.

According to Fig. 2.21, total efficiency coefficient of LED3 56 W luminary system is 90.5 %, electromagnetic compatibility (EMC) tests of the system were conducted at the LEITC laboratory, and the tests showed compliance with regulations, as it is provided in reports in detail [15],[16].



a) light dimming efficiency;



b) efficiency by power regulation.

Fig. 2.21. Efficiency measurement results of full LED3 56 W luminary system.

The largest light return of LED light source in the case of matrix connection was detected with continuous current control method that emits by 19 % more light compared to pulse width modulation (PWM) and by 25 % more compared to the LED light source string on/off method.

LED light source light output is non-linear in respect to regulated output current value of power supply, and this characteristic can be used to increase the total light output of LED luminary, efficiency, colour rendering index and service life, using appropriate control methods in the LED light source driver.

Analytically and experimentally obtained data prove that the efficiency of the light regulator referred to above is high with all tested control signal techniques. Efficiency of the FM regulation method that was determined experimentally is constant in a wider range of power, but the constant pauses FM method ensures higher regulation accuracy.

The electromagnetic compatibility tests at the LEITC laboratory prove that the LED light source ballasts with the efficiency over 0.92 more often comply with regulatory requirements of electromagnetic compatibility or are closer to their threshold values compared to ballasts with lower efficiency.

Creating the smart LED light source ballast using separate electrical devices (power supply unit, driver, communication node, etc.), which individually comply with the requirements of electromagnetic compatibility but in the joint circuit (housing of luminary), does not meet the requirements due to the interaction between the emitted radio-interference. It can be prevented by installing additional electromagnetic interference filters.

In lighting control systems, for the purposes of electricity consumption accounting control signal data transmission it is possible to use different wireless communication types, using half-duplex and duplex data transmission mode. In experimental tests, it was observed that ZigBee data transmission requires stronger signal (antenna) to cover the distance of up to 100 m, however, no communication issues were observed for the standard radio signal (RxTx). Although the manufacturers of wireless communication modules and the tests of the actual transmitter-receiver prove the data transmission distance of above 500 m (and even >1 km) in a straight line, in case of more complex and larger lighting systems (long streets, the number of luminaries at least 25, many trees on the streets), the experimentally determined data transmission distance is limited to 100–120 m that covers 2–3 closest lighting poles with the average distance of 33 m. Therefore, geographical location of the segment controller (for example, ZigBee-WEB gateway) is of importance to ensure that in the star or MESH layout it would be located as much as possible in the centre, or it requires an antenna that can receive the signal better.

3. Street Lighting System Analysis

According to general and functional application, three main lighting types can be classified: indoor lighting, outdoor lighting, and decorative lighting, where each of them has more detailed types of use.

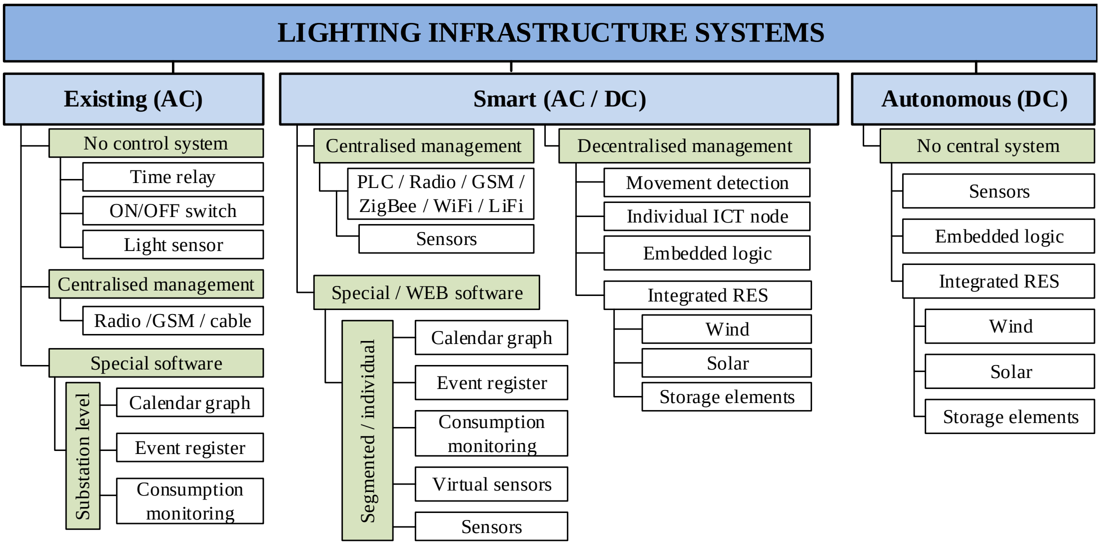


Fig. 3.1. Street lighting system classification by type of technology.

Street lighting systems can be divided in existing, smart and autonomous systems with different control options. In the course of technological development, lighting system market offers LED lighting sources that are more efficient compared to the existing ones and they allow to use new functions and features that, along with the development of information and communication technologies (ICT), allow to create lighting system classification by the technological solution (Fig. 3.1).

The smart lighting systems can be used almost in any lighting application type, because the only thing that changes is the constructive solution of lighting source, and the technological solution can be used as is. As the street lighting sector is rather energy-intensive and it is financed using public funding sources, the street lighting sector will be further analysed in this Doctoral Thesis.

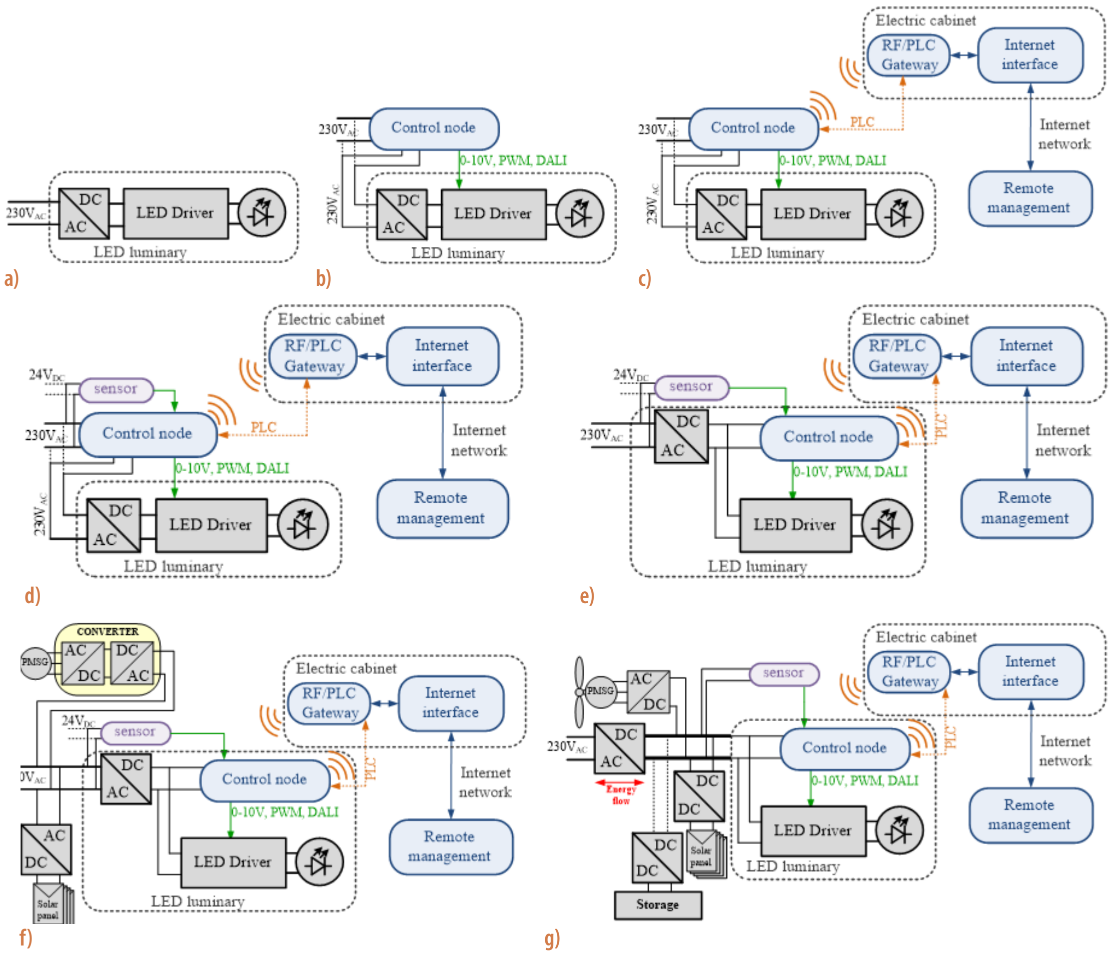


Fig. 3.2. Types of lighting system architecture.

There can be different types of lighting system architectures, as it is shown in Fig. 3.2: (a) is a simple LED luminary circuit and connection with the existing lighting network; architecture (b) is integrating (a) with an individual luminary calendar schedule control node, or with control node and communication network (c), and smart LED street control systems with external control node and movement sensor (d), or with a built-in control node and movement sensor (e); as well as future architecture with renewable sources connected in an AC network (f) and renewable sources connected in a DC micro-network (g). Replacing HPS luminaries with LED, the benefits of the architecture (a)–(e) can be analytically compared, as it is reflected in articles in detail (17 and 18).

Retaining similar 4,352 hour lighting per year and ME4-ME6 quality and traffic safety requirements for "Zunda krastmala" street section with 30 gb HPS (Philips Malaga SGS102 150 W) luminaries, in case of change to LED (Philips Indal BGP623) the electricity consumption decreases by 47.2 % (Type a)), and with the control node and sensor self-consumption, by 67.49 % (b), 65.67 % (c), 76.75 % (d), and 77.93 % (e), which proves that the smart control systems provide additional 30 % savings compared to simple replacement with LED (18). To determine savings of movement or "context-type" (13) sensors, the night time intervals provided in Fig. 3.3 and traffic intensity data of SJSC Latvian State Roads were used, as well as electricity consumption over the period of E_{12} applying Formula (3.1).

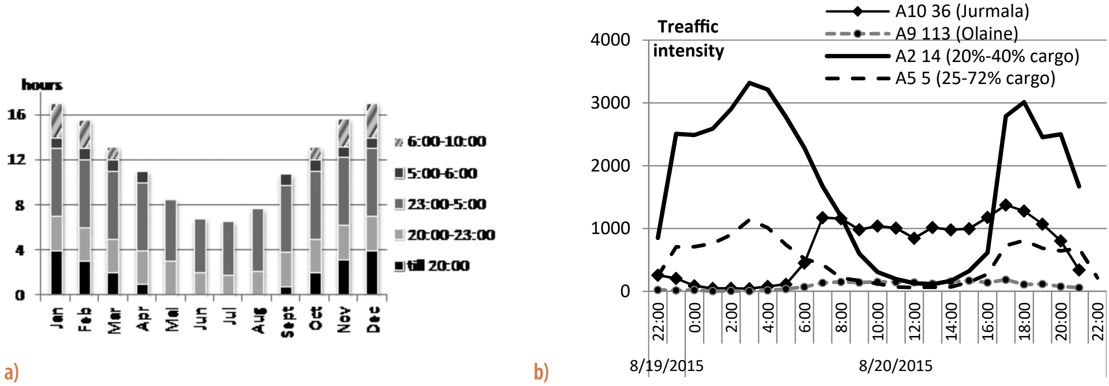
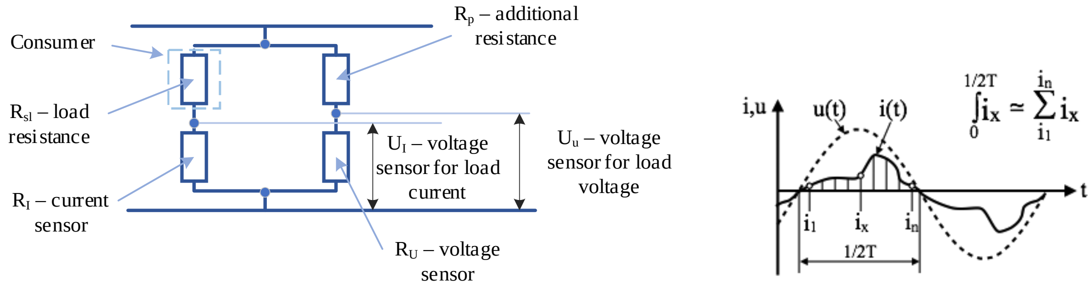


Fig. 3.3. Hour distributon of night zones (a) and LVC traffic intensity data (b).

$$E_{12} = P_{\min} \times (t_1 + t_2) + \frac{(P_{\max} - P_{\min}) \times (t_1 + t_2)}{2} + P_{\max} \times t_{ON}, \tag{3.1}$$

where P_{min} is the lowest set power level of luminary;
P_{max} is maximum set power level in the specific night period;
t_1 is set time from the moment when sensor starts operating until reaching P_{max};
t_2 is set dimming time (from P_{max} to the moment of reaching P_{min});
t_{ON} is the period when luminary operates in P_{max} mode.

One of the key tasks of smart lighting system is to perform accounting and monitoring of each individual LED luminary in real time, and, with the help of ICT, transfer the data to WEB server. It means that every luminary requires electricity consumption device that can measure voltage and current, therefore determining the momentary active power values (Fig. 3.4 b)) and calculating full and reactive values. Different measuring methods can be used, but one of the solutions (patented by the author) is provided in Fig. 3.4 a).



a) shunt type current and voltage measurement sensor; b) principle of processing the obtained data.

Fig. 3.4. Consumption current and voltage measurement [13],[14].

Figure 3.5 provides measurement data example for one-week experimental power measurements (for the case of P_{max}) for three 400 W sodium luminaries (P1) and three LED luminaries (P3) with equivalent emitted light flux; supplied voltage and surrounding parameters were the same in both cases. It can be observed that the power consumed by sodium luminaries varies over one day and week, where changes are in the range of 12.5 %, but in case of LED, the consumption is steady and similar over the period of all week. To have accurate data in the smart lighting management system, real measured power values have to be used instead of the analytically calculated (assuming that the consumed power is constant over time).

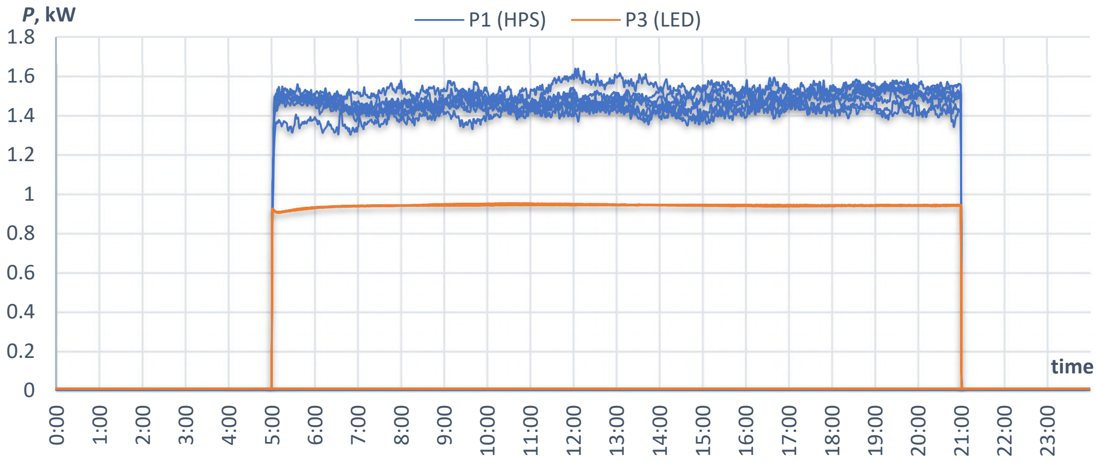


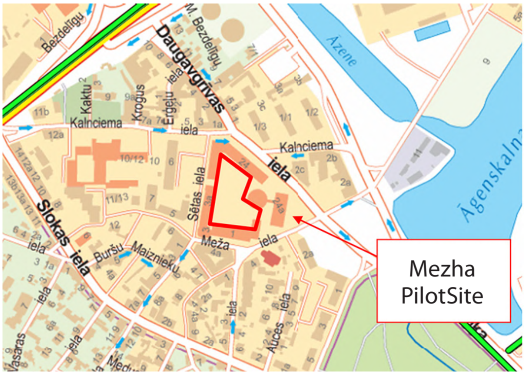
Fig. 3.5. Eksperimentally obtained data.

To determine electricity consumption of LED luminaries, Hall type sensors with clear hysteresis loop show different (dual) measurement resulting values in case of increase and decrease of current, therefore, such a solution is not accurate. After testing several industrially manufactured electricity meters (9), their measurements at different network voltage values showed 0.1 % error with two exceptions, where it reaches 0.7 %. In case of different network frequencies, measurement error increases up to 0.5 % on average, with some exceptions (at 65 Hz) up to 1.15 %. Light poles might be connected to AC network at night and to DC micro-grid during the day-time using renewable energy resources and electric vehicle or electric scooter charging opportunities, therefore, it will be a necessity for dynamic and two-way electricity accounting (9), similarly as in the case of industrial DC micro networks (11).

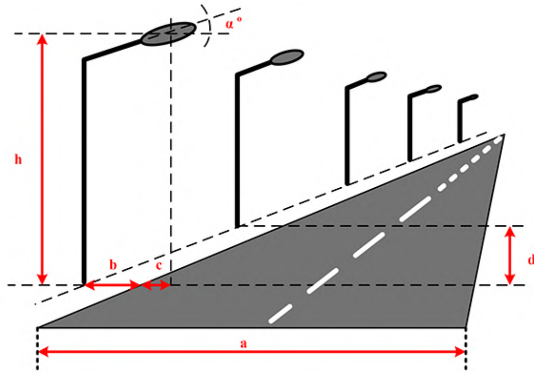
The created thermally compensated shunt can measure energy consumption in both directions (receives or returns to the network) (15), moreover, for both sinusoidal and non-sinusoidal signals, with different impulse widths (12), where, compared to industrial shunt-type power analyser Newtons N4L PPA5530, the developed option was on average by 08–3.22 % more accurate and at low power values – even by 21.6 % more accurate (12). This allows to integrate the node that detects the electricity consumption of LED luminaries in PCB plate itself, thereby reducing manufacturing expenses compared to offered solutions that use more expensive material with low resistance temperature coefficient. The novelty of the solution is proved by the received WIPO patent (28).

4. Experimental Tests of the Developed New Lighting System and Analysis of Obtained Results

In total 7 pcs of LED1 luminaries were installed in Riga on Meža Street lighting line that is located in the inner yard of Riga Technical University (Fig. 4.1). As the selected line was built earlier, measurements might be impacted by the condition of the old cables, therefore, overhead line was installed and the old poles were re-equipped. The line is long enough for the measurements to be close to average typical lighting line of parks, parking lots and similar squares in Riga. Street/square type profile applicable standards, geometric and lighting class parameters are given in Table 4.1.



a) LED luminary installation at Meža Street;



b) street profile.

Fig. 41. Testing at RTU – Meža Street Pilot-Site.

Table 4.1

Street/area type profile parameters and other data

Meža Street average profile parameters:			Other parameters:
a =	4 / 30	m	Lighting situation description D1 (from CIE 140)
b =	0.7	m	Existing lighting class: S4
c =	1.3	m	Testing class: S4
d =	15 / 20	m	Maintenance coefficient: 0.67 (approx.)
h =	8.5	m	Existing luminary: Philips Malaga with high pressure sodium vapour lamp SON-T (150 W and 70 W). Accordingly retrofitted with LED1 and LED2 type luminaries
α =	15	°	
lanes:	1	pc	
Street tarmac:	Porous asphalt		

According to long-term measurements, the system, without dimming mode (only replacement of luminaries), saved on average 40 % electricity, comparing to the consumption by sodium high pressure luminaries, and using calendar dimming mode it can save up to 60 %. In the case of LED2 luminaries, testing was conducted in Meža Street and Zunda Krastmala using a previously set calendar schedule for the day (Fig. 4.2). As a result, after 22 sodium luminaries (2604 W consumption) were replaced with LED (1628 W), savings without dimming were 37 %, but with dimming mode 49 % (in winter) and 83 % (in summer) that is related to the duration of night hours, in total saving 56 % on average.

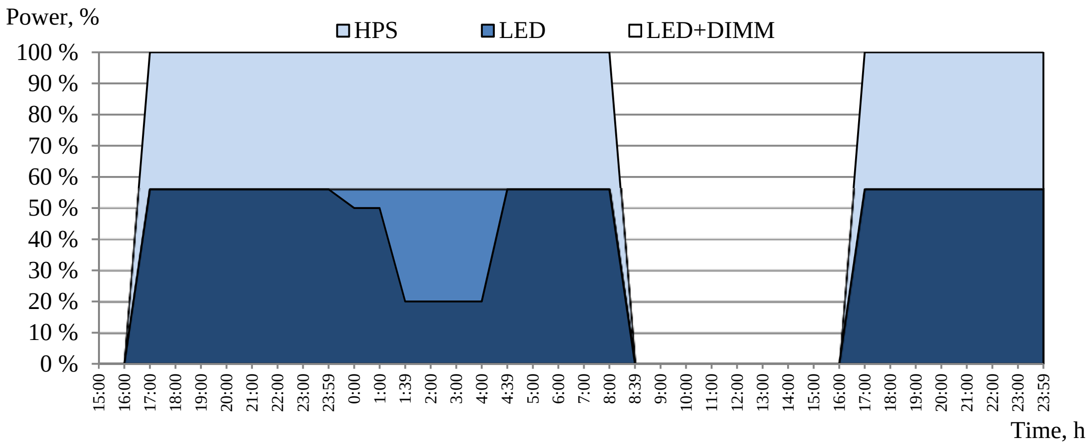


Fig. 4.2. Applied ON/OFF dimming profiles during daytime.

Smart lighting system with movement sensors was developed (Fig. 4.3), and in total 29 LED3 luminaries were installed at Ķīpsala campus, 11 luminaries (95 W) on Zunda Krastmala and 18 luminaries (65 W) on Azenes Street. Electrical connection circuit of luminaries is provided in Fig. 4.4, and energy meters were installed in the metal poles (Fig. 4.4.c) in order to compare with the data from the smart control system. To detect movement and control luminaries, Steinel IS3180PF and Bosch DS720i TriTech® sensors (Fig. 4.5) were used, and in 2020 the radar-type detecting sensor was added that is able to determine also the traffic movement direction and approximate speed (Figs. 4.6 and 4.7).

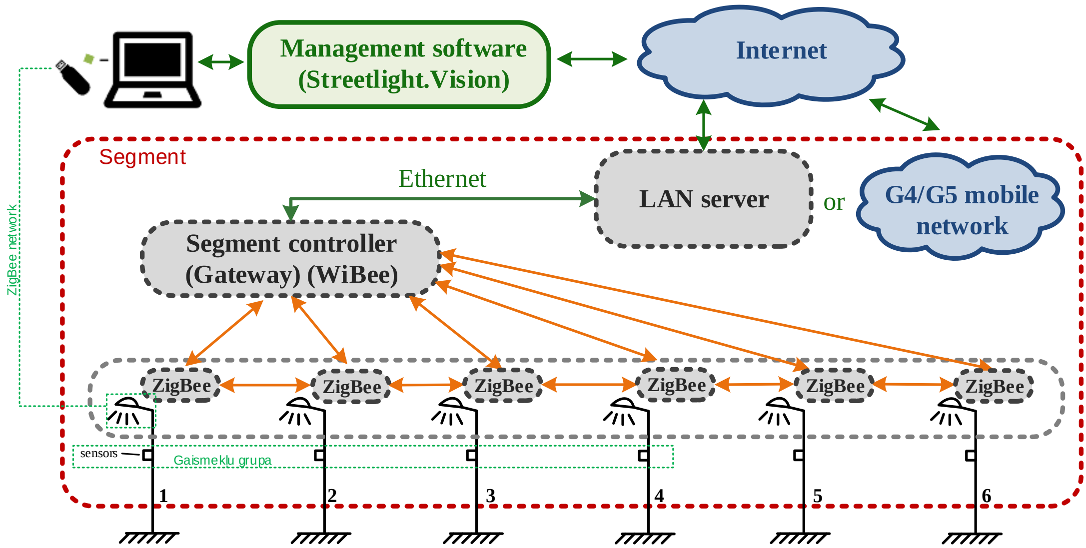


Fig. 4.3. Structural diagramm of created smart lighting system.

For the radar (Doppler effect) sensor (2 and 8) complex Fourier transformation (FFT) was applied, where the measured speed is proportionate to the Doppler deviation frequency $f_{doppler}$, in line with Formulas (4.1) and (4.2).

$$f_{doppler} = bin \times \frac{f_{sample}}{N_{FFT}} = bin \times \frac{f_{sample}}{256}, \tag{4.1}$$

$$v = \frac{bin \times f_{sample}}{256 \times 44{,}7 \times \cos a}, \quad (4.2)$$

where bin – FFT is output value that is proportional to Doppler frequency;

f_{sample} – FFT measurements/resolution frequency;

N_{FFT} – FFT width in bits;

v – speed value, km/h.

a) metallic (zinc) pole; b) LED luminary placement; c) ABB C11 110-300.

Fig. 4.4. LED luminary placement and electrical wiring at Ķīpsala Pilot Site.

a) Steinel IS3180PF; b) Bosch DS720i TriTech®; c) microwave radar sensor.

Fig. 4.5. Kipsala Pilot Site used movement detection sensors.

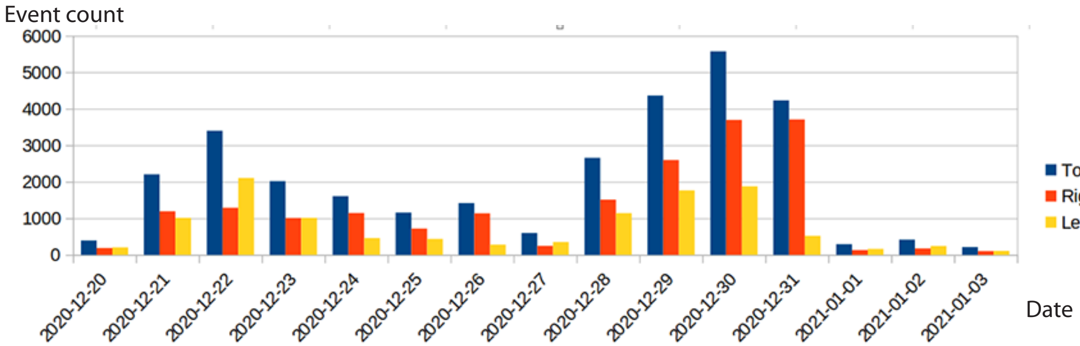


Fig. 4.6. Measurement sample of developed radar sensor movement direction.

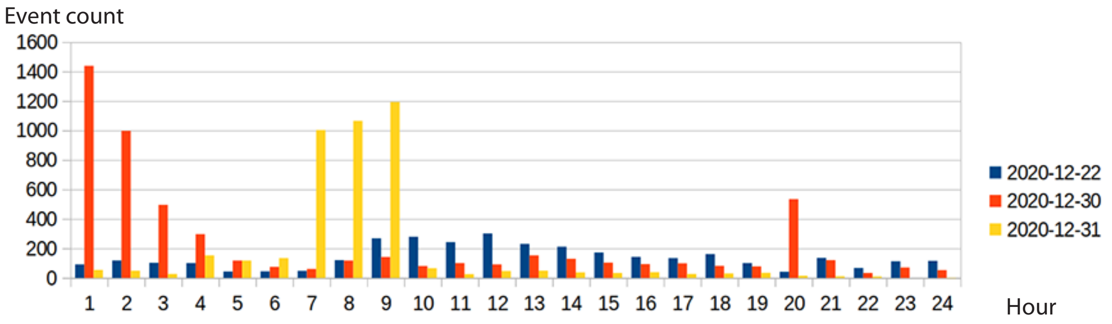


Fig. 4.7. Measurement sample of developed radar sensor traffic intensity.

At the Ķīpsala Pilot Site, Philips SGS high pressure sodium luminaries with total power of 3450 W (18 light bulbs (100 W) and 11 (150 W) light bulbs) were replaced with 29 smart LED luminaries Thorn Dyana (71.22 Lm/W, 4000 K), installed power of 2094 W that provide by 40 % less installed power and by 20 % better average lighting (E_{AV}, lx) and by 34 % better lighting homogeneity (U_L), (L_{av} = 0.52 cd^{-1}m^2 and U_0 = 0.62). Lighting pollution U_{FR} (4.3) is the ratio of direct upward light flow (U_{DLF}) to upward light flow reflected from the road surface (U_{RLF}).

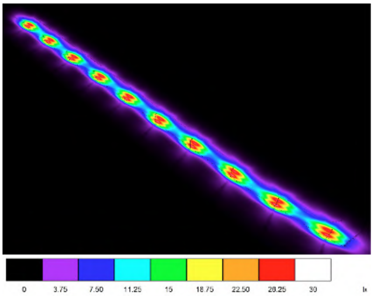
$$U_{FR} = \frac{U_{DLF}}{U_{RLF}}. \tag{4.3}$$

If U_{FR} value is below 10, it is considered a very good result, if U_{FR} < 1, it is an excellent result. After Dialux 4.0 modelling (see Fig. 4.8 a)) and practical measurements (see Fig. 4.8 b), c)), in case of Philips SGS luminaries U_{FR} = 3.0 and in case of Thorn Dyana LED luminaries with full power U_{FR} = 2.75, and U_{FR} = 1.0 at 20 % dimmed mode.

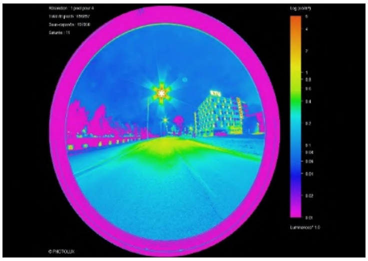
Table 4.2

Dialux modelling and real power/illumination measurement results in different regimes

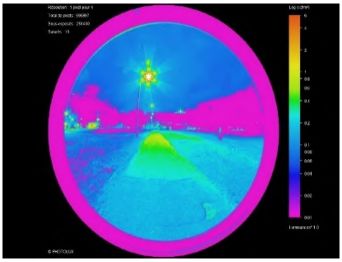
Illumination / measurement points	E (80 %), lx			E (60 %), lx			E (40 %), lx			E (20 %), lx		
	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3
$E_{(lx)}$ (measured in 2020)	25	7	24	20	6	20	14	4	14	8	3	8
Measured in 2014	28	10.7	17	-	-	-	-	-	-	7.1	3	7
Dialux simulation in 2014	20	8.19	20	10	4.49	10	6.24	2.92	6.24	3.12	1.35	3.12
Deviation, %	+19	-17	+17	+50	+21	+49	+56	+33	+56	+61	+49	+59



a) *Dialux* simulation (150 W HPS);



b) 95 W LED measurements at full power;



c) at 20 % power.

Fig. 4.8. Ķīpsala Pilot Site: a) Dialux simulation; b) 95 W LED measurements at full power; and c) at 20 % power.

The Dialux model was compared with real measurements obtained over several years, conducting

E(lx) measurements (Table 4.2) in the middle of the street, M1 and M3 are points perpendicular to the lighting pole, and M2 is the point between M1 and M3 poles. Comparing simulations of LED luminaries conducted in 2014 (at MF of 1.00) and measurements taken in 2020, it can be concluded that there is more light than necessary according to the standard, and the power can be reduced (dimming value increased), thereby obtaining additional savings. As smart lighting was installed before, to determine savings caused by the replaced luminaries, analytical calculation approach can be applied if the calendar schedule of city lighting is known, or by calculating the length of night (T_d, hours) of a specific day of the year (n), using the sun movement vector [18] with declination angle (δ) and degree of latitude of the specific location (φ) with Formula (4.4).

$$T_d = 24 - \frac{2}{15}\left(a\cos\left(\min\left(\max\left(-\tan(\varphi)\tan(\delta), -1\right), 1\right)\right)\right), \tag{4.4}$$

where $\delta = 23{,}45 \times \sin\left(\frac{360}{365}(284 + n)\right)$.

Based on calculations, it can be concluded that reduction of electricity consumption in the case of LED2 luminary would be 38 %, but in the case of smart LED luminaries it is 42 %, according to the consumption division by months (Fig. 4.9).

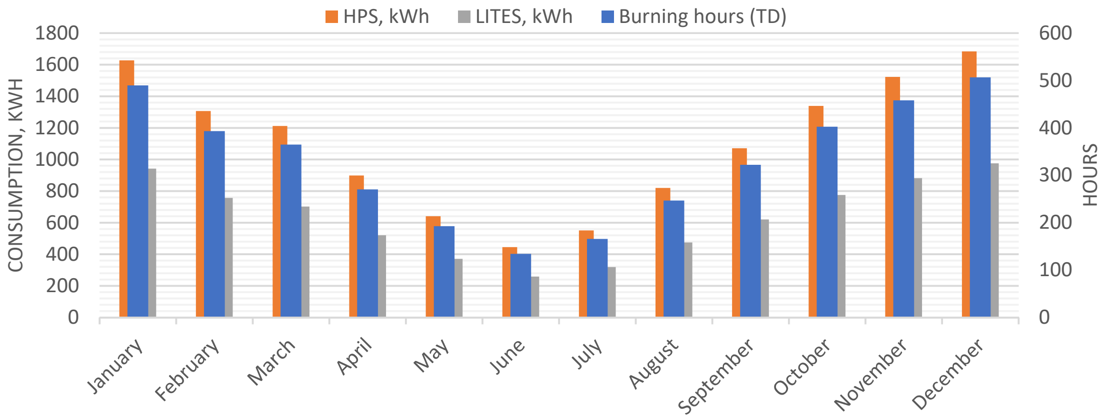


Fig. 4.9. Analytically calculated electrical energy consumption for high pressure vapour (HPS) and smart LED luminary cases.

Based on the data provided by installed electricity meters (Fig. 4.10) that were read twice per month in the respective period, it can be concluded that 4 LED luminaries (01–04) consume more electricity compared to others, which is related to the fact that luminary LITES95_01 is installed at the crossing and its sensor turns on the next 3 luminaries, therefore causing additional 88–108 kWh (18 %) consumption. Therefore, it can be concluded that movement sensors or statistical data algorithm is required that can identify traffic movement direction at the crossing, which would consequently reduce the consumption when traffic moves in another direction.

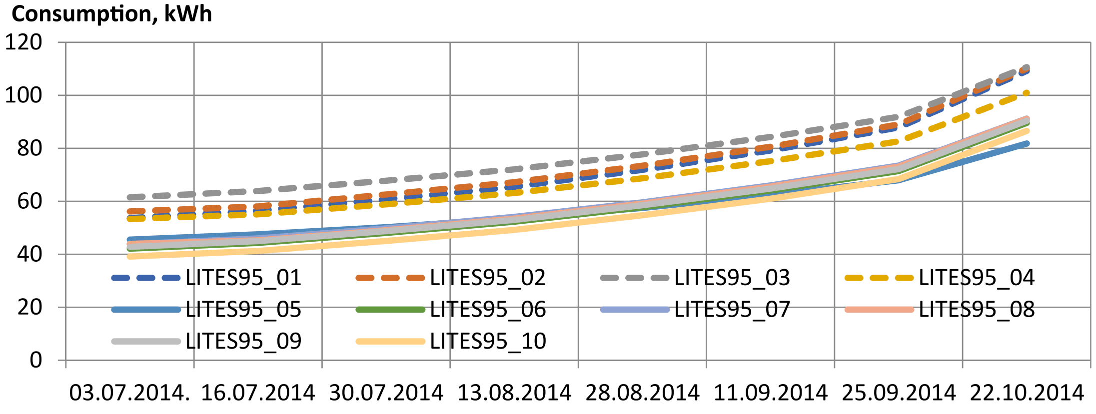


Fig. 4.10. Cumulative electrical energy readings (kWh) for each lighting pole.

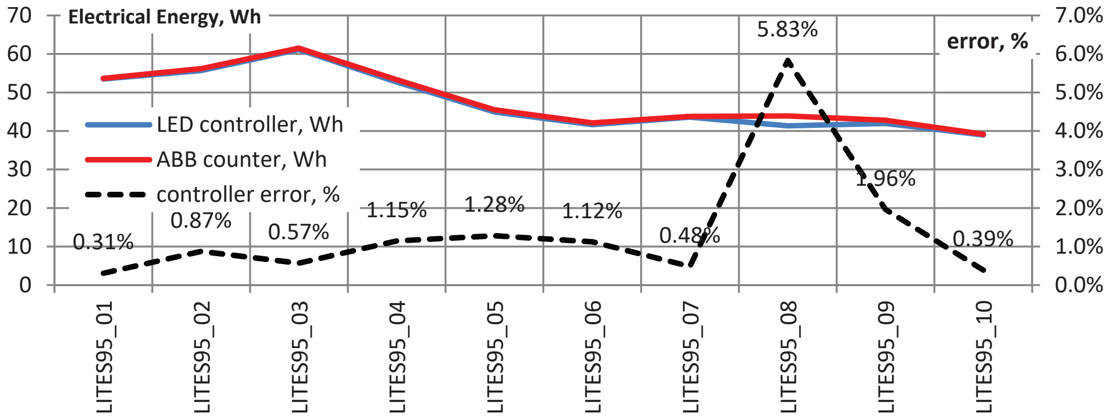


Fig. 4.11. Comparison of 95 W luminary (# 1–10) controller and energy meter readings.

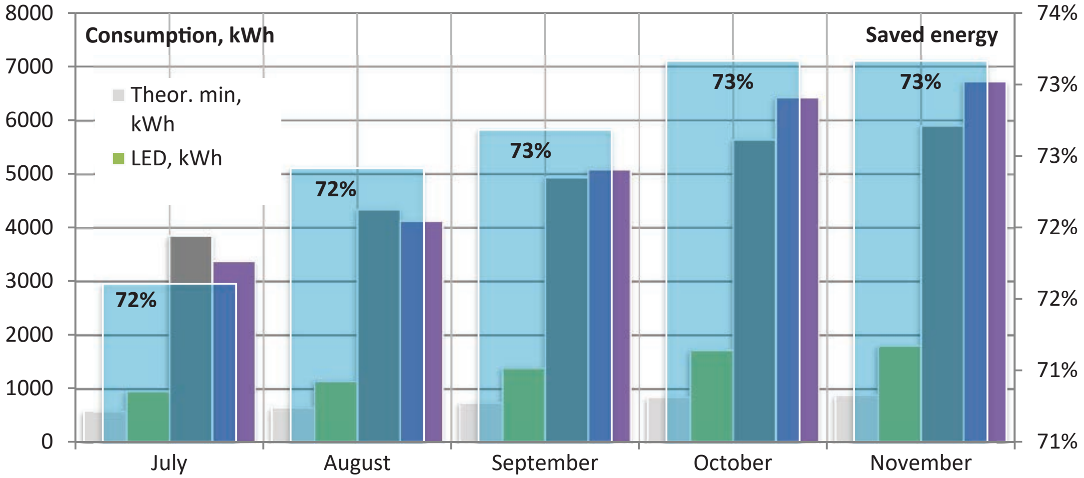
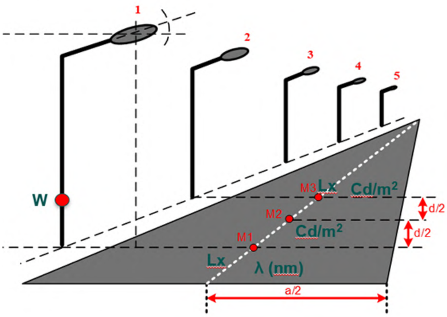


Fig. 4.12. Real energy consumption of smart lighting system at Ķīpsala Pilot Site.

Comparing the data sent by the LED luminary controllers to the segment controller (Fig. 3.2 e)), which sends data to WEB control software with the installed electricity meter readings (Fig. 4.11), it can be concluded that the deviation is 0.31–5.83 %, which in this case provides average error of 1.4 % that is a good result for the LED luminary power measurement node.

The lighting system of smart luminaries (LED3 type) with the movement sensor regulating mode reduces electricity consumption by 73 %, compared to the previously installed sodium luminaries over several months (Fig. 4.12). To understand street load against traffic intensity, the minimum consumption was analytically calculated: when no traffic intensity exists and LED luminary is dimmed to the minimum level, and maximum consumption was calculated: when luminary operates in maximum power mode, in line with the programmed luminary regulating profile (maximum traffic intensity for the respective hour of the day). It can be concluded that during the dark months of the year, energy efficiency and safety can be improved (the amount of lighting) if traffic intensity data for specific hours is known, which would consequently allow to apply the street M class (according to LVS 13210 standard).

The smart lighting system Citintely installed in Daugavpils was analysed as an independent system (it is similar to the smart system installed in Ķīpsala (Fig. 4.3)) that uses radio (RxTx) signal communication, and to detect movement – a radar (*Doppler effect*) type sensors are used. System with 1346 LED luminaries was installed in three city areas with different traffic intensity, on 65 different streets, out of which 33 streets were in the centre (M3/M4/M5 class) and others were M4/M5 and M5/M6 class streets in the suburbs. The goal of the measurements of power, lux, candle and spectral content was to determine the compliance of lighting system quality with the Dialux calculations (standard LVS CEN/TR 13201-1:2015) for M class, as well as to assess the dimming modes of LED luminaries in real life (1).



a) Smart lighting system measurement plan;

b) GPS coordinates.

Fig. 4.13. Smart lighting system measurement plan (a) and suburban GPS coordinates (b).

Light spectrum of each LED luminary was measured (AvaSpec-2048-USB2-UA (200–1200 nm)) and E_{spot} (luxmeter Hagner EC1) under the luminary in the middle of the street (Fig. 4.13), and for each rated power type of LED luminaries (37–137 W) power (Rohde & Schwarz RTH1004) value, street lighting and reflected illuminance from the road surface (candles – Konica Minolta LS-110) measurements (in total 130) were conducted.

Based on the measurement data, it can be concluded that in almost all cases, the actual lighting in the measurement spot on the street is higher than needed according to the Dialux model to comply with the minimum requirements for the specific ME class (Fig. 4.14). Exceptions were observed only on the streets with dense tree leafage or incorrectly placed lighting consoles. Based on the obtained values, it can be concluded that the actual amount of lighting is on average by 63 % higher than necessary, which can serve as energy saving potential. Such a deviation can be partially explained by the fact that in the Dialux calculations maintenance coefficient (MF) was used with the value 0.8–0.85, average street width and average distance between lamp poles not always comply with the actual situation.

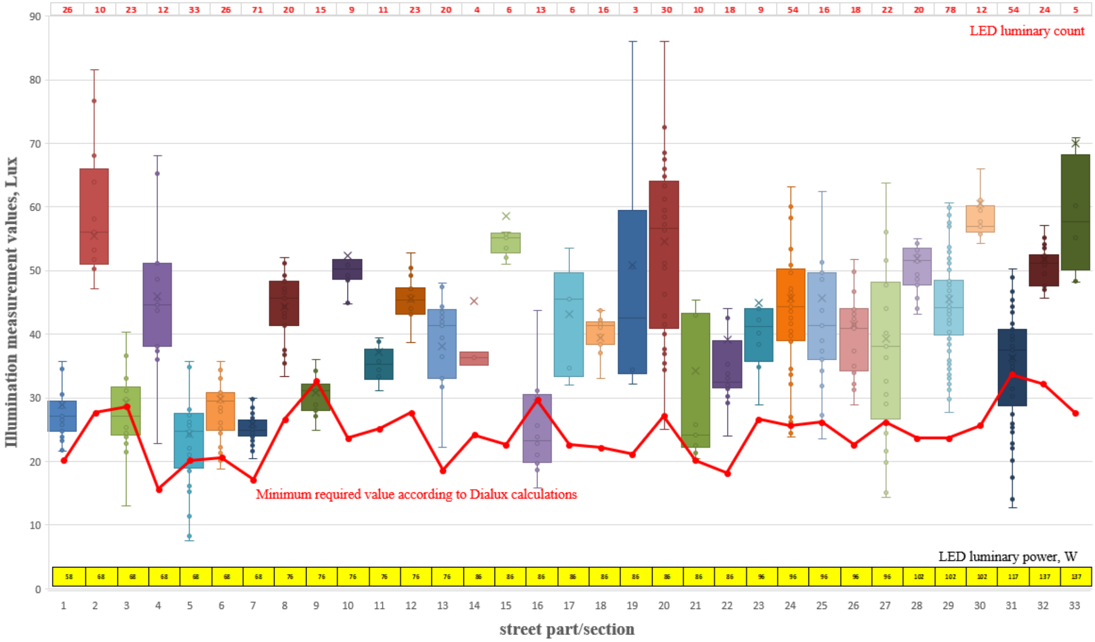


Fig. 4.14. Comparison of measured and Dialux calculation values.

As it is a smart system that is regulated based on the movement sensor and previously set dimming profile, it is interesting to view the total actual energy consumption of the devices installed in the lamp post in working conditions. In the Dialux calculations, linearised (proportional light and power) reduction approach was used to determine compliance with the respective ME class for the specific street.

According to Fig. 4.14, it can be concluded that the actual power reduction is not linearly proportional to percentage reduction, therefore non-linear approach has been applied, which is characteristic for LED diodes vs. light output. In the graph, differences between the planned installed power (P_{nom}) and actually measured ($P_{measured}$) power can be viewed, which are related to changes in the installation progress without introducing changes in the work plans (project). As opposed to the dimmed modes, at 100 % power, it can be concluded that LED luminary consumes on average by 6.7 % more than the nominally defined, which proves that the regulating method has to be improved, including also self-consumption of control and sensor devices, which would comply with the concept of smart luminary and the end user could count on realistic total consumption value.

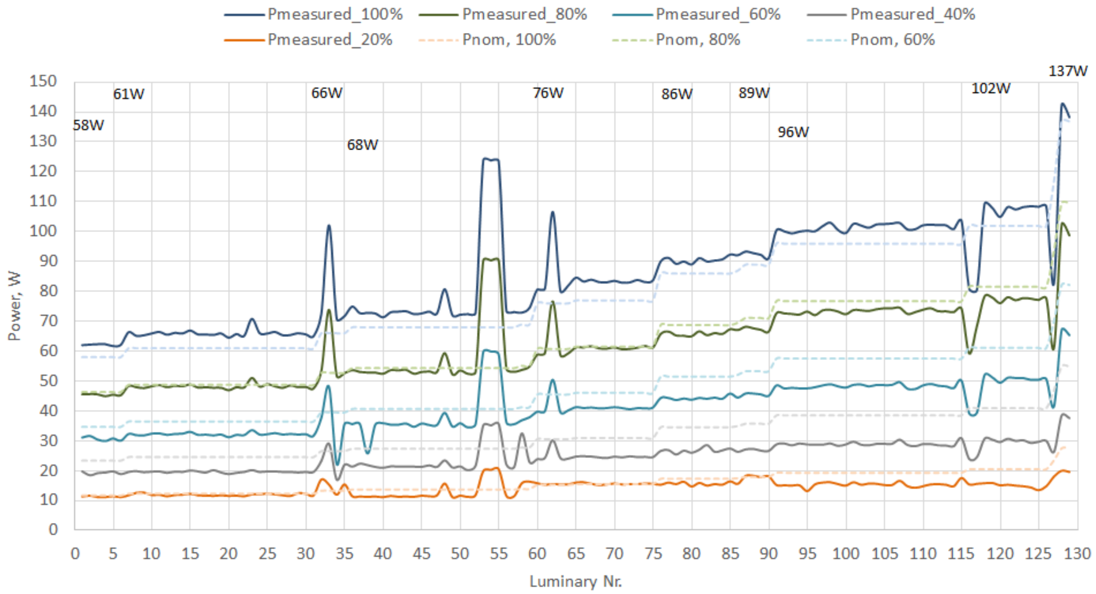


Fig. 4.15. Measured LED luminary (130 pcs) power values in dimming regime.

Smart street lighting systems, equipped with LED luminaries and movement sensors, can reduce electricity consumption by 69–73 %, and at the same time reduce the power of the installed luminaries by more than 50 %, ensuring the same or improved lighting quality parameters, if compared to the existing sodium high pressure light bulbs.

In case of smart LED lighting systems without movement sensors, it would allow to save approximately 51–72 % of electricity per month, which is up to 60 % on average per year, and the power of installed luminaries could be reduced by approximately 40 %, ensuring also lighting quality that complies with the norms and regulations.

Practical lighting measurements of new LED lighting systems show that the amount of actual lighting is on average by 63 % more than necessary, which consequently can be a potential electrical energy savings. Such a deviation can be partially explained by the fact that in the Dialux calculations maintenance coefficient (MF) was used with the value 0.8–0.85, average street width and average distance between lighting poles not always comply with the actual situation. As a result of measurements of the smart lighting systems, it is comparatively easy to change the almost linear light return (lx) and power (W) coherence, ensuring appropriate lighting class (M) for each lighting pole.

5. Adaptive Control Algorithm for Lighting System LED Luminaries

"Lighting upon demand" [19] or traffic-adaptive [22], [23] lighting management systems remain a topical issue. According to the LVS standards [10] it is already allowed to create 4 time zones (Δt_n) during night, defining their M or C classes, increasing or decreasing the lighting and P_{max}/P_{min} power levels respectively. If PIR (2 and 4), radar (7) or other dynamic movement detection sensors are used (1), the number of zones can be higher – every hour of night time can be a separate zone. The existing lighting management systems already can provide more than four of such time zones (Fig. 5.1). In this case t_0 is 3:00 p.m.; t_1 = 5:00 p.m.; t_2 = 10:00 p.m.; t_3 = 00:00 p.m.; t_4 = 5:00 a.m.; t_6 = 7:00 a.m.; and t_7 = 9:00 a.m.

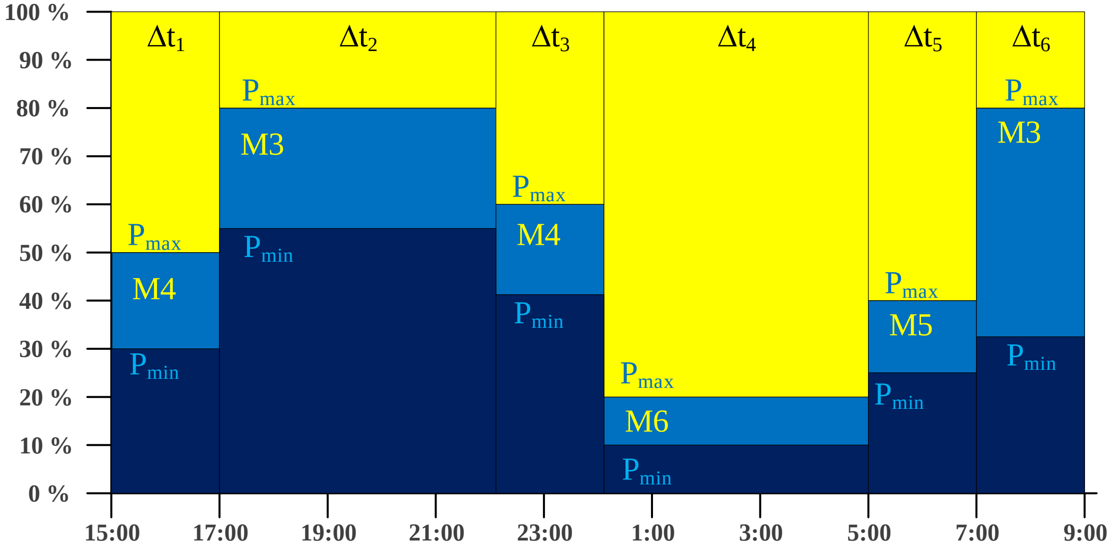


Fig. 5.1. Time slots of LED luminary dimming regimes and M class application sample.

Standard 13201-1 [10] provides road lighting of M class and C class conflict zone selection principles, considering geometric and traffic data. Standard 13201-2, in turn, provides minimum requirements for each class, where key quality parameters are average lighting (L, cd·m^{-2}), regularity of horizontal lighting (U_0), irregularity of longitudinality (U_l), dazing coefficient (f_{TI}) and background lighting (R_{EI}), and for C class average horizontal lighting (E, lx) and regularity (U_0).

Table 5.1

Minimal illumination average values for C and M class

M class	M1	M2	M3	M4	M5	M6
L, cd·m^{-2}	2	1.5	1	0.75	0.5	0.3
C class	C0	C1	C2	C3	C4	C5
E, lx	40	30	20	15	10	7.5

Comparatively, the lux values of C class are higher than M class, but to go from the candle units to approximate lux units, a linear coherency can be used (5.1). In the management software, such approach would allow to simplify the E_{spot} lighting value obtained in Dialux programme and actually measured, therefore allowing to determine more accurate required power to comply with the requirements of lighting class (5).

$$E(lx) = 1.027 \times (M)^2 - 13.7 \times (M) + 52. \quad (5.1)$$

The lighting Class M (or C) is determined by applying Fformula (5.2), where the varying weighted sum (VWS) is used or individual parameters that create the sum are analysed, where dynamically varying parameters (Table 5.2) are traffic speed () and traffic intensity (), and the constant parameters are the content of traffic participants (V_c), density of crossings (V_s), presence of parked vehicle (V_p), surrounding lighting (V_a), and complexity of navigation (V_n), considering that it is night time. The sum of constant parameters can vary between the whole value range from +8 to −1. If the VWS sum is less than 0, value "0" is used for calculations, if $M \leq 0$, Class M1 is applied.

$$M = 6 - VWS, \quad (5.2)$$

$$M = 6 - \left(V_v + V_i + V_c + V_s + V_j + V_n + V_a + V_n\right). \quad (5.3)$$

Table 5.2

Dynamic parameter (V_v) and (V_i) weight value conditions

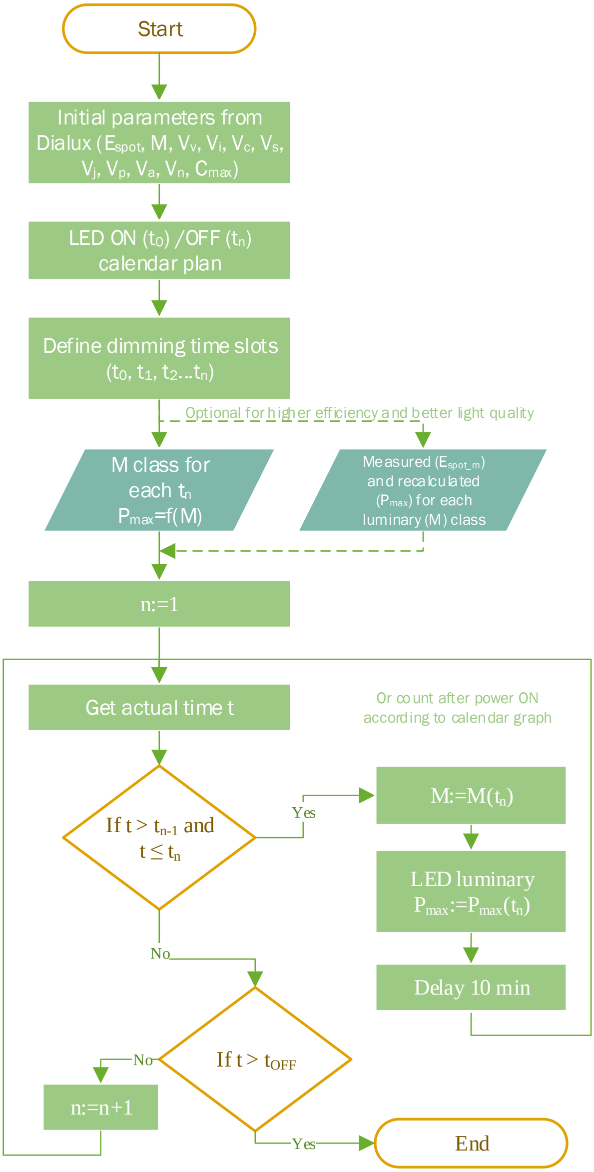
Parameter	Condition	Weight value, VW
Traffic speed (V_v)	$v \geq 100$ km/h	2
	70 < v < 100 km/h	1
	70 < v < 100 km/h	-1
	$v \leq 40$ km/h	-2
Traffic intensity (V_i) for roads with less than two lanes	>65 % of maximum capacity*	1
	35–65 % of maximum capacity	0
	<35 % of maximum capacity	-1
Traffic intensity (V_i) for roads with more than two lanes	>45 % of maximum capacity	1
	15–45 % of maximum capacity	0
	<15 % of maximum capacity	-1

* maximum capacity is maximum car count that passes road or lanes in given conditions and time slot in both directions, expressed as cars per hour or day.

LED luminary management algorithm for the option without movement sensor is provided in Fig. 5.2, where the luminary can operate independently or in case the controller has a communication node, receives management command from the central management system (segment controller). Controller memory stores initial parameter values (E_{spot}, M, V_v, V_i, V_c, V_s, V_j, V_p, V_a, V_n, C_{max}), defines the calendar lighting schedule for every day or by applying Formula 4.4, as well as sets the number and duration of dimming time zones.

From the Dialux model, M class of each zone is determined and the initial value of P_{max} power that provides it.

To ensure energy efficiency and improve lighting quality, after installation of luminaries it is possible to conduct lighting (E_{spot}) measurements (Fig. 4.13 a)) once in five years, afterwards correcting the initially set values. Further on, the actual time is determined based on the management system, built-in integral circuit or time-counting based on the city calendar schedule, according to which the time zone of the respective time of the day is determined and the appropriate M class is selected, based on which the controller regulates the LED ballast at the necessary power level. Afterwards, the actual time and actual time zone is checked every 10 minutes. If $t > t_n$, it is also checked whether it has not exceeded the turning off time when the luminary is turned off, otherwise variable n is increased by 1 and the cycle repeats in the next time zone.



5.2. att. LED luminary control algorithm for scenario without sensor data (standalone regime).

Figure 5.4 shows LED luminaries with dynamically adaptive management algorithm for the option with movement sensor data for local and network connected mode, where one sensor can manage also the nearby luminaries. Similarly to the independent mode algorithm, the beginning is identical, but as smart PIR sensor detects the traffic movement speed (V_v), traffic intensity (V_i) and maximum traffic capacity (C_{max}), traffic direction (N_L – left; N_R – right) and the number of each direction movement event or number of vehicles N over the respective time frame T (in this case it is one hour), these parameters are used for calculations. N_i is an "i" measurement in succession over a specific time period (in this case one hour), regardless of the movement direction, i.e., $N_i = N_L + N_R$.

$$V_i = N = \sum_{T}^{T+1} (N_i) \tag{5.4}$$

C_{max} is expressed as the number of vehicles per day, and maximum value can be the maximum value of the previous day or maximum value over the period of several days (for example, a month). It is assumed that the maximum value of traffic capacity can increase unexpectedly only due to extraordinary circumstances or due to planned events (exhibitions, concerts, etc.), and to avoid seasonal impact on the changes of class values, shorter period is better.

$$C_{\max} = \sum_{T-24}^{T} (N) \tag{5.5}$$

Traffic intensity (V_i) is the actual number of vehicles at one spot, i.e., near the lighting pole.

Traffic speed (V_v), according to the standard, is the maximum speed limit that is determined by a road sign for a specific street section (or time of the day) because the actual speed data have not been obtained so far. Therefore, this parameter can be dynamically changed based on the actual values that can be obtained from the movement sensor (for more detailed construction and operating principles see publications (2 and 4). Average speed based on sensor data can be calculated in two ways:

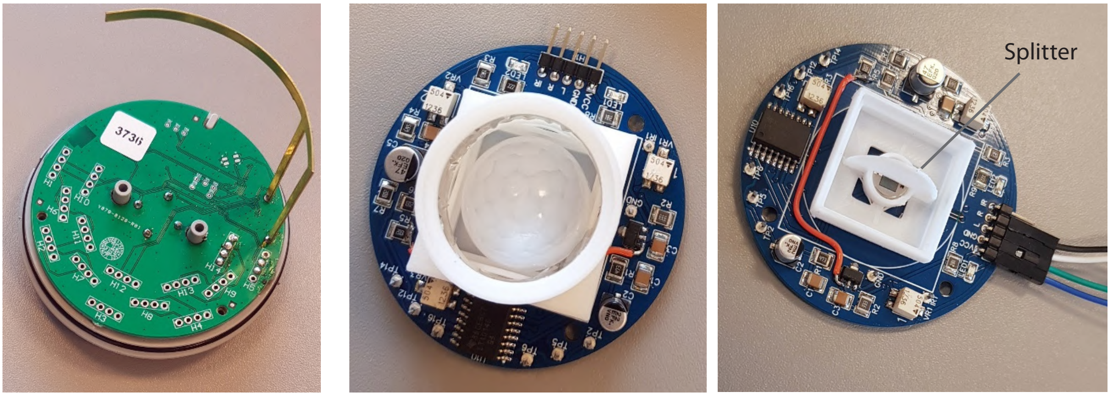
$$\overline{v} = \frac{\Delta x}{\Delta t}, \tag{5.6}$$

$$v_i = v_{\text{avg}} = \frac{d}{\Delta t}. \tag{5.7}$$

where $\overline{v}$ is the average speed for the movement over a specific period of time $\Delta t = t_{end} - t_{beginning}$ that complies with the radar sensor approach when there are several measurements while the vehicle is in the sensor visibility zone.

v_{avg}, in turn, complies with the PIR sensor approach whose visibility zone is at 19° angle and, depending on the height of the installed sensors, the road width "*d*" in the sensor visibility zone changes and it is *d*/2 for the specific element. As the PIR sensor (Fig. 5.3 b)) has two detecting elements that are separated by a "barrier" (Fig. 5.3 c)), one of the elements detects $t_{beginning}$ and the second t_{end}; it should be noted that in the event of movement direction change, the times are registered as opposite calculating Δt_{LR} or Δt_{RL}. As the speed can be inconsistent over entire section of the street, the speed value can be calculated as average value for entire street section, based on the total distance between lamp posts and total time spent, however, it is more difficult to identify and make calculations with such an approach for every vehicle, considering the peculiarities of the used sensor. M class requires average V_v values are calculated once in an hour ($t = 0$ up to $t = 60$ min) or once in a minute ($t = 0$ up to $t = 60$ sec), depending on the needs of dynamic algorithm accuracy.

$$V_{\text{v}} = \frac{\sum_{t=0}^{t=60} v_i}{i} \tag{5.8}$$



a) communication module in ZHAGA housing; b) PIR sensor PCB plate; c) splitter.

Fig. 5.3. Developed PIR sensor prototype.

For a more dynamic or more predictable lighting class change, sensor data can be calculated over a shorter period of time, for example, every 10 minutes, thereby improving the accuracy of the selected M class or creating a coefficient system, based on historical data that would predict potential increase or decrease of the M class in the coming hour.

Further on the algorithm checks in which range V_v is, consequently changing M class (), and determines the impact of V_i parameter on M class (). Then it detects whether the luminary has to be individually regulated or entire group has to be selected for new regulation parameters, consequently changing the set P_{min} and P_{max} values. The actual time is obtained and it is checked whether it does not exceed t_n, in that case turning off the lighting, if not, the cycle is repeated after the delay of 10 minutes.

As dusk or glare sensor, the developed comparatively cheap RGBC integral chip based spherical sensor (6) can be used, which can determine the spectral content of the LED luminary (peaks of red, green and blue spectrum) and the relative amount of light, by some modifications it can determine the bright or dark time of the day, the increase of the reflected light, for example, approaching vehicle or wet asphalt in rain or snow conditions, therefore allowing to decrease the lighting level and creating additional energy savings, or otherwise increasing it and thereby improving the comfort of the driver [20], [21], traffic safety from the point of view of lighting.

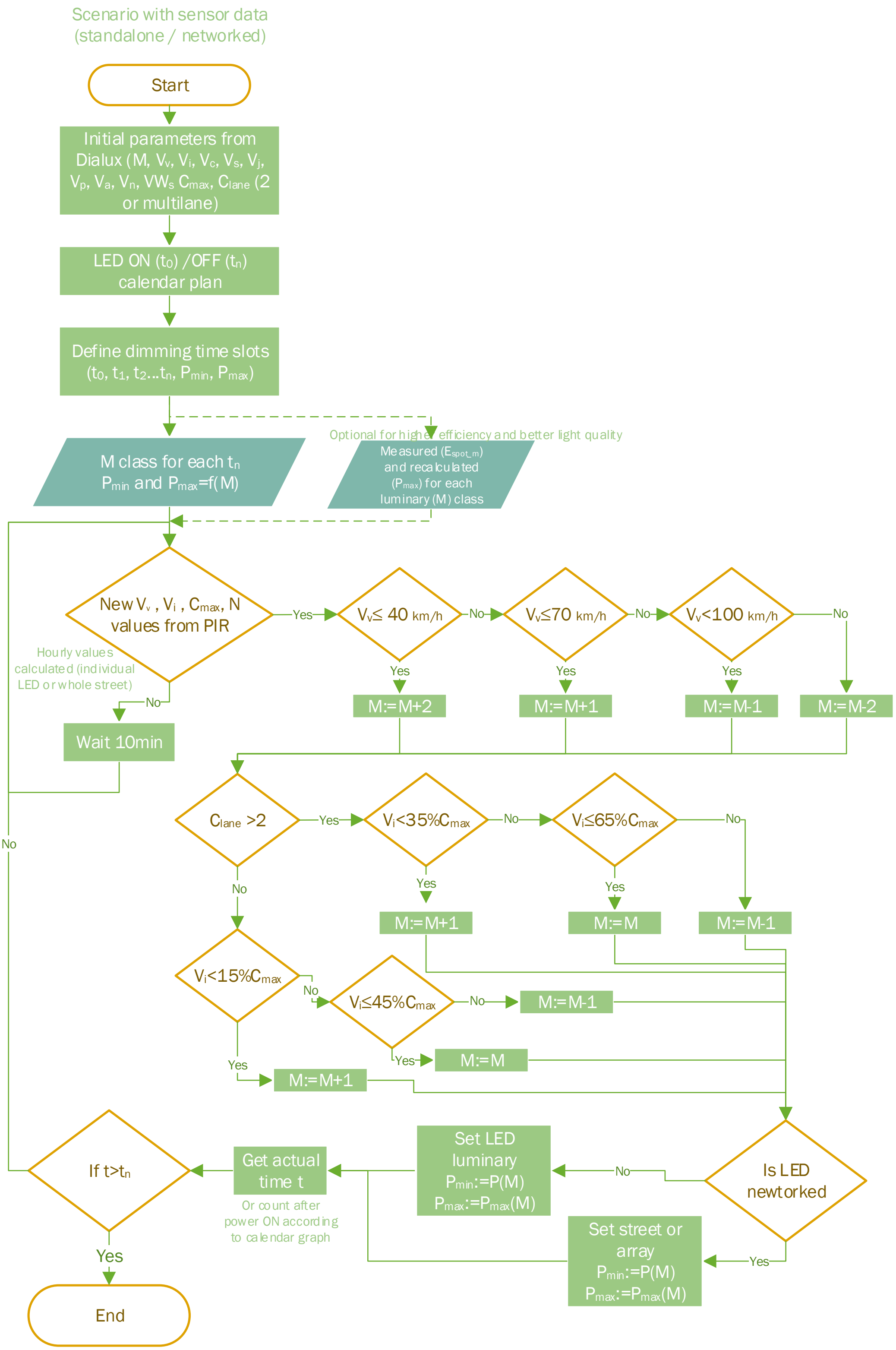


Fig. 5.4. LED luminary adaptive control algorithm for scenario with smart sensor data (standalone or networked regime).

The created dynamic management algorithm actually allows to manage lighting adaptively to the traffic intensity based on historical data, moreover, individual luminary and centralised system management can be provided for entire street or groups of streets over the ranges of several time zones of the day, therefore obtaining maximum efficiency and not reducing the traffic safety from the point of view of lighting.

Conlusions

The efficiency coefficients of smart LED lighting ballasts (including LED driver node and control node consumption) at nominal load parameters are above 0.80, which is proved by experimental measurements, where efficiency coefficient is 0.88 at the load of 150 W and input voltage range from 130 V to 256 V. Efficiency can be improved by choosing parts with specific nominal parameters and type of housing (for example, resistors, condenser, semiconductors) that would improve the efficiency by at least 2–5 %.

The created thermally compensated shunt allows to integrate the electricity consumption meter of LED luminaries in the PCB plate, thereby reducing manufacturing expenses compared to other solutions that use more expensive material with lower temperature coefficient of resistance. The novelty of the solution is proved by the received WIPO patent.

Smart street lighting systems equipped with LED luminaries and movement sensors allow to reduce electricity consumption by 69–73 % and reduce the installed power of luminaries by more than 40 %, systems without movement sensors allow to save approximately 51–72 % electricity per month, which is up to 60 % on average per year, and the installed power of luminaries can be reduced by 40 % approximately, thereby ensuring the same or improved lighting quality parameters if compared with the existing high pressure sodium luminaries.

Practical lighting measurements of new LED lighting systems with radar movement detection sensors show that the amount of actual lighting is on average by 63 % more than necessary, which consequently can be a potential electricity savings source. As a result of measurements of the smart lighting systems, it is comparatively easy to change the almost linear light output (lx) and power (W) relationship, ensuring appropriate lighting class (M) for each light pole.

The developed dynamic control algorithm allows controlling lighting adaptively to the traffic intensity, based on the historical data, moreover, it is possible to control individual lighting and centralised system – entire street or groups of streets.

In future research, it is planned to improve dynamic control algorithm, implementing predictive model and applying histogram coefficients, as well as to study replacement of the existing alternating current (AC) lighting system electrical grid with the direct current (DC) micro-grid, where it could be possible to reduce the existing electricity consumption by additional 5–10 % and obtain additional functionality of lighting infrastructure (for example, charging of electrical appliances, local solar energy transmission, communication network, etc.).

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Appendices / Publications

Appendix 1

A. Avotins, L. R. Adrian, R. Porins, P. Apse-Apsitis, L. Ribickis. Smart City Street Lighting System Quality and Control Issues to Increase Energy Efficiency and Safety. Baltic Journal of Road and Bridge Engineering, **2021**, Volume 16 Issue 4: 28–57. ISSN 1822-427X/eISSN 1822-4288.

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SMART CITY STREET LIGHTING SYSTEM QUALITY AND CONTROL ISSUES TO INCREASE ENERGY EFFICIENCY AND SAFETY

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Abstract. According to standards, the lighting system is one of the key elements to provide safety on city roads, defined by quality parameters. LED technology and movement detection sensor interaction bring about new regulation techniques, creating an energy-efficient smart LED lighting system concept. This paper reveals extensive comparative data analysis of Dialux simulation results before the project implementation phase and in-situ quality parameter measurements for various street profiles and LED luminary power types. After the project implementation phase, more than 1000 measurement points are

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reached. Further, energy efficiency increase issues in smart lighting systems are described in terms of LED luminary dimming profile analysis and future dynamic control application modes. The first findings clearly show that in most cases light output in simulation results is lower than in real situations; therefore, LED luminary power can be decreased, allowing for higher energy savings in first luminary maintenance years, keeping the same defined ME class or safety level. Let us suppose that the traffic intensity data are obtained from smart system sensors. In that case, the ME class can be dynamically selected during different night times, thus increasing safety and providing extra energy savings using the same system elements, as well as leading to better ROI values.

Keywords: energy efficiency, road safety, LED lighting systems, quality, smart city, intelligent control, in-situ measurements.

Introduction

Street lighting technology was created to increase safety on roads and decrease burglary during darkness hours of the day (incl., dusk, dawn and nighttime). When looking at traffic accidents or automobile fatalities, this statement is described in a journal article (AIEE, 1935) analysing data from various USA cities and revealing that without daylight, fatalities are 3–4 times higher than in normal lighting conditions, even traffic intensity decreases. Studies (Crabb & Crinson, 2008) devoted to public roads of Great Britain also show that in nighttime less accidents happen than in daytime, and streets that have a lighting system still have more accidents than streets without it, but the severity ratio is much lower. In later years, street lighting systems became more prevalent in large and small cities with the introduction of high-pressure mercury vapour lamp (HME) luminaries. Later, they were changed to more energy-efficient high-pressure sodium vapour (HPS) lamp luminaries, which are still used as the primary technology around the world. Also, several quality standards (CEN/TR 13201 part 1-5) for measurements and maintained photometric parameter limits, adopted by many countries worldwide, were developed for this technology and continuously updated according to technological developments.

Introduction of high-power white Light-Emitting Diode (LED) by Shuji Nakamura led a new revolution in the lighting industry, making possible to install new luminary designs in street lighting applications. LED manufacturing companies (such as Cree, Philips, Osram) continuously improve the LED efficiency (Lm/W) ratio, at the same time also decreasing the LED costs, which also affects the final costs of the LED luminary at the end-user side. LED luminary total lumen (see Fig. 1) output is influenced by many factors during the luminary manufacturing process. Therefore, the initial LED chip manufacturer efficiency (Lm/W)

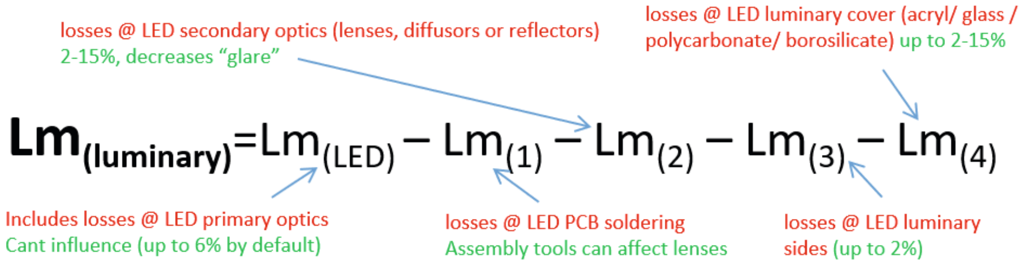


Figure 1. Typical places of total luminary lumen losses in LED luminary manufacturing process

decreases, creating a considerable difference between light source efficiency and luminary efficiency.

The LED luminary total power consumption (W) is determined by the nominal power of the light source (LED), summed with LED driver (power supply) losses and also the consumption of other peripherals, like sensors, communication and control nodes. Many parameters can lead to various interpretations in LED luminary datasheets and Dialux (Dialux EVO) type software modelling input data precision, affecting the overall street reconstruction project or luminary retrofit plan, as wrong power maximum or LED luminary itself can be selected. Furthermore, the choice of proper LED chip (see Fig. 2) for the application field (street, indoors, decorative, park, for example) can have large differences in overall efficiency. We can see that small-size LEDs are more efficient

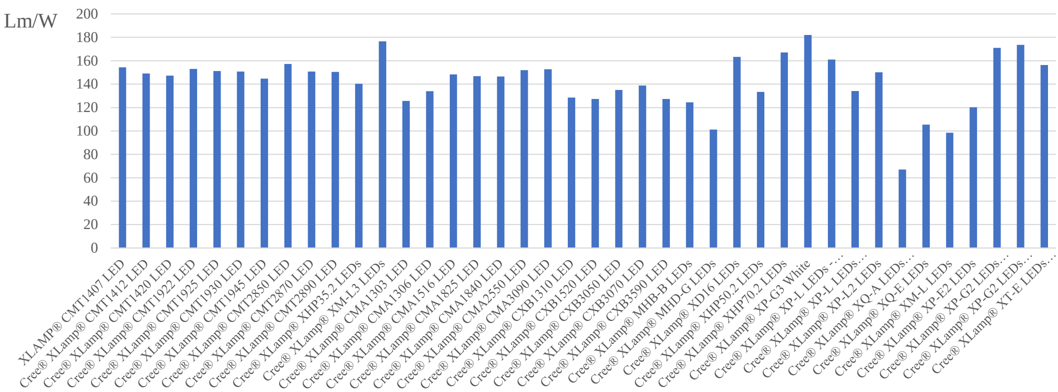


Figure 2. Cree LED manufacturer different LED chip comparison in terms of efficiency (Lm/W), date obtained at the end of 2020

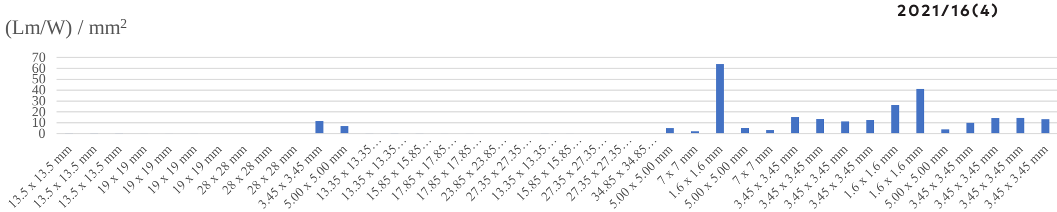


Figure 3. Cree LED manufacturer different LED chip comparison in terms of efficiency (Lm/W per its size in mm^2), data obtained at the end of 2020

(see Fig. 3), but not applicable to street luminary design due to low power and light output.

As street profile geometrical properties and LED luminary quality parameters can vary, we can state that Dialux modelling results can have large errors in specific parts of street compared to in-situ measurements, using decreased safety (light quality is too low) or increased energy consumption (there is too much light). Further, the article will reveal some practical results of PilotSite measurements in Latvia for the period of 2009–2020, in the meantime also introducing to a lighting system advancement timeframe.

1. General aspects of street lighting evaluation

1.1. Related standards

For LED luminary, lighting pole, cables, communication and control equipment, many quality and safety-related standards have been developed that are mandatory in EU countries. Some are related to electrical quality (Low Voltage Directive and Electromagnetic Compatibility), others – to components used (RoHS and WEEE), housing (IP and IK class), light hazard to vision, etc. Latvian standard LVS CEN/TR 13201-1:2015 is directly related to safety and quality parameters on the street (or road) lighting, as it provides guidelines for the selection of lighting classes and is a part of EN13201 standard group (CEN/TR standards, parts 1–5). This standard was updated in 2015, introducing four-time intervals (Δt_1: ON time till evening rush hour, Δt_2: evening rush hour till midnight, Δt_3: midnight till morning rush hour, Δt_4: morning rush hour till OFF time) for road lighting operation time. The need for such time intervals is that nowadays LED luminary power supplies can be programmed or controlled by PWM, 0-10VDC or DALI signals. Smart city lighting systems (Kuusik, et al., 2016) are equipped

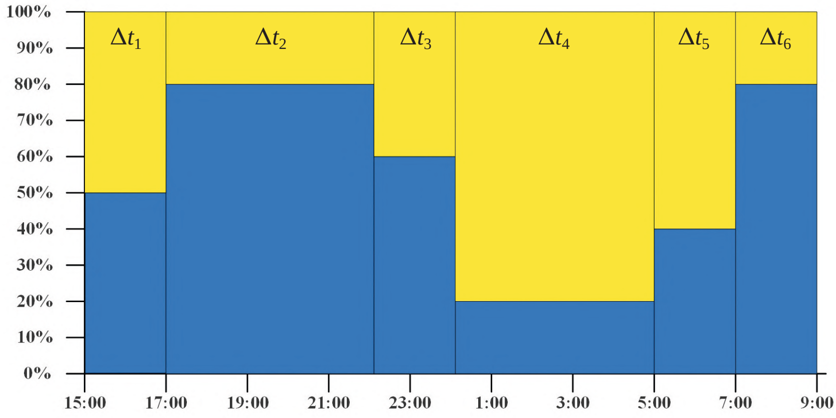


Figure 4. LED luminary nighttime intervals and programmed power output minimums/maximums for the movement sensor triggering signal control

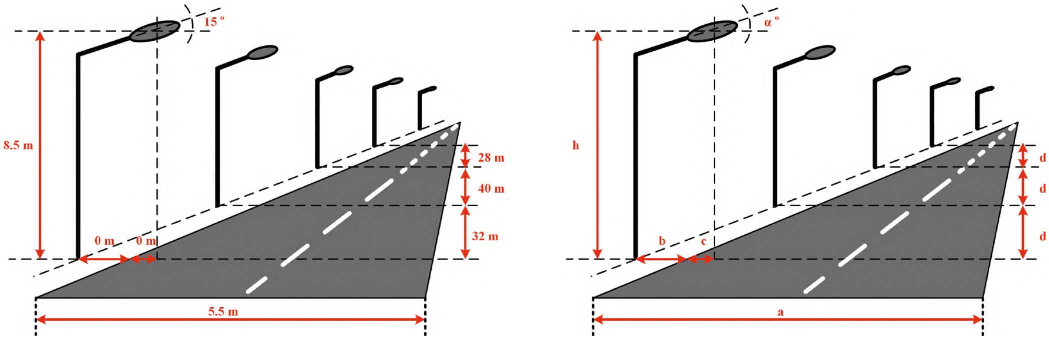
with motion detection sensors or remote-control systems (Avotins, et al., 2014), thus promoting additional energy savings, utilising sensor-triggered luminary switching ON/OFF in minimum or maximum power (light output). Moreover, it could be mentioned that some manufacturers create even more time intervals as shown in Fig. 4.

Each of these time intervals can have six different lighting classes for motorised traffic (M) (in Dialux versions it can be named ME1 – ME6) or conflict areas (C), also specified with quality parameters (average luminance L, U_0, U_l, f_{TI}, R_{EI}) by "Part 2" of this standard. The number of M class is determined by Eq. (1), using the sum of weighting (range: −2…0…+2) values of each criterion, such as design speed or speed limit, traffic intensity (% of max capacity), traffic composition, separation of the carriageway, junction density, parked vehicles, ambient luminosity, navigational task.

$$M = 6 - \Sigma VW_i M \quad (1)$$

1.2. Modelling in Dialux type software

When ME class number is determined for a particular road, it is possible to calculate light output quality parameters in modelling software like Dialux 4.0, Dialux EVO, Relux and similar for a particular LED luminary on lighting poles. Initially, all street profile geometrical parameters (a, b, c, d, α) must be obtained (Fig. 5b), such as type of road tarmac, lighting pole placement, traffic and pedestrian lane count, traffic directions and grass zones. In Latvia, two situations are



a) b)

Figure 5. The necessary geometrical input data for Dialux light distribution calculations

$$d = \frac{\sum L_n}{n} \quad (2)$$

possible, where pole distance is constant, typical of new or central streets of the city with steel poles (Fig. 5b), or with various pole distances (Fig. 5a), typical of old and smaller streets in rural parts of the city, mostly concrete or wooden based poles. It is difficult to carry out Dialux calculations for each pole distance; therefore, it is common in the industry to calculate average distance per street (Fig. 6), using Eq. (2) to have constant value d. This unified approach has an impact on safety and energy efficiency.

Standards also determine LED luminary light distribution measurements in (C, γ) system, where C is semi-plane every 5 degrees and γ – gamma angles every 2.5 degrees. After these measurements are performed in the laboratory (using goniophotometer), a luminary light

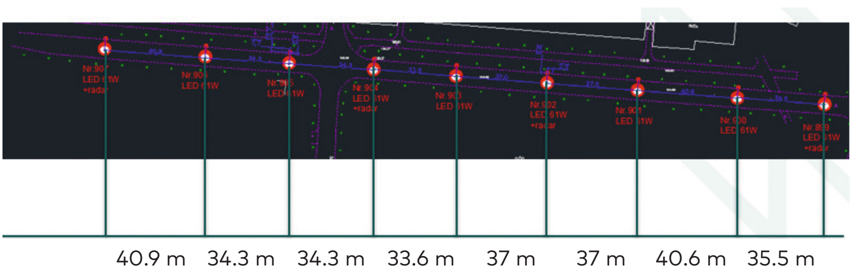


Figure 6. Sample of AutoCAD format (*.dwg file) topographical layout for street lighting with various pole distances

Table 1. The main lighting parameters describing safety performance of a road lighting system

Parameter	Formula	Notes
Illuminance, *E*, lux	$E = \frac{\Phi}{A} \times \cos\alpha$ (3)	Can be measured with luxmeter
Light intensity, *I*, cd	$I = \frac{\Phi}{\omega}, I \approx \frac{E \times r^2}{\cos\alpha}$ (4)	Can be measured with luminance candela meter
Luminance, *L*, $cd \cdot m^{-2}$	$L = \frac{I}{A}$ (5)	Can be measured with luminance meter
Threshold Increment, *TI*, %	$TI = \left(\frac{k \times E_e}{L_{av}^{0.8} \times \Theta^2} \right); k = 641 \times \left[1 + \left(\frac{A}{66.4} \right)^4 \right]$ (6)	Calculated from measurable values, *k* is a constant depending on age (*A*) of the observer
Maintenance Factor, MF	$MF = (LLMF \times LSF) \times LMF \times RMF$ (7) *LLMF* – lamp lumen maintenance factor *LSF* – lamp survival factor *LMF* – luminaire maintenance factor *RMF* – room maintenance factor *SMF* – surface maintenance factor	Calculated from street, manufacturer datasheets/ test reports, maintenance performed, etc.

distribution file in *.ies or *.ldt format can be obtained from luminary manufacturer and used for Dialux simulations. According to Czyżewski (2018), the more accurate the measurement step of C and γ angles, the more realistic modelling results can be obtained afterwards. This can influence the overall safety on the road, as too much light has an impact on Threshold Increment (f_{TI}), which is a measure of disability glare expressed as the percentage increase in contrast required between an object and its background for the object to be seen equally well with a source of glare present (luminary itself and road surfaces, especially if wet).

After Dialux calculations, the software gives resulting values of quality parameters (average luminance L, U_0, U_l, f_{TI}, R_{EI}) and fulfils the minimum requirements of the EN 13201 standard. Also, it gives light distribution across the street surface in candelas (I) or lux (E) values, using the isoline curve 2D graph of the predefined resolution matrix. This way we can select the resolution matrix (4 × 11 points or more) according to our street width and pole distance to measure those values after luminary installation and compare them with Dialux simulation results. If such a procedure is performed, then the street quality and safety can be increased, and potential energy will decrease, especially if too powerful LED luminary has been installed in the specific road part. Table 1 gives an overview of the main parameters used in Dialux modelling and formulas that can be used for measurement analysis or the obtained result comparison.

1.3. Road lighting safety issues and different perspectives

The lighting system has evolved to "smart lighting system", exploiting integrated ICT nodes and getting the ability to control and monitor individual LED luminaries. Nevertheless, the high system installation costs and low ROI values have added additional value to the lighting system, becoming an essential part of what we call "Smart City". Thus, now we have different perspectives of such a system, as we can distinguish *city level*, road *user level* and lighting system *component level*.

At the *city level*, the municipality (or subcontracted lighting maintenance company) is interested in keeping the maximum traffic safe at the lowest operating costs and potentially adding new functions & services. In this way, it is a mix of needs. Depending on a decision-maker and available budget, the focus and strategies can differ, but the budget issues will always prevail over the safety. The typical solution in Latvia for HPS luminary lit streets is to switch OFF 2/3 of phases, and it means that each third light pole is ON. In smart LED luminaries, they can be dimmed, thus keeping at least some safety level, even it will not fulfil the ME class criteria. The luminary damage or even complete street blackout due to cable damage can be detected by individual luminary communication fail, or by using computer vision and image data processing to remotely localize and monitor blackouts (Zanjani et al., 2013). In large and wealthy cities, a smart LED lighting system is a key to decreasing human work maintenance costs. However, in smaller cities it could be a problem to find damaged LED or HPS luminary (or trace the lumen deprecation); thus, traffic users or volunteers could help maintain urban safety by using smartphone application-based idea (Alam et al., 2020), which is scanning lighting parameters under to pole, while the user is riding a bike.

At the *user level*, it is expected that the roads and streets are safe and lighting is available as much as possible, since studies (Mattoni et al., 2017) show that pedestrian safety perception (and also evaluation) is linearly related to the mean horizontal illuminance. It also means no blackouts, stable light output, long lifetime, high-quality products, resulting in higher installation and operating costs. The main complaints to smart city lighting systems are unused white-spectrum of LED light compared to yellowish HPS light, if sensors attached to speed up (up to 1 second) light ramp-up un ramp-down times turning light ON and OFF create "disco effect" annoying the people. So far, the slow ramp-up time slope (1–3 seconds) helps the human eye adapt to light changes and eliminates this problem.

At some point it could be possible that the *city* and *user levels* start to interact, as described in the article about hybrid city lighting (Siess et al., 2015), where it is suggested that the street can become a display, thus enabling interactivity and increasing safety for pedestrians (especially children). The main focus is placed on attracting pedestrian attention to dangerous situations (for example, pavement, street crossing) using visualization and game elements such as “soccer”, “footprints”, “the floor is lava”, “clear ice detection”. The car traffic user can also be notified, for example, by sending a visual warning that can be seen ahead, especially useful if a child runs onto the street unexpectedly hiding behind car/bus (not visually detectable by the car driver).

Interaction between the user levels can also be obtained; to increase safety on streets, the exciting idea is to implement a “panic button” (Priyanka et al., 2019), which can be installed in light poles and help road users in case of an emergency (car accident, unexpected health problems, or any other “112” case). An integrated microphone or web-cam can improve the safety and data reliability even further, as the system can send some additional information to the central system for proper decision making.

At the system *component level*, the challenge is the highest. Here, demands from the city level and the user level must be fulfilled; thus, the system, component design and production require a lot of knowledge and continuous improvements. For example, we know that power LED chip used for street lighting emits blue light, and a phosphoric layer makes this light in the white spectrum of visible light. The dominant wavelengths depend on the materials used by LED manufacturer, and a luminary manufacturer typically uses 1 type of LEDs on the same PCB as the light source. One of the spectrum parameter related studies (Maierová, 2018) deals with safety and visual comfort on the streets, as the sensitivity of the human eye, according to CIE *Purkinje shift* and activity of photoreceptors, differs during nighttime (scotopic, mesopic and photopic visual function). Red+Amber LED biodynamic lighting is introduced to stimulate user perception during evening and morning rush hours biologically, and non-stimulating lighting for rest in the nighttime (blue LED spectrum is switched OFF) also helps decrease biological impact on wildlife and not disturb resident sleep.

The manufacturer is willing to sell the product; therefore, the product must have a low price, long lifetime and good ROI values. For this reason, it is a tradeoff of price, component selection, compatibility, quality and functionality. The electrical safety of lighting system starts with protection against indirect contact (automatic power supply disconnector) and good TT, TN-C or TN-S grounding system selected (Parise et al., 2011), further, the luminary and AC-grid connecting wires should have Class II reinforced insulation to be installed in metal poles. Another safety aspect is a lightning strike that can hit one luminary and pass to the next luminaries through lighting grid, thus destroying a large number of luminaries or even the whole street. In this case, a protecting device can be used to avoiding such damage, but once again it affects the end-price of product.

The street profile and street crossings can also experience dangerous situations, such as multilane crossing, low visibility conditions, oblique crossing of lanes, absence of adaptive zones, crossing outside a marked pedestrian crossing. The study (Bláha et al., 2014) shows that cloth luminance decreases nine times in such cases (from 17.7 cd/m^2 to 0.5 cd/m^2). Thus, proper CE class selection is essential. Post-installation measurements should be mandatory, especially if Charge-Coupled Devices (CCD) or cameras (Armas et al., 2007), like LMK Mobile Air, are available on the market. Such preliminary or approximate validation (Kuusik et al., 2016) can save much time and allow for the analysis of many parameters.

2. Light control for smart street lighting

2.1. Smart street lighting system components

Smart street lighting systems have several main system components, as shown in the LITES project example (see Figs. 7 and 8a). Management software communicates with ZigBee gateway through the Ethernet network, mainly taking readings of luminary status, power consumption, and updating light control profiles to the luminary or the gateway. The gateway communicates by ZigBee mesh network with the LED luminary "control node", which is an electronic device/controller that reads the signal from a motion detection sensor (True/False status

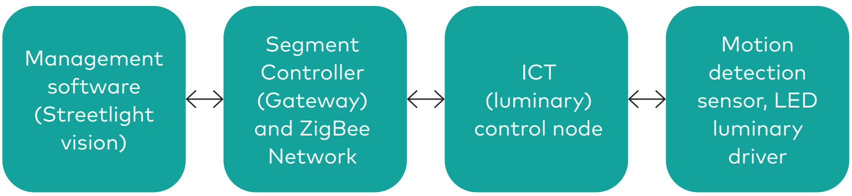
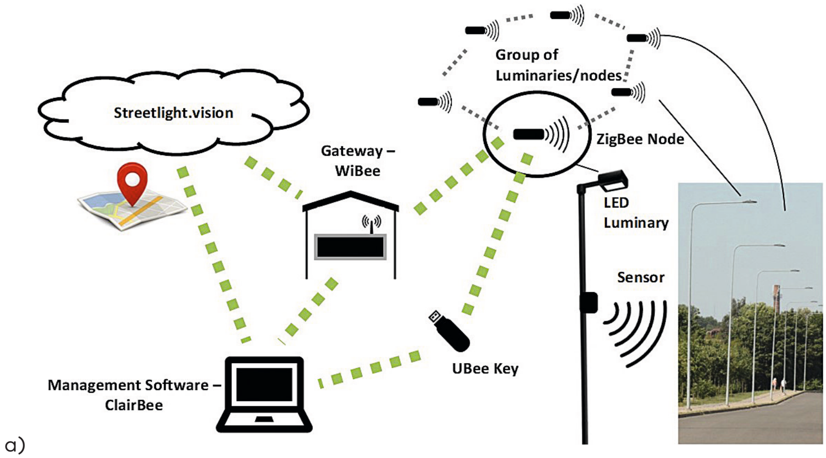
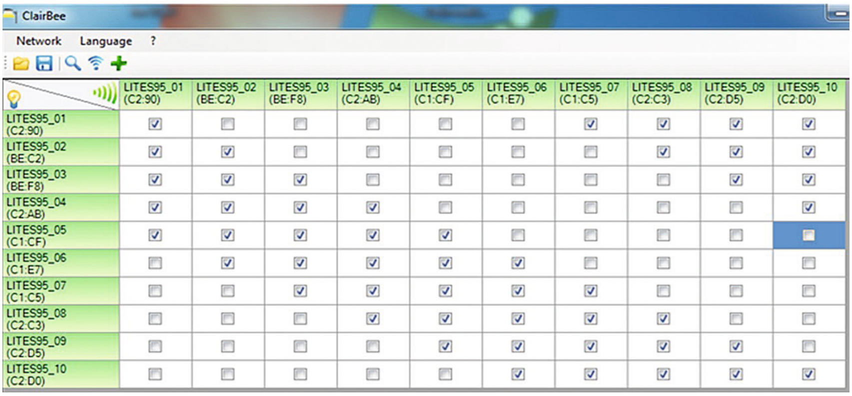


Figure 7. Smart street lighting system layout created in LITES project and used in Riga PilotSite



a)



	LITES95_01 (C2:90)	LITES95_02 (BE:C2)	LITES95_03 (BE:F8)	LITES95_04 (C2:AB)	LITES95_05 (C1:CF)	LITES95_06 (C1:E7)	LITES95_07 (C1:C5)	LITES95_08 (C2:C3)	LITES95_09 (C2:D5)	LITES95_10 (C2:D0)
LITES95_01 (C2:90)	☑	☐	☐	☐	☐	☐	☑	☑	☑	☑
LITES95_02 (BE:C2)	☑	☑	☐	☐	☐	☐	☐	☑	☑	☑
LITES95_03 (BE:F8)	☑	☑	☑	☐	☐	☐	☐	☐	☑	☑
LITES95_04 (C2:AB)	☑	☑	☑	☑	☐	☐	☐	☐	☐	☑
LITES95_05 (C1:CF)	☑	☑	☑	☑	☑	☐	☐	☐	☐	☐
LITES95_06 (C1:E7)	☐	☑	☑	☑	☑	☑	☐	☐	☐	☐
LITES95_07 (C1:C5)	☐	☐	☑	☑	☑	☑	☑	☐	☐	☐
LITES95_08 (C2:C3)	☐	☐	☐	☑	☑	☑	☑	☑	☐	☐
LITES95_09 (C2:D5)	☐	☐	☐	☐	☑	☑	☑	☑	☑	☐
LITES95_10 (C2:D0)	☐	☐	☐	☐	☐	☑	☑	☑	☑	☑

b)

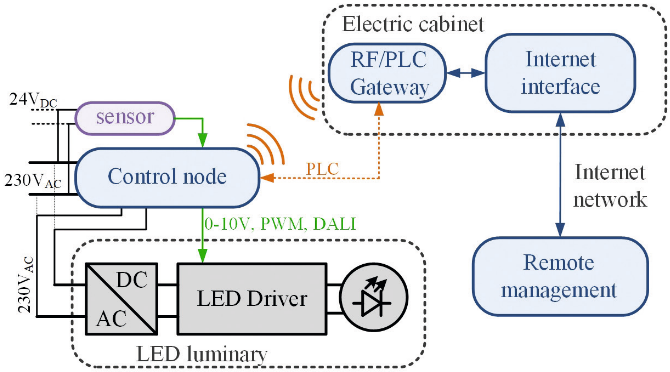
Figure 8. LITES smart LED lighting system (a), luminary network configuration (b)

signal) and sends a control signal (PWM, 0-10VDC, DALI) to the LED driver (power supply). Luminary configuration is performed by the gateway, by sending configuration files directly to a specific luminary, using UBee key (ZigBee communication stick) and software on laptop computers to communicate directly (in-situ) with LED luminary network. Sensor and luminary network association/configuration form is shown in Fig. 8b. It is easy to control five LED luminaries when one motion sensor is triggered, furthermore – as the distance between poles is 33m typically, it can lit light (to max value) 3 or 5 luminaries ahead, reaching the distance of 100–160 m, which is very safe for visual identification of obstacles or in case a car must stop rapidly.

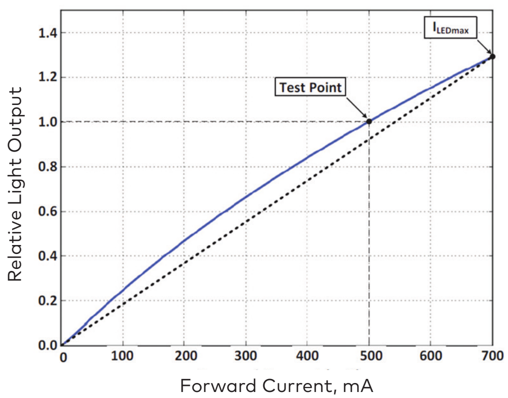
Movement detection sensor reads the movement and utilising a "dry contact" closes the relay output, and the control node understands that movement is happening; another luminary control node sends a "MAX level" signal/value of the predefined time interval (Fig. 4) to the LED luminary driver (Fig. 9a). When the sensor does not detect any movement, the contact releases (is open) and LED luminary gets a "MIN level" signal.

2.2. Dimming or light output control

In many control systems, the light output level or "dimming" control is implemented by linear means, assuming that LED luminary power output is proportional to the luminary light output value. From LED diode (Fig. 9b) measurements, we can see that this is not entirely true,



a)



b)

Figure 9. A sample of smart lighting LED luminary (a), and the relation between LED current and light output (b)

as LED diode volt-ampere characteristic is also nonlinear. By higher forward currents (A), the p-n junctions heat up more, also causing less light to be emitted, unless adequately cooled. Typically, LED luminaires have passive radiators; therefore, they cannot be entirely cooled down to avoid this impact at high currents.

Thus, depending on a LED luminary PCB design, nominal forward current (power) and LED driver feedback signal type, we can get around 8% error in light output, regulating the luminary in the 20–100% interval.

The same linearized light output and power relation approach is used for Dialux calculations to model the light parameters in the dimmed regime of the luminary, to check compatibility with ME class in dimmed regime, which typically is lower if the needed light amount is reduced. Therefore, we can assume that additional precision errors can also be found at this stage, causing too much light at specific power values. It can affect glare values in marginal cases. However, if Dialux calculations show ME or CE class compatibility, then the chance is really low, and safety should not be affected. However, in terms of energy efficiency, we could find extra savings here.

2.3. The existing control methods for dimming

The existing control methods of switching ON/OFF luminaries or even whole streets/districts are calendar-based. Each day of the year has different sunrise and sunset times, and city lighting is adapted. This method has been known for a very long time and is the most commonly used method for HPS luminary lighting. An upgrade to this system adds a photo-sensor to the transform substation or electric cabinet, controlling whole streets. HPS luminaires can be dimmed till a certain level (60–70%) of nominal power, using voltage regulation techniques, but LED luminaries – in the range of 1–100%. As some ballasts are programmable (built-in astronomic calendar, for example), they can have different power levels through certain time intervals of the night. These focus on energy consumption reduction, but only partly considering the safety or lighting quality issues on the road, as traffic intensity data are “assumed” values in specific periods. Next step in lighting control is to exploit the opportunities of movement detection sensor data. It can obtain periodic traffic count (intensity) data or even the direction and speed of traffic (Adrian & Ribickis, 2014). A car is a typical traffic user. Compared to a pedestrian, detecting a car can reduce danger for all traffic users; therefore, detection precision does not need to be of very high accuracy. Virtual sensors as context application (Avotins & Bicans, 2015) data from other systems can also be used to reduce energy consumption by 76% compared to the non-controlled LED lighting system.

In terms of hardware and software for smart lighting systems, many studies have been performed recently, and logical next questions lie in safe and energy-efficient control algorithm development. Even for LEDs, a *Brute force algorithm* (Mahoor et al., 2017) can be applied, as it uses movement sensor statistical data of previous periods to evaluate lighting levels (controls HPS luminary power). The approach is simplified and focuses on energy efficiency. The disadvantage is the safety issue, as the only element considered is the rush-hour time interval, where the algorithm is limited in dimming capabilities. Also, the HPS luminary power (150 W typically is bulb power) and light output relation are assumed to be linear, raising doubts about light quality on the street and compliance to the ME classes. Theoretical energy savings for Light-on-Demand model, considering traffic uniformity, speed and distance to stop it safely, is described in the research (Cela et al., 2019). It also includes symmetrical dimming around the car (from min to max level). It seems to be better suited for long and straight streets. It looks very complicated, as it uses SUMO model and does not calculate the required luminary power level according to current traffic amount.

A very promising LED lighting control strategy proposed in the research (Shlayan et al., 2018) considers traffic and road characteristics combined with traffic sensor data to determine ME class and exploiting *Greenshields' Traffic Model*. As a result, in two use cases, 86% and 89% power (P,W) reduction per pole can be achieved if compared to a non-controlled LED luminary case. To predict a traffic user behavior, *Cellular Automata (CA)* models (Yang et al., 2015), both for vehicle traffic and pedestrian, exploiting zone movement detection sensor data and interpreting the direction and path, make use of lighting control strategies of Light-on-Demand to next four LED luminaries.

3. PilotSite and experimental analysis

3.1. LED luminary tests for the period of 2009–2012

Initially, LEDs were designed for retrofit purposes (to replace HPS bulbs or whole luminary). In 2009, we were able to test first products in Riga (Latvia) PilotSite within Zunda Krastmala street premises (see Fig. 10a). At that time, LED was a new technology, and a lack of detailed technical data was a common problem for an end-user (like a municipality) to evaluate the quality. As in most cases, manufacturers (also wholesalers) declared incorrect or approximate time values, at the

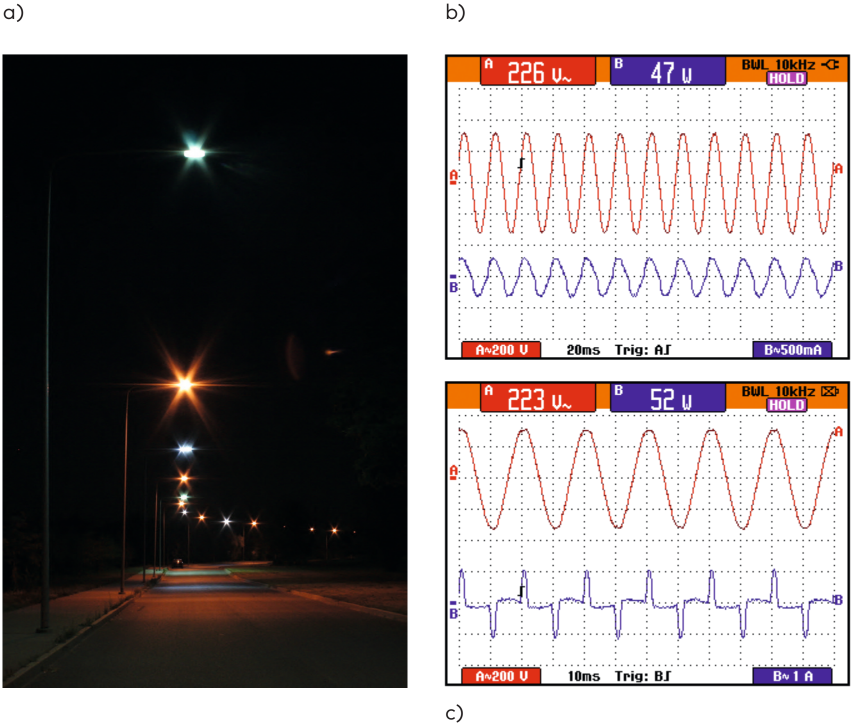


Figure 10. Results of measurements performed in 2009: a – picture of dry road PilotSite in Riga; b – AC voltage and current waveform for Cobrahead 48.7W luminary; c – AC voltage and current waveform for Diodella 52W luminary

same time keeping high prices (Joliet JOL6 225W sales price was around 1200 EUR and others were around 800–900 EUR, the retrofit bulb was around 200 EUR), which decreased the trust in LED technology itself.

In Table 2, we can observe initial parameters compared to laboratory and PilotSite measurement results. We can also observe that luminary efficiency was different by light colour temperature. The warm-white region (4000 K) was 48.5 Lm/W, and in the region of blue light (6000 K) it reached 60 Lm/W. Low power (or light output) allowed using these LED luminaires only on streets with ME5 or lower classes, and ME2 class was reached only by high power and blue light spectrum luminary. Also, the large difference of LED colour temperature compared to the yellow/orange colour of HPS was not well accepted by traffic users, if analysing more in details – it was also due to glare when entering the LED luminary zone. The consumed reactive power Q (VAR) is another quality-related issue. In Fig. 10, we see two different current waveforms:

Table 2. The main parameters of SMD/SMT based LED luminary tested in LAB and Riga PilotSite in 2009

Luminary	Lumens, Lm (by manufacturer)	Power measured, W	Temperature colour, K	Efficiency, Lm/W	ME class qualified
GE Cobrahead 25W	1203 (48.12 Lm/W)	24.8	4500	48.5	ME5
GE M250 Cobrahead 48.7W	2235 (45.89 Lm/W)	47	4500	47.55	ME5
Joliet 28W (retrofit bulb)	2100 (75 Lm/W)	35	5500–6500	60	ME5
Joliet JOL6 225W (street lamp)	12 600 (56 Lm/W)	219	5500–6500	57.53	ME2-ME5
Diodella (84 LEDs)	N/A (80 Lm/W)	52	4100	N/A	ME4-ME5
Starium Dragon	2367 (57.73 Lm/W)	Not measured	5600	N/A	Not measured
Cobrahead (80W)	4749 (59 Lm/W)	Not measured	5500–6500	N/A	Not measured

Note: In 2009, LED datasheets did not include detailed technical data.

luminary GE M250 Cobrahead 48.7W (Q = 17 VAR, cosφ = 0.97) (Fig. 10b) and luminary Diodella 52W (Q = 70.73 VAR, cosφ = 0.95) (Fig. 10c).

The end of the year 2010 marked another test that was performed at RTU laboratory and on another street of Riga, testing three different power Photon-L street luminaries named "PH-ST", see the results in Table 3. Total LED luminary efficiency value (Lm/W) was not correctly identified in many datasheets. Lumen value was used from the LED light source (diode), ballast/driver consumption was not included in total power, creating confusion in procurement tenders for end-users. The waveform of Photon-L luminary voltage and current consumption was measured as sinusoidal (PF ~ 0.97) because an LED driver with an integrated PFC circuit was used.

Dialux v4.10, Relux and similar light output simulation software tools, to check the luminary quality (street) on a specific street, were not very

Table 3. The main parameters of photon-L LED luminary tested in LAB and Riga PilotSite in 2010

Luminary	Lumens, Lm (by manufacturer)	Power measured, W	Temperature colour, K	Efficiency, Lm/W	ME class qualified
PH-ST-140 (140W)	7081 (50.57 Lm/W)	150.02	6000–7000	47.20	ME3-ME4
PH-ST-112 (112W)	5954 (53.16 Lm/W)	124.55	6000–7000	47.80	ME4-ME5
PH-ST-84 (84W)	5079 (60.46 Lm/W)	107.42	6000–7000	47.28	ME5

popular in Latvia. Typically, street reconstruction project architects and authors used an approximated approach, recommendation documents of manufacturers, basing only on luminary power and lumen output ratio, as the retrofit option was a choice between HME or HPS luminaires. In 2012, Latvia had a unique CO_2 emission quota-based funding instrument (KPFI) enabled for municipalities to retrofit (partly reconstruct) old lighting system luminaries to a more energy-efficient LED technology. For this issue, such simulation tools became very widely used, as it was one of the application evaluation requirements.

For all Mamba luminaries, the same Cree diodes (CREE-XPG-R3) were used. A fascinating fact is that programmable power supplies were introduced in this application, which also caused installation or factory programming errors, as 97 W luminary was limited to ~69 W, as shown in all power measurements of Table 4, obtained during in-situ measurements. In 2012, dimmable power supplies (0–10 VDC) were more commonly used with the first control nodes – calendar-graph dimmers or five nighttime zones with minimum and maximum light output levels (for L56/L70 luminaries – Philips DynaDimmer). For both manufacturers' use cases, Dialux calculations were used (see Fig. 11a), in-cooperating the measured power consumption values to meet the real light output situation on the street. The obtained results (Table 5) in lux were compared with the measured lux values in the same spots on

Table 4. The main parameters of two LED luminaries tested in Incukalns city in-situ in 2012

Luminary	Lumens, Lm (by manufacturer)	Power measured in-situ, W	Temperature colour, K	Lumens by Dialux (Lm), Efficiency, Lm/W	ME class qualified
PLAZA L56 (56W)	6300 (>100 Lm/W)	51.1	5000	5610 (@57.1), 98.25	ME6
PLAZA L56 (56W)	6300 (>100 Lm/W)	52.5	5000	5610 (@57.1), 98.25	ME6
PLAZA L70 (70W)	9100 (>100 Lm/W)	46.7	5000	7200 (@70), 102.85	ME5, ME6
PLAZA L70 (70W)	9100 (>100 Lm/W)	63.8	5000	7038 (@70), 100.54	ME5, ME6
Mamba A042B (97W)	8447(>100 Lm/W)	69.8	5000	6959 (@93W), 74.83	ME5
Mamba A042B (97W)	8447 (>100 Lm/W)	68.6	5000	6959 (@93W), 74.83	ME5
Mamba A028B (60W)	5512 (>100 Lm/W)	67.5	5000	4971, 73.65	ME5, ME6
Mamba A028B (60W)	5512 (>100 Lm/W)	66.0	5000	4971, 75.32	ME5, ME6

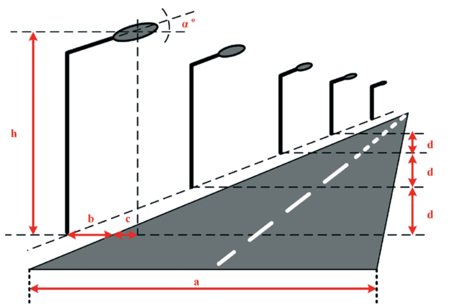
Note: In-situ measurements can contain 5% error in the current probe (power) measurements and control node consumption, explaining deviation in table power values.

Table 5. Dialux modelling results of PLAZA L70 LED luminary in the real situation power/light output ratio (dimmed) regime

Dimmed regime (as in a real situation)	L_{av}, cd/m²	U_0, V	U_l, V	*TI*, %	*SR*
Obtained values	0.44	0.39	0.48	11	0.76
ME5 class minimum requirements	≥ 0.50	≥ 0.35	≥ 0.40	≤ 15	≥ 0.50
Class requirements fulfilled or not	✗	✓	✓	✓	✓

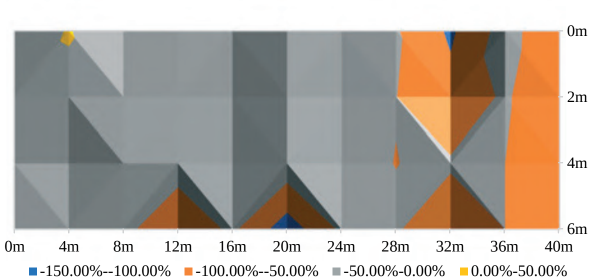
the street (see Fig. 11b). For LED luminary PLAZA L70 at full power of 70 W, Dialux modelling, for L_{av}, results from a result of 0.65 cd·m^{-2}, thus fulfilling the ME5 class criteria.

Analysing the obtained results of Dialux (v.4) modelling (modelled 4×11 points), using Light Loss Factor "1.0" value in Maintenance Plan, and for new luminaries, it should have the same output on the street and real measured value (measured 4×11 points), we can see high difference throughout the whole street (see the difference in Fig.11b), in most cases more than 50%, reaching even 150%. In that period of time, such a street layout (length 41m and height 8.3 m) was very challenging for LED luminary optics, but such a high difference still could raise some doubts and questions.



a	b	c	d	h	α
6 m	4.4 m	−0.9 m	41 m	8.3 m	0°
Street layout		Surface/Tarmac			
Two lanes		Old and porous asphalt			

a)



b)

Figure 11. Incukalns city street comparison in 2012: a – street profile; b – comparative difference (%) between the measured and modelled street profile values

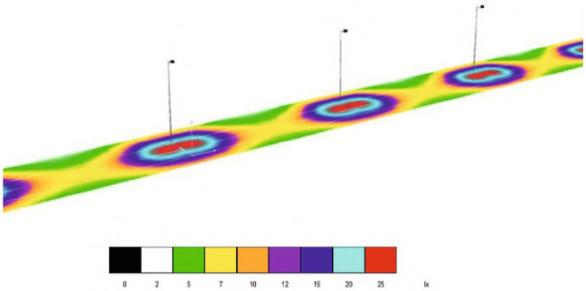
3.2. LITES project results – PilotSite in Riga

During the project implementation, a PilotSite was created on Kipsala island (Zunda Krastmala street) in Riga, where 29 pcs of existing HPS luminaires with a total power of 3450 W (18×100 W and 11×150 W HPS bulb) were replaced with LITES system (Fig. 8) using 29 pcs of Thorn Dyana LED luminaries (71.22 Lm/W, 4000 K) with total installed power of 2215 W (18 pcs of 65 W and 11 pcs of 95 W), to have equal or better quality and safety parameters. Decrease in the installed power was 54%, but actually, it was more, as HPS electromagnetic ballast consumption was not included. PilotSite was simulated in Dialux v4 both for HPS and LED luminary arrangement (Fig. 12a), obtaining modelling results, later to be compared with in-situ measurements by a lux meter (Table 6), luminance meter and video-photoluminance meter in full power (maximum was 80%) and dimmed state up to 20%. Table 6 shows illumination (lux) values of Dialux simulation and in-situ measurements in the middle of the street, where M1 and M3 are under the pole and M2 is between the poles (see Fig. 13). We can see that in most cases the simulation shows less light (@MF 1.00) to be given by this LED luminary, if compared to measurements of the year 2014 and 2020, also in the dimmed stage.

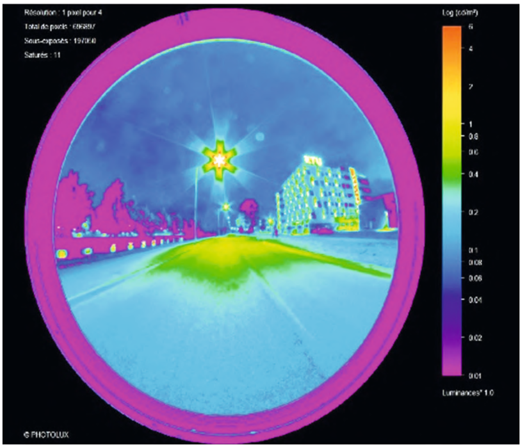
The obtained energy savings of LITES smart lighting system using sensors were 72–73% in average per year. We can observe that during 7-year work (4400 hours per year) the lumen depreciation (light loss) is up to 20%. However, the real values are still above the simulation results. We can conclude that the MF value is around 0.80, and the LED luminary gives more light actualy than the manufacturer defines it.

Table 6. Dialux modelling results of LITES LED luminary in real situation power/light output ratio (dimmed) regime

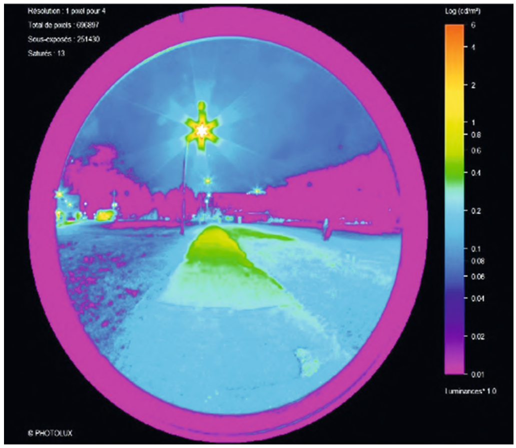
Illumination points	*E*(80%), Lux			*E*(60%), Lux			*E*(40%), Lux			*E*(20%), Lux		
	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3
AVG (Measured in 2020)	25	7	24	20	6	20	14	4	14	8	3	8
Measured in 2014	28	10.7	17	–	–	–	–	–	–	7.1	3	7
Simulated in 2014	20	8.19	20	10	4.49	10	6.24	2.92	6.24	3.12	1.35	3.12
Difference %	+19%	–17%	+17%	+50%	+21%	+49%	+56%	+33%	+56%	+61%	+49%	+59%



a) Dialux simulation model (results of 150W HPS)



b) LED full power

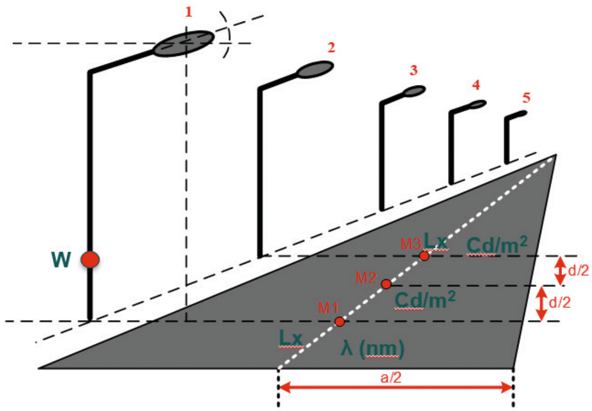


c) LED 20% power

Figure 12. LITES PilotSite: Dialux simulation results (a), Measurements of LED 95W luminary (b) and (c)

3.3. Large smart lighting system measurements in 2020

Small pilot sites do not give precise analytic results to make a general conclusion. If Dialux simulations give lower light output results than in reality they can be measured in-situ, and to avoid street layout geometry, trees, and their leaf and other parameter effects that could influence comparison, an extensive data set needs to be gathered and analysed. Smart LED luminaires were installed in three city regions: one was a central area (higher traffic), and two were sub-urban areas (lower traffic); overall more than 1300 lighting poles were measured (Lux, Ra), and more than 100 luminaries were measured in dimmed regimes (P, W, Lux, Candela). To compare Dialux results with real in-situ measurements, 21–50 measurement points were obtained using lux meter. However, if we speak about large pilot sites with >65 streets (>1000 luminaries), there would be too many measurements that would take a long time. Simplification was used as shown in Fig. 13a. In all places, lux values were taken in one measurement point in front of the pole and in the middle of the street. It must be noted that the street width and distances of poles were different and not constant even in the same street. Lighting pole (luminary mounting place) height and rotation and perpendicularity to the street of luminary were observed to have variations. The lighting system is a rather old heritage of the Soviet times, using poles (metal, concrete, wooden) and electrical cables of



a) Measurement points of street profiles

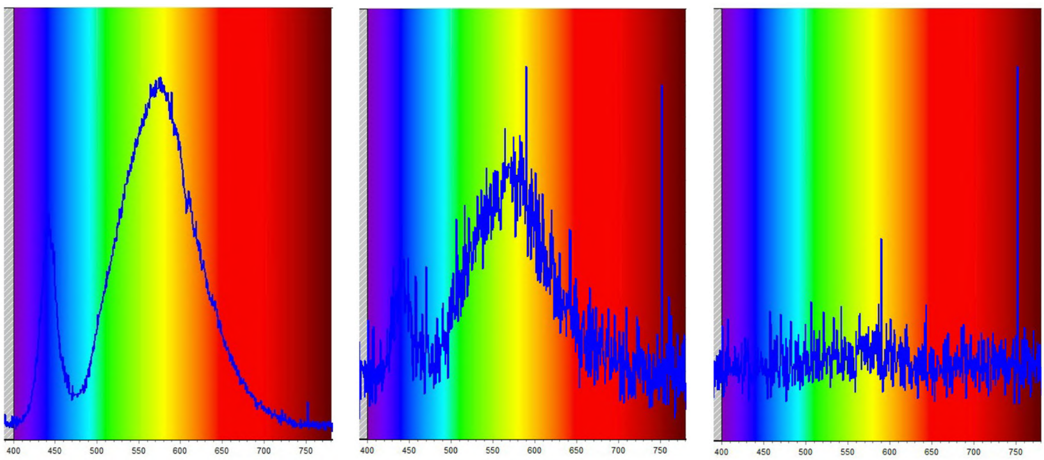
b) GPS coordinates of measurement points of large PilotSite

Figure 13. Large-scale street profile measurement plan (a) and GPS coordinates of the taken measurements

different quality. Some repair works have been done, and new zinc-metal poles installed individually, or whole streets changed. The central part of the PilotSite had 33 ME3/ME4/ME5 class streets, and the urban areas had 19 streets each, ME4/ME5 and ME5/ME6, accordingly.

In-situ spectrum measurements were done using AvaSpec-2048-USB2-UA (200–1200 nm) spectrometer for all PilotSite LED luminaries. From the measurements, AVANTES software allowed also calculating *CRI* (*Ra*) values from the obtained light spectrum. Thus we can see that *CRI* (*Ra*) values are in the range of 51–78. The *CRI* value in field measurements is affected by additional noise (Fig. 14b) and surrounding trees (Fig. 14c), which cover part of light creating. From Fig. 14a, we can see that the typical spectrum is at 442 nm and 580 nm; thus, all luminaries were using the same quality LEDs, as all of them had the same spectrum maximum pikes (variation observed was 1–5%) and colourimetric parameters. Candelas were measured using Konica Minolta LS-110, in two points (Fig. 13a), and in most cases showed values more than in Dialux calculations, at the same time keeping the uniformity parameters proportionally. Differences were related to the trees and their leaves, double-console (luminary) on pole, or different road surface type selected in Dialux.

Figure 15 shows samples of voltage and current waveform measurements in the pole (also including the control node and the movement detection sensor consumption), using Rohde & Schwarz RTH1004 digital oscilloscope. For power parameter evaluation,



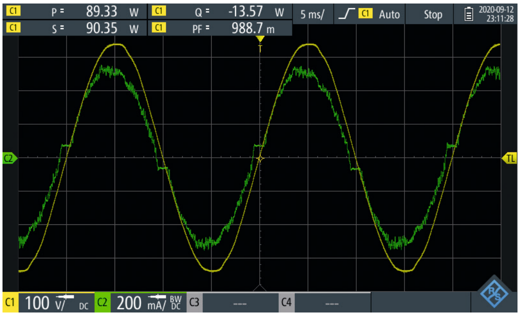
a) Normal spectrum

b) Indirect measurement / noise

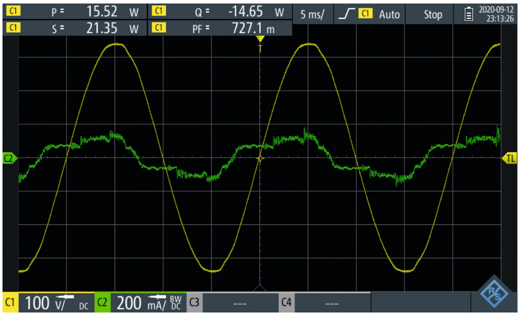
c) With great leave and noise impact

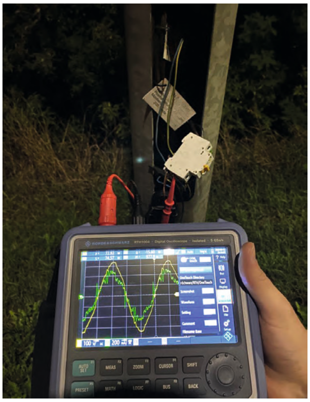
Figure 14. Typical samples of spectrum measurements

a) Full power (100%)



b) Dimmed to 40% of nominal power





c) pole

Figure 15. A sample of power measurement waveforms of 86W LED luminary

five measurements for each LED luminary (wattage nominal) were carried out using 20% dimming step. At the same time, illumination *E*, lux was measured under the luminary in the middle of the street. Dimming was done by sending to the radio signal-based control system the "dimming value" command using a system compatible segment controller. The particular street LED luminary (Fig. 15) is 86 W according to specifications; thus, the radio communication & control node can be assumed to consume around 3.3 W, as the measured power was 89.3 W at full power (light output also 100%). The illumination E value was 20.7 lux. At the dimmed state of 20%, the power consumption was 15.52 W and *E* was 3.1 lux. The dimming was nonlinear; if we calculated the dimming, the power value at 20% should be 17.2 W and *E* = 4.14 lux, or we could say that at 15.52 W it should be 3.59 lux. It means that in terms of light quality on the street, at the 20% level, we get 14% less, due to the "dimming regulation" algorithm implemented. However, this algorithm gives a better energy efficiency value (~10%). Accurate and stable dimming profile (power and light output consistency) is a challenging task; also, the

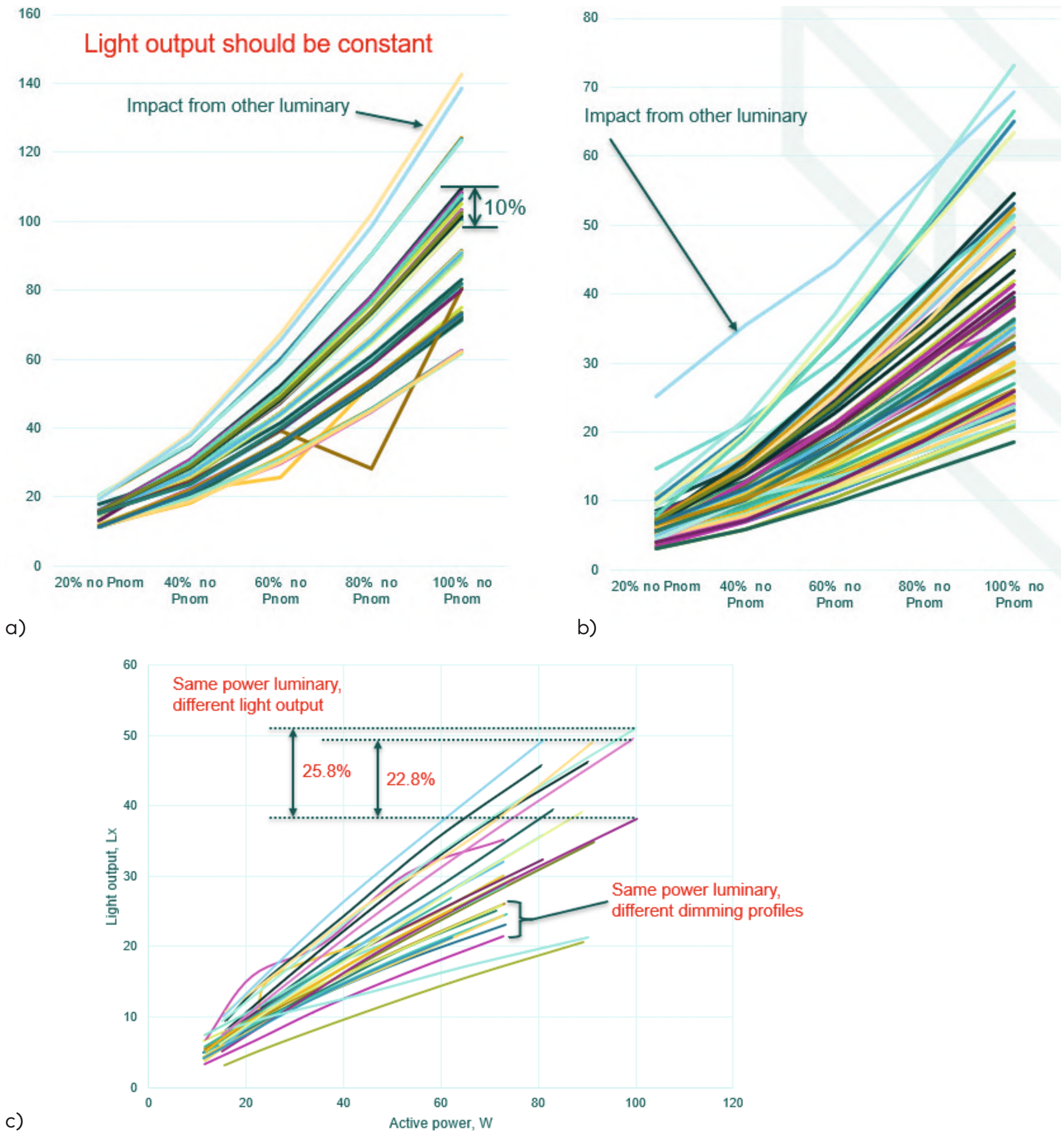


Figure 16. Graphical relation of power consumption, dimming value and measured light output values

efficiency of LED driver in the dimmed stage decreases, which must be considered.

The dimming profile non-linearity can also be observed in Fig. 16, where Fig. 16a represents the consumed active power compared

Table 7. Table 7. Measured *E*(lux) value distribution min, average and max values from 717 measurement comparison per street

MIN	22	3	13	23	2	19	17	12	21	45	24	33	3	31	51	16	4	2	32	25	21	24	19	21	24	17	14	29	17	44	8	7	48
AVG	28	54	28	44	23	28	25	43	30	50	34	44	36	35	54	25	36	37	39	54	29	37	39	45	42	38	37	49	45	57	35	48	57
MAX	39	82	40	65	45	41	35	52	36	57	39	54	48	37	56	44	54	44	51	99	45	66	62	95	71	52	64	55	74	66	50	57	71

to dimming, Fig. 16b – measured light output (lux) compared to dimming command, and Fig. 16c – 30 luminary dimming profile measurements. The difference between the same luminary powers can be reached at 22.8–25.8%, thus identifying the need for more proper calculation algorithms that include a street layout and potential power losses/consumption in the lighting pole.

A rather large difference between MIN, AVG and MAX values in measurements for real streets was obtained, as shown in Table 7. The extremely low values (minimums) of illumination level *E*(lux) relate to the street trees. The trees were relatively high, and their foliage was very thick, thus covering the LED luminary and the emitted light to the road surface. It brings about problems in the city related to ensuring a balance of tree branch cuts and appropriate light amount; therefore,

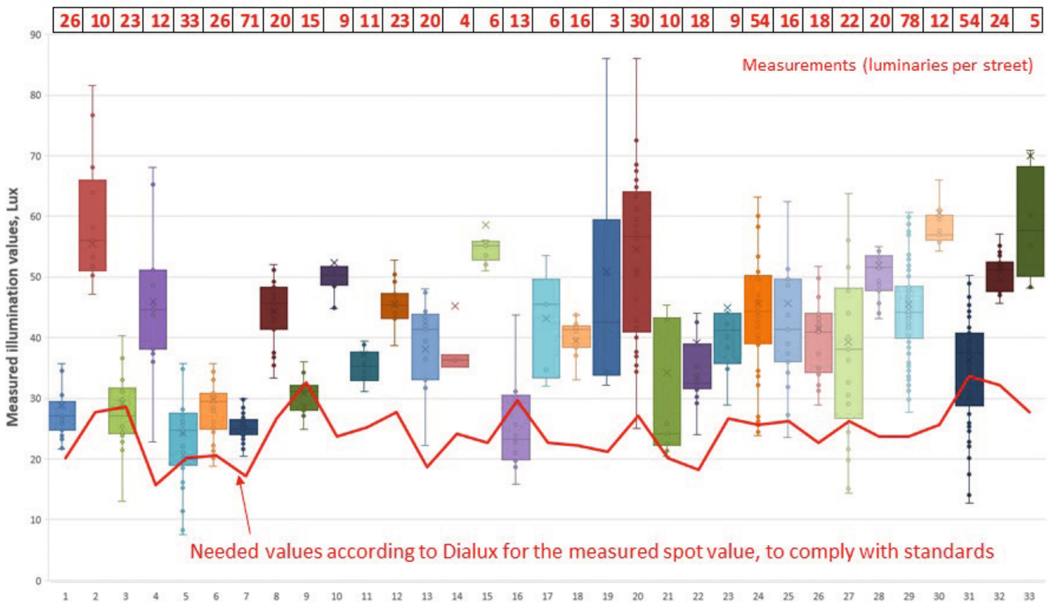


Figure 17. The measured illumination value distribution per street and needed minimums, according to Dialux

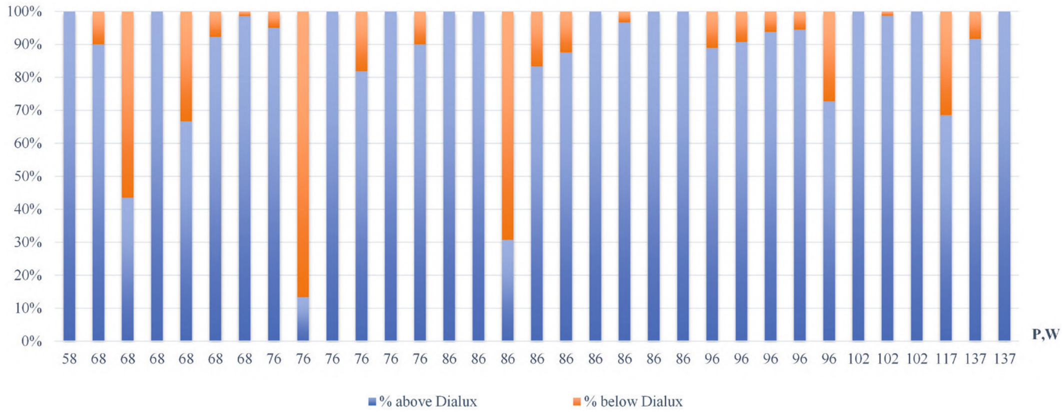


Figure 18. Measured value comparison with Dialux 4.13 obtained result values by luminary power type

professional arborist care must be provided in such places. Nevertheless, even for roads not affected by trees or other elements, the light deviation is still substantial. According to averaging the pole distances it was expected to have such an impact, but to get the difference in real lux values around 50% or even more, Dialux precision was around 10–15% for light distribution.

Figure 17 shows illumination level (lux) value distribution per street graphically. The red line represents the needed minimum value of Dialux calculation of the specific point of measurement to fulfil the M class criteria. The red numbers above show measurement points (luminaries per street), the bars show the median analysis of all measurements (min to max), as well we can see how much light points are outside the median. The median (bar in the graph), could be treated as normal distribution according to the simulation results. There are many points above average or outside the median, which proves the quality and safety issues.

Suppose we want to consider numerically the measured values and red line (Dialux needed minimum to comply with M class) in Fig. 17, then in Fig. 18 we can see the results, by how much % we have more light (above) than needed in Dialux per luminary power type. We can exclude that particular luminary power affects this, but it is common to all types; thus, it is affected by street profile parameters and precision of the topographical measurements.

Light decrease potential per luminary power is given in Fig. 18, which is obtained by AVG measured values to reach minimum required ME Class illumination value for comparison with the measured spot

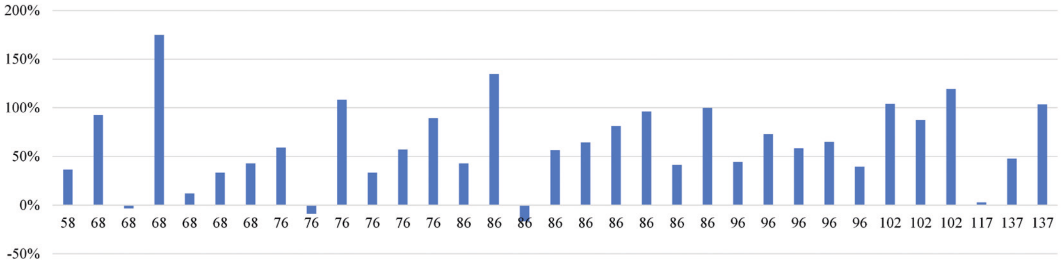


Figure 19. Light difference between Dialux and measured values by LED luminary power

value. The overall average potential is 63% reduction in terms of light during first years of LED luminary exploitation. This has happened because Dialux calculations use Maintenance Factor values of 0.85, 0.8, but in new installation, it is 1.00, which could explain the difference of 15%, but not of 63%. It means that after the installation it is advisable to make comparative measurements, as extra savings can be obtained and safety could be improved, as too much light causes high Threshold Increment (glare) values, which was observed in most cases of candela measurements.

Conclusions

During last ten years, LED luminary total efficiency values increased from 50 Lm/W (6000 K) in 2010 to 127 Lm/W in 2020 at 4000 K. Lenses also improved to get better illumination uniformity values, as overall luminary quality was continuously improving.

Comparing Dialux simulation results with in-situ measurements, we can observe that in the period of 2009–2012 real light values were less than the simulated ones, but in the period of 2014–2020 we obtained higher values than the simulated ones. Too much light affects Threshold Increment and glare parameters, which can be dangerous to the traffic participants. In this case it also creates too much energy consumption and these are unnecessary costs for city/municipality; therefore, measurements after LED system installation should be mandatory, as the smart LED lighting systems can be adjusted properly, if needed. The average energy saving potential reaches 63% of nominal (maximum value programmed) power, at the same time fulfilling necessary road lighting quality and safety requirements. Simplifed lux measurement method can be applied to road lighting measurements, and uniformity can be validated by candela meter or by CCD type camera measurements.

Pole distance averaging, various street profiles and topographical parameters (CAD data) affect LED luminary selection before installation, but for an end-user it is better to have more light than needed instead of having less. Modelling precision could be improved if more accurate/variable street layouts could be created in simulation software.

LED ballast and control node regulation precision for a "dimming profile" algorithm can be improved, as it shows rather wide variations in the real illumination values on the street and can give 8–10% of energy savings.

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Appendix 2

L. R. Adrian, **A. Avotins**, D. Repole, O. Tetervenoks. Development of New Radar and Pyroelectric Sensors for Road Safety Increase in Cloud-Based Multi-Agent Control Application. Baltic Journal of Road and Bridge Engineering, **2021** Volume 16 Issue 4, p. 76–107.

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DEVELOPMENT OF NEW RADAR AND PYROELECTRIC SENSORS FOR ROAD SAFETY INCREASE IN CLOUD-BASED MULTI-AGENT CONTROL APPLICATION

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Abstract. The paper concentrates on the design, architecture, and monitoring of smart LED street lighting control, with focus on traffic safety and safe road infrastructure. The use of a CMAS (Cloud-Based Multi-Agent System) as a possible framework is investigated. The work is based on previous developments by the authors in the production and design of close and long-range hybrid Pyroelectric Infrared (PIR) motion detection sensors. It also introduces the advances in radar-type sensors used in smart SLC (street lighting control) application systems. The proposed sensor solutions can detect the road user (vehicle or pedestrian) and determine its movement direction and approximate speed that can be used for dynamic lighting control algorithms, traffic intensity prediction, and increased safety for both driver and pedestrian

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traffic. Furthermore, the street lighting system infrastructure can monitor city environmental parameters, such as temperature, humidity, CO_2 levels, thus increasing levels of safety and security for smart cities. Utilising other hybrid systems within intelligent street lighting applications represents a new specialisation area in both energy-saving, safety awareness, and intelligent management.

Keywords: CMAS, LED lighting, lighting control, Pyroelectric, radar, traffic safety.

Introduction

The expanding use of cloud computing services in all forms of application control lends itself well to incorporating a Multi-Agent System (MAS) into existing and developmental structures. The smart LED street lighting system eventually will become a part of smart city concept, but already it is a complex system, as it consists of several components, such as dimmable LED luminaire, movement detection and other sensors to control the light output, integrated luminaire controller that allows for communication between LED driver and gateway (called also street segment controller) and the centralised control system (cloud or web-based software). Each component has certain means of control, precision and technical limits, thus posing impact on lighting quality parameters defined by standard (EN13201 part 2), where for Class M they are average lighting (L, cd/m^2), regularity of horizontal lighting (U_0), irregularity of longitudinality (U_l), dazing coefficient (ƒTI) and background lighting (REI), and for Class C – average horizontal lighting (E, lx) and regularity (U_0). To ensure traffic safety and safety of road users, a lighting system needs to maintain parameter values above the minimum requirements. Accordingly, the lighting class M (or C) is determined by applying Eq. (1), where the varying weighted sum (VWS) is used or individual parameters (2) that create the sum are analysed. Dynamically varying parameters, taking into account also specific conditions, are traffic speed ($V_v \in \{2;1;-1;-2\}$) and traffic intensity ($V_i \in \{1;0;-1\}$), and the constant parameters are the content of traffic participants (V_c), the density of crossings (V_s), presence of parked vehicle (V_p), surrounding lighting (V_a), the complexity of navigation (V_n), considering that it is night time. The sum of constant parameters can vary between the whole value range from +8 to −1. If the VWS sum is less than 0, the value "0" is used for calculations. If M ≤ 0, Class M1 is applied.

$$M = 6 - \sum VW_i M \tag{1}$$

$$M = 6 - \left(V_v + V_i + V_c + V_s + V_j + V_n + V_a + V_n\right) \tag{2}$$

Traffic speed and traffic intensity data play a significant role in class selection and thus also in traffic safety. These parameters can be detected by new radar and PIR sensors described further in this article. Existing smart LED lighting control systems, such as LITES PilotSite in Riga, Zunda krastmala street (LITES project), "CityLight", "Citintelly", "Tvilight", Schreder "Owlet Nightshift", Thorn "UrbaSens", "MovU" with integrated sensor solutions, are based on a much simpler approach, as they use the sensor just to detect the movement event, and if it happens, the luminaire controller sends a control signal to LED driver in order to increase the light (or power) output to maximum level of individual or nearby luminaries. Further the signal/event is also sent to the control software for manual data analysis.

Another widely used approach is to control a lighting system without movement detection sensors, using just a luminaire controller for communication means (such as "AAEON", Philips "CityTouch", "Gridens"), and in this case there are pre-programmed minimum and maximum power (light output) values of a certain time slot of the daytime. The "Streetlightvision" (Itron) is the most used software system, and it is able to integrate various communication controllers into a single platform, as special communication bridge protocol TALQ is used; therefore, companies (like "Telensa") use it as a control system backbone for their products.

In all these cases, the predefined light output values are approximately or statistically determined, and they do not reflect a real-time situation on the road and traffic safety. The authors propose using the developed radar and PIR sensors that are able to give necessary dynamic data outputs of traffic intensity, speed and direction. Therefore, this paper also explores MAS inclusion into smart LED street lighting technologies (Avotins et al., 2014) and includes control mechanisms for the use of improved radar sensors (see Section 9), long-range hybrid pyroelectric sensors (Adrian & Ribickis, 2014) and in future also context-based sensors (Avotins & Bicans, 2015) within lighting systems. Adoption of energy-efficient and smart LED street lighting is increasing; thus, reduction of energy consumption has reached its main focus, but also traffic safety should be addressed properly. With the increased implementation of Photovoltaic Assisted Street Lighting (PVAL), we must also consider another Distributed Energy Resource (DER), added to the emerging list of microgrids requiring smart control systems (Huerta-Medina, 2016). MAS cloud control of DER is shown in (Bertagna et al., 2013), and the energy evaluations of the street lighting may be monitored and controlled using MAS.

MAS, selected as a distributed control architecture described by (Colson et al., 2011), represents a collection of autonomous computational entities. In this scenario, "*the agents*" (Adrian & Ribickis,

2014) are described as individual LED street lights with hybrid long-range control sensors. These “agents” perform tasks based upon predefined goals. When provided remedial intelligence (currently fuzzy logic architecture), the agents pursue goals to optimise given performance measures in an environment that can be difficult to define analytically. An agent can act upon its territory or Workspace Envelope (WE), which defines the Cartesian range of movement or the field range of its sensors and allows it to interact with other agents with conflicting goals towards a common goal. The ability of agents, when imbued with limited or global perception of situational variables, to affect the system environment is dependent entirely upon implementation. Merging MAS with cloud computing for inclusion in street lighting control and traffic safety is both novel and sensible considering the ease of consolidation.

It is generally assumed that street lighting systems require only illumination, darkening and dimming at predefined times and require no further consideration. Incorporating the hybrid sensor system into each agent brings with it a completely new range of data sets, which not only lend themselves to MAS control but to a new level of safety characteristics previously not addressed within similar systems.

Cloud computing architecture also permits and extends the diversity of control services for Smart LED street lighting technologies. If it is successful, it will significantly increase public safety (Bertagna, 2013; Adrian et al., 2014) and may substantially reduce the deployment costs across the whole system. As MAS is designed to operate on sensor-based arrays specifically, the opportunity exists to explore many other initialization avenues, including fault detection in automotive power printed circuit board (PCB) (Repole et al., 2017) or as a CMAS for sensor networking city transport systems.

From the authors’ experience in LITES project, radar sensors have some false detection during rainy conditions, and PIR sensors have issues of detection in case when ambient (or asphalt) temperature is similar to car temperature, like during hot summer nights, or in winter, when a car is just started and emits less infra-red radiation. This can be solved by implementing changeable sensor sensitivity ranges and proper signal filtering.

The solution could be a hybrid/modular sensor system, through combination of two technologies into one sensor, or installing both sensors on the same streets but on different lighting poles, thus creating a more robust system, where such an approach also allows checking system errors and is interchangeable with the PIR system as either a primary or secondary structure. From an operation perspective, the two approaches are at either end of the spectrum yet work together to form a stable system. The developed sensor array is an end solution to numerous requirements, which lends itself to safety, big data retrieval, statistics evaluation, smart metering, and control of energy usage.

Another challenge is the reduction of the sensor self-consumption and the unit price, where in LITES project Steinel PIR sensor had price of 60 EUR, Micas radar sensor had 90 EUR, and sensor consumption with communication node was around 5 W. Nowadays such radar sensors are cheaper (around 60 EUR), but final price depends on sensitivity and area coverage and initial integral circuit price, where 60 GHz (IWR6843AOP) from Texas Instruments costs 25 EUR, but 80 GHz chip (IWR1642) – 12 EUR. The PIR sensor components proposed by the authors cost up to 9 EUR when ordering in small volumes; therefore, benefits of the device include low cost per agent, ease of use and installation due to NEMA socket usage and compact size.

1. Research essentials

Each array consists of several short-range sensors, and we envisage after final testing there will be the initialization of one long-range sensor per array. Sensors are a hybrid of sensing elements and require no more

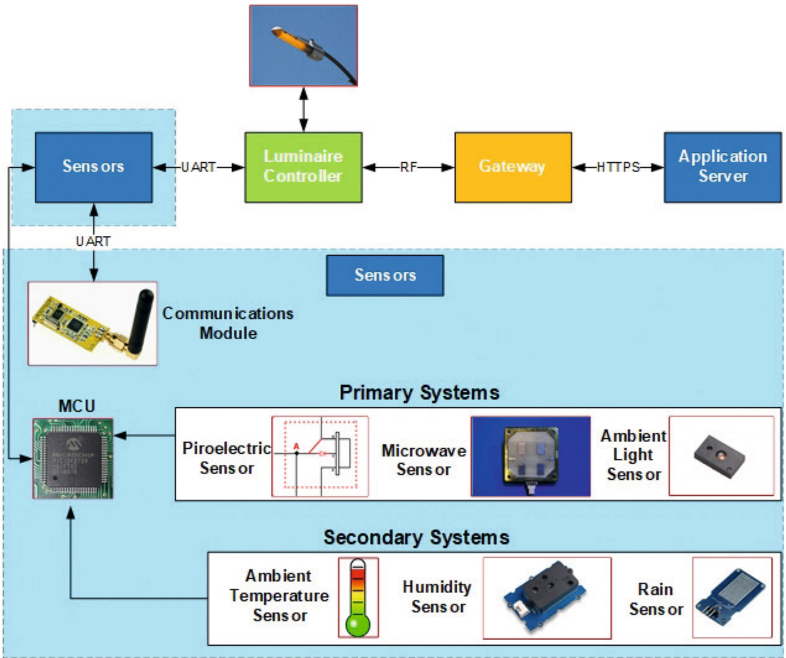


Figure 1. Primary element configuration

than a passing mention. The temperature, humidity and rain sensors will initially be off the shelf components, easily included and do not require scientific research or study except within their specific fields of use. It is sufficient in our case to have them based on overall data retrieval and evaluation. In reality, the inclusion of sensors will be determined to be unnecessary or more required depending on preference and system design. Figure 1 presents the primary element configuration for a single long-range agent. Short-range agents vary only in excluding the long-range lens, which is replaced by the appropriate Fresnel lens in the short-range version.

2. MAS development factors

Describing the whole system, we must define the actors. Figure 2 demonstrates a micro-array (*Array A to Array...n*) being a road, a street, or a walkway, or any other area designated for installing the system. The defining features are the *agents or actors;* the intelligent streetlights complete with their sensory systems.

An agent (*Agent_1 to Agent_n*) may be interconnected or islanded from the network and is composed of two distinct states. The agent is ascribed asynchronous communication. The process of sending and receiving messages and control data is independent of a coordinated clock signal between agents due to the requirement for each to operate within a unique and dynamic environment. In this way, a single agent can react to unpredictable event triggers yet maintain information transfer to the network simultaneously. Utilising this approach, the

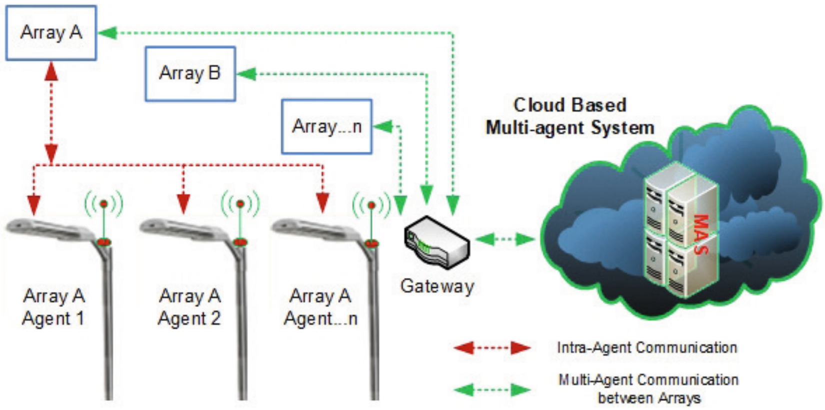


Figure 2. Remedial model indicating micro-arrays and agents

agent becomes separated and decentralized dependent on individual event triggers, which may not be affecting other agents within the array.

As a distributed MAS, individual elements of micro-array management must adjust to varying conditions within each state framework. An interconnected micro-array in cooperation with its agents must manage switching, illumination levels, energy consumption analysis, and data transfer to and from the CMAS, which maintains constant analysis of the combined network of micro-arrays. An example might be the various management modes under the decision algorithm of the CMAS, which may affect shared intersections of micro-array A and micro-array B due to any number of location-specific incidents that may vary significantly across a town or a city.

When islanded, or when an agent has entered standalone mode due to a specific event trigger, all systems of that agent may become autonomous yet continue to transmit data between its brother agents and therefore to the CMAS relying upon its decision-making process will become actively involved or remain silent. Regardless of the agent state, the CMAS will seek the most favourable solution to allocate objectives where necessary.

3. The strategy of a non-synchronous system

Unlike many MAS systems, a synchronization strategy holds little importance due to the agent dynamic nature described in Section 2 above. Operation as a distributed system requires typically that all agents operate in a synchronous manner. Various agents and synchronization within the system are a primary and necessary objective. Without synchronization, complex software modelling and simulations applications fail to function. For example, in a pedestrian counting simulation, the physical area where targeted pedestrians are located may be segregated into various parts and monitored by an agent. However, those pedestrians may wander from one physical location to another. Without a synchronization mechanism, pedestrians walking from one agent to the next would be misplaced in real-time, where one Agent is ahead or behind in the model simulation. Therefore, uncontrolled synchronization would generally invalidate the simulation process due to overlapping past, present, and future tense events or triggers. It should be apparent that even a non-synchronous system dealing specifically with random data collection may be synchronous after an event when collated in date/time format.

Therefore, the main goal is to achieve data transfer to the CMAS, which is the primary decision-maker at the heart of the operation.

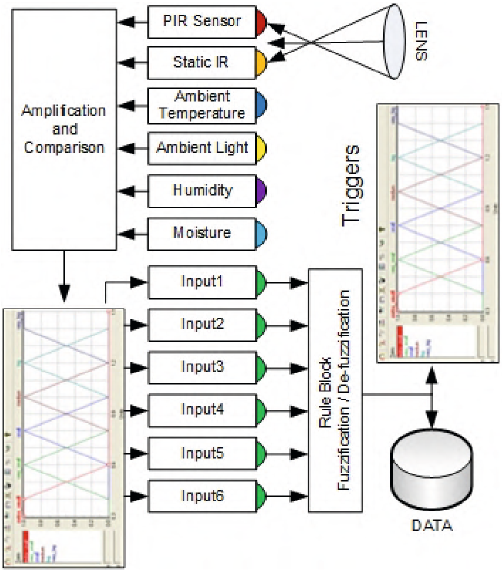


Figure 3. Original fuzzy logic system model. Recent model addition includes Radar module

The problems associated with synchronization are system overhead, requiring more complex data retrieval and processing algorithms. Within the proposed system, there is a view to total removal of synchronization overhead, which does not trade accuracy or performance.

4. Power Management and Smart Power

An exciting facet of creating a data collection system that doubles as a decentralized Micro-Grid and Power Management scheme provides the breadth of control algorithm possibilities. Power management is controlled by the CMAS decision algorithm and may be refined over time; however, the primary triggers are initially within the control loop of each agent designed to respond to environmental or physical changes within its WE. As shown in Fig. 3, the original authors' preferences lie in the fuzzy logic arena. The system built primarily on non-proprietary software lends itself to a whole array of possibilities regarding the choice of protocol and subsequent proprietary software. In this respect, the hardware of the system can become the main focus of the proposal.

The Hybrid Long Range Sensor consists of one quad PIR sensor (incorporated lens), 4x static IR sensors, temperature sensor, ambient light sensor, humidity sensor and moisture sensor.

5. Agent capabilities

One challenge facing distributed MAS with DER systems has been the vast diversity of different components connected to the many micro-grids involved. Interoperability is a key to a successful MAS deployment. Therein, the reasoning makes intelligent street lighting systems ideal and very capable in agent classification processes without extensive additional programming and, therefore, an ideal solution for a hybrid Cloud/MAS. Currently, the LED street lighting system with hybrid sensors (the agents) in Fig. 2 is capable of the functions described in Table 1.

Table 1. Hybrid sensor (operating under assessed architecture)

Long- and close-range vehicle and human detection	We are planning that each array (Fig. 1), would likely house one long-range sensor with the balance of the array consisting of close-range.
Movement direction	Movement direction (L/R or R/L) detection, including detection of approaching or departing vehicles. The modified PIR sensor can enable detection of directional movement (see Adrian & Ribickis, 2014; Repole & Adrian, 2019).
Road user count	Vehicle counting and to a lesser degree pedestrian counting, utilising vehicle and pedestrian counting sensors is an indispensable benefit for the system data collection and statistical aspect.
Speed detection	Approximated vehicle velocity and vehicle headlight recognition. The triggering methodology gives rise to the ability to ascertain vehicle velocity, which also adds to the data collection and statistical aspect.
Environmental sensors	Ambient temperature sensing, ambient light sensing, wet weather and freeze detection. We are planning to equip all agents with these additional sensors that require no further explanation.
System compatibility	Modular approach allows for compatibility with most existing lighting systems.

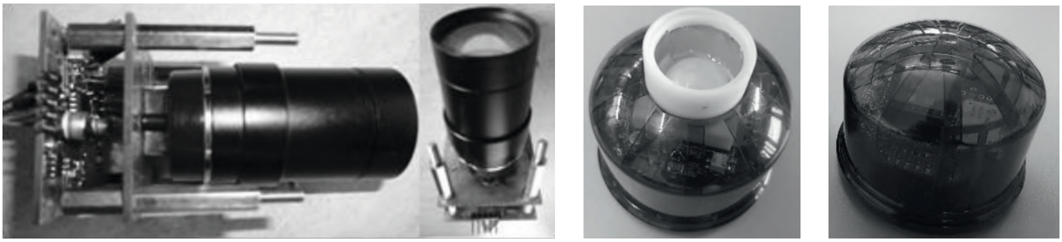
LED street lighting system (using hybrid sensors)

As mentioned earlier, this study is mainly aimed at reducing energy consumption (over the past decade, a major step towards improving the energy efficiency of street lighting has been the replacement of old gas discharge lamp based luminaires with new LED luminaires) and improving safety on the streets/roads by introducing modern technologies, modern control systems for street lighting. As in all other areas, the safety on the streets is based on compliance with the standards. In the present research, we focus on street lighting; thus, the road lighting standard EN 13201 should be considered a key reference. In this standard, a whole chain of parameters defines the minimum required lighting class for a particular road / street. Particular attention should be paid to time-variable parameters, since the lighting system can be made dynamic, adaptable to certain specific conditions at the moment. We consider this dynamic adjustment of the lighting system to be the second most significant step in reducing the energy consumption of a street lighting system without compromising road user safety and without deviating from the standard requirements.

Thus, particular attention in this research is paid to sensors as depicted in Fig. 4, which are the primary control system input elements to determine motion/traffic flow/direction/speed/user type. The radar (RAdio Detection And Ranging) type (Fig. 4c), long-range hybrid PIR sensor (Fig. 4a) and close range PIR sensor (Fig. 4b) are discussed in this article as the key sensors that can cope with this task.

The requirements for the street lighting system and possible functionality can be summarised as follows:

- Increased energy efficiency – light delivered only when and where needed (less light pollution);
- Exact lighting class determination on real traffic data according to EN13201;
- New services and functionality added to the system (improved return of investment values);
- Introduction of new prediction, maintenance and control algorithms;
- Decentralized control, the system can analyse and make decisions – the system becomes smart;
- Context data application to enable participation in energy price markets (like Nordpool) or adjust consumption according to current price forecast;
- Safety: Forecast warning system for the road user (weather and road conditions).



a) Long-range PIR hybrid sensor b) Close range PIR sensor c) Radar sensor

Figure 4. The developed sensor prototypes

All sensor elements, as depicted in Fig. 3, are "off the shelf" components except for the ambience sensor whose task is to control the responsivity of the sensors according to ambient lighting conditions. The component, though simplistic in design, is of great importance in the response triggers associated with passive infrared sensors.

Intrinsically, the variable resistor R_{var} consists of a single resistor layer {2-1} and a wiper {3} that adjusts the ratio between both halves. Within the circuit, as can be seen in Figure 5, the addition of a light dependent resistor dramatically alters the effect of the standard voltage divider allowing for a dimming effect on U_{ref} that in turn increases sensitivity on sensors in that array. In this manner, more accurate triggering is achieved under bright or low light conditions. Calculation of U_{ref} parameters may be performed using (3).

$$U_{ref} = \frac{R_{var1}}{R_{var1} + \left(R_{ldr} + R_{var2}\right)} \times U_{in} \tag{3}$$

Table 2 denotes an average voltage swing on U_{ref} of 2.09 V between bright and darker environments.

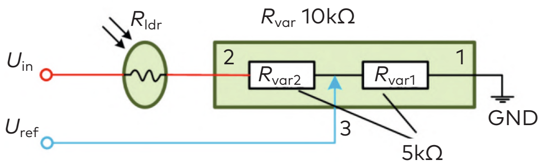


Figure 5. LDR /VAR potential divider configuration for ambience control

Table 2. Example of calculated sensitivity of reference voltage

Ambient lighting level	R_{LDR}	$R_{VAR1\,@\,2.5k\Omega}$	Ratio $R_{VAR1}/R_{VAR1} + (R_{LDR}+R_{VAR2})$	U_{REF}, V
500 Lux	1 kΩ	2.5 kΩ	0.22	1.11
250 Lux	10 kΩ	2.5 kΩ	0.125	0.63
100 Lux	100 kΩ	2.5 kΩ	0.02	0.11
Ambient lighting level	R_{LDR}	$R_{VAR1\,@\,5k\Omega}$	Ratio $R_{VAR1}/R_{VAR1} + (R_{LDR}+R_{VAR2})$	U_{REF}, V
500 Lux	1 kΩ	5 kΩ	0.45	2.25
250 Lux	10 kΩ	5 kΩ	0.25	1.25
100 Lux	100 kΩ	5 kΩ	0.04	0.02
Ambient lighting level	R_{LDR}	$R_{VAR1\,@\,7.5k\Omega}$	Ratio $R_{VAR1}/R_{VAR1} + (R_{LDR}+R_{VAR2})$	U_{REF}, V
500 Lux	1 kΩ	7.5 kΩ	0.68	3.40
250 Lux	10 kΩ	7.5 kΩ	0.375	1.88
100 Lux	100 kΩ	7.5 kΩ	0.068	0.34

6. Fuzzy logic controller

The authors preference for a fuzzy logic controller depicted in Fig. 3 and Fig. 6 is the outcome of a careful evaluation of several controller techniques within several projects. The decision process shows an advantage when used with the parallel computation capability and the possibility to integrate the fuzzy logic controller into a more comprehensive, self-adapting and self-learning system (Repole & Adrian, 2019), with the ability to utilise the shared information between the agent and cloud.

The previous sentence is of paramount importance for establishing a robust design for the long-range hybrid PIR sensors within a smart

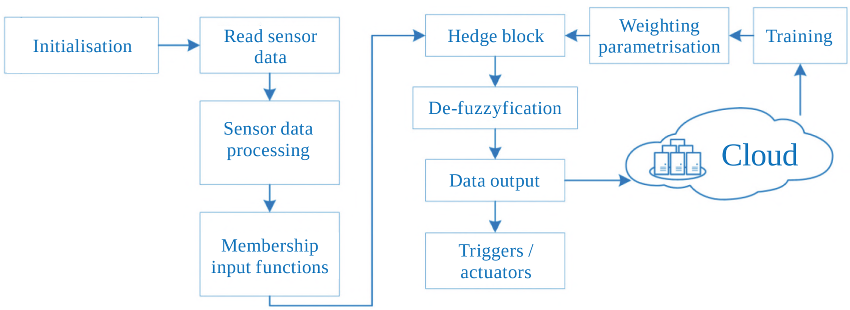


Figure 6. Fuzzy logic block diagram of agent and cloud interaction

LED street lighting system. Environmental variables heavily influence this specific application. The ability of the system to use the shared information between the agents and the cloud is beneficial, especially in light of the possibility that the shared information may also be used for self-training purposes and allow for the system evolution to environmental variables. Additionally, this functionality may be beneficial in minimising the effects of faults within local agents.

Therefore, a relevant approach to the research goal becomes the design of an adaptive fuzzy logic *rule block* capable of accepting and utilising weight change commands from the cloud. For this framework and the authors' licence, the controller implements a small form factor, cost effective Field-Programmable Gate Array (FPGA) for the physical implementation of the decentralized controller. A dedicated paper (Repole et al., 2019) explores the decision process, which generates the outcome described herein.

7. Data transfer

Adjustments to the control approach were implemented as a cloud computing service. This approach is easily extended with new functionalities without modifying the internal logic of the gateways. The cloud is used to store the data related to the different points of the grid. The proposed architecture provides neighbourhood management

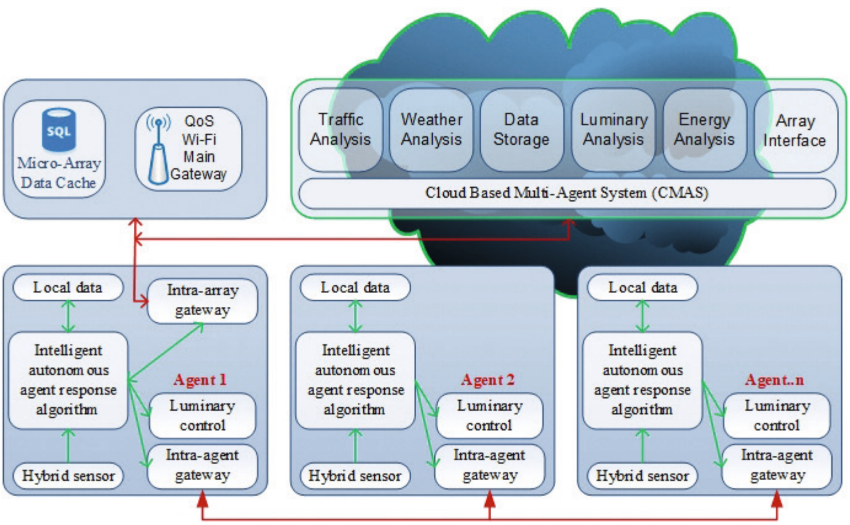


Figure 7. Cloud-based multi-agent system model

as a service. MAS may maintain the grid stability using only local area information (distributed control) of the luminaire grid. Cloud-Based Multi-Agent System (CMAS) architecture is shown in Fig. 7.

System connectivity should and can be an end-user customizable variable, which will be essentially defined by the application specific environmental and technical requirements. In other words, the ideal MAS systems should be capable of being easily adapted to utilise any of the commonly used data transfer methods, for example:

- ST LORA – LPWANs;
- Wireless;
- GSM/3G/4G internet connection;
- ZigBee.

Data transfer is readily achievable, adding to the "agent" one specific, or more, communication modules. The fuzzy logic "parallel computational capability" increments the system performance, especially if using an FPGA based gateway that is capable of parallel interaction with all system agents within an array (as in Fig. 2).

The study case requires that the agent covers a wide area and shares relatively little information, usually one or two bytes for each parameter to be transferred. Data transfer speeds between agents is not an essential parameter in that the communication range capabilities are privileged. ST LoRa technology is the perfect solution for the study case. It is a modular / plug-in unit able to deliver, under optimal conditions, data at speeds up to 300 Kbit/s. However, a communication speed of 56 Kbit/s, selected to be RS232 compatible, is larger than the minimum communication speed calculated with Eq. (4).

$$Com_{\min} = \left(2 \times Sen_{\text{refresh}} \times Param_{\max} \times Data_{\text{res}} \times Agents_{\max}\right)$$

$$= \left(2 \times 6\ \text{Hz} \times 8 \times 16\ \text{bit} \times 32\right) = 49.152\ \text{Kbit/s}$$

$$T_{\text{learn}} < \left(\frac{(MOB\,\text{Mb}) \times 2\text{e}^{20}}{\left(\left(Sen_{\text{d}} \times 1\right) + \left(Sen_{\text{a}} \times 2\right)\right) \times S_{\text{ps}} \times S}\right), \tag{4}$$

where:
$Com_{\min}$ – minimum communication speed;
Sen_{refresh} – sensor refresh cycle frequency;
$Param_{\max}$ – maximum number of parameters;
$Data_{\text{res}}$ – parameter data resolution;
$Agents_{\max}$ – maximum number of agents per array;
T_{learn} = maximum run time;
Sen_{d} = digital sensors @ 1 byte per sample;
Sen_{a} = analog sensors @ 2 bytes per sample;
S_{ps} = samples per second;

S = number of seconds;
MOB = onboard memory in Mbytes.

Some problems generally relate to MAS systems and simulations requiring evaluating and impacting data packet arrival at the cloud/MAS and relate specifically to the time synchronization departure/arrival at the system MAS or gateway side. Due to the truly agent nature of each streetlight, the intrinsic ability to enter standalone mode upon receipt of specific triggers provides the system with the added advantage of stability. Each part of the system (e.g., CMAS, main gateway, inter-array and agent array) is designed using standalone algorithms to operate their system component with data transfer to the MAS if a trigger occurs. In this aspect, MAS may be viewed as a data collection, distribution centre that can override all other systems when required. The main priorities of the system are that the MAS collects all transmitted data, providing the instruction to arrays (streets), which control the agents (streetlights). The agents (streetlights) maintain control of their WE (workspace envelope) reacting individually or in unison with other agents to received triggers. With these parameters, it may be said the CMAS is a truly reactive system where, in a given situation, the whole may consist of many parts or vice versa.

8. Current research progress on long-range sensor lens

Our research has determined that a limited detection range of PIR sensor is primarily due to an absence of unequal exposure, so placing a specific type of lens in front of the sensor extends its detection range. Without a lens in front of a PIR sensor, when an IR emitting body is close to the sensor, at about one m, moving across the sensor path, the radiated IR will expose one element more than the other resulting in voltage output. However, when the IR emitting body is further away from the sensor, its radiation pattern becomes fuzzy, and both elements are exposed more uniformly, resulting in zero voltage output. Simultaneous exposure of both elements is the cause of the limited detection range. A method under evaluation to prevent the IR from simultaneously exposing both elements is ongoing.

Simultaneous exposure of both elements is the cause of the limited detection range. What is required is to prevent the IR from simultaneously exposing both elements as the IR emitting body moves across the sensor path at greater distances from the sensor. Standard dual PIR sensor elements are product independent, range

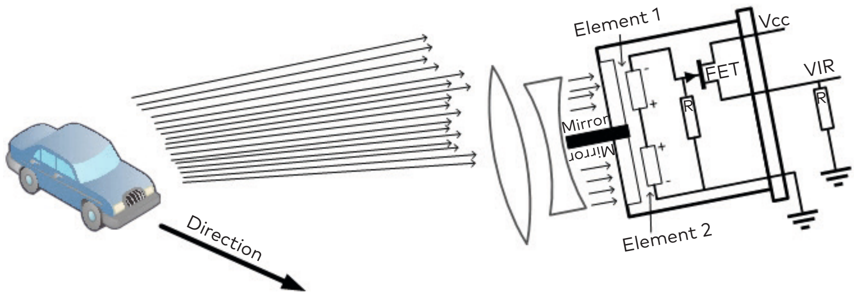


Figure 8. Long-range PIR methodology

in size from 0.9 to 1.2 mm and are spaced approximately 1 mm apart. The PIR has a partition, included to divide the elements. Placing a thin strip of reflective, IR opaque material between the sensor elements we can direct the IR radiation to strike one and then the second element, regardless of direction as depicted in Fig. 8.

The long-range lens consists of a Plano-Convex lens reformed as a Fresnel lens, a collapsed version of the original lens, as seen in Fig. 10. The thinness of both the flat lens and the Fresnel lens is of paramount importance as it is imperative to minimise IR losses through those lenses. Lens construction is from ultra-clear polymethyl methacrylate (PMMA), which is transparent to IR radiation, rugged, and often used as a substitute for glass in products such as shatterproof windows.

In Fig. 9, the baffle allows tuning the field of view (FoV), which at 100 m represents a requirement of approximately 20° to cover the road width adequately. The pyroelectric sensor is susceptible to rapid temperature

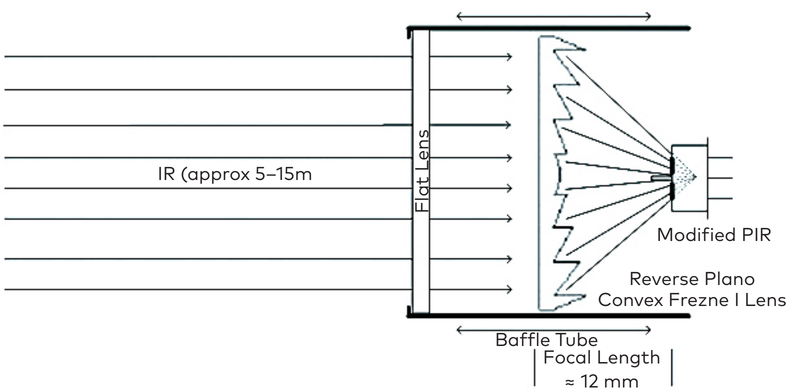


Figure 9. Long-range FoV lens schema

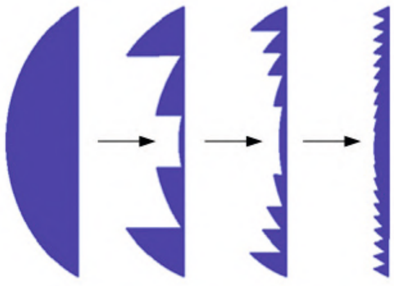


Figure 10. Plano-Convex Fresnel lens

changes; however, the flat lens inclusion enables the sensor to operate inside a stable shell.

The required basic principle is to ascertain an output voltage, that is a function of the amount of infrared radiation sensed at the input of the (PIRA) Passive Infrared Sensor Array. Therefore, responsivity is of the detectors' elements is vital. Two factors are determining the electrical response. The first is the detector's thermal response due to incident radiation, and the second is the pyroelectric material response due to temperature changes. A typical pyroelectric detector system consists of four essential elements. These are the sensor, amplifier, window comparator and coupler.

We look specifically at current response (RI), and voltage response (RV) (Hyseni et. al., 2010), considering C_{th} and G_{th} be the thermal capacity and conductance, respectively:

$$\tau = \frac{C_{\text{th}}}{G_{\text{th}}} = \frac{c'Ab}{G_{\text{R}}A} = \frac{c\rho b}{4\eta\sigma T^{3}}, \tag{5}$$

where:
c' – volume specific heat, J/(cm^{3}K);
c – specific heat of material, J/(mgK);
ρ – density, gm/cm^3;
b – sensor thickness, μm;
G_{R} – irradiative conductance, W/(cmK);
A – detector area, cm^2;
η – emissivity of the crystal;
σ – Stefan-Boltzmann constant, $5.67{\cdot}10^{-12}$ W/(cm^{2}K^4);
T – temperature, K.

Current responsivity of various photovoltaic materials, R_{I} (6), is the ratio of the output current flow Δ_{I} to the input radiation power incident to detector surface P_I. The current responsivity can be calculated as (Beerman, 1969):

$$R_I = \frac{\Delta_I}{P_I}. \tag{6}$$

Pyroelectric charge ΔQ is given by:

$$\Delta Q = \Delta I = pA\Delta T = AP_S, \tag{7}$$

where p is the pyroelectric coefficient of material and P_S is the polarisation.

Suppose that radiation power is a sinusoidal function; therefore, temperature changes Eq. (8) of whatever detector due to irradiation flux are given by the steady-state equation of Ciupa (1997):

$$\Delta T = \frac{\eta P_I}{c'bA} \times \frac{\tau}{\left(1+\omega^2\tau^2\right)^{1/2}}. \tag{8}$$

Substituting Eqs. (6) and (7) into (5), the final expression for this current responsivity becomes Eq. (9):

$$R_I = \frac{p\eta\tau}{c'b\left(1+\omega^2\tau^2\right)^{1/2}}. \tag{9}$$

Voltage responsivity of various photovoltaic materials, R_V Eq. (10), is determined as a ratio of the voltage generated in the detector ΔV and radiation power incident to detector surface P_i. From this definition, we have (Beerman, 1969):

$$R_V = \frac{\Delta V}{P_i}. \tag{10}$$

The generated detector voltage Eq. (11) is given by:

$$\Delta V = \frac{\Delta Q}{C_d}, \tag{11}$$

where $\Delta Q = pA\Delta T$ is electric charge and $C_d = \varepsilon_r\varepsilon_0 A/b$ is detector capacitance.

When substituting Eqs. (7), (8) and (10) into (11), we get the final expression for the voltage responsivity Eq. (12):

$$R_V = \frac{p\eta\tau}{c'\varepsilon_r\varepsilon_0 A\left(1+\omega^2\tau^2\right)^{1/2}}. \tag{12}$$

Graphs, too large for inclusion within this paper, and indicating the wavelength dependency of the voltage responsivity for different pyroelectric materials, may be found (Beerman, 1969).

8.1. Technical analysis of the PIR

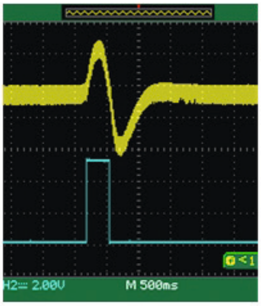
Fraden (2010) proposed a model for the PIR motion detectors. We have described the working principles of the PIR sensor in accompanying sections. Fraden's model uses the following assumptions: the subject has uniform temperature distribution and is a diffuse emitter, an image formed on the sensing element is always sharp irrespective of the distance between the subject and the sensor, and the surroundings and the subject are ideal emitters and absorbers. The model considers the sensing element temperature change rate (due to the subject), its thermal capacity, and the absorbed thermal power. Fraden's model is given by (13):

$$I \approx \frac{2Pa\sigma\gamma}{\pi hc} bT_a^3 \frac{\left(T_b - T_a\right)}{L^2}, \quad (13)$$

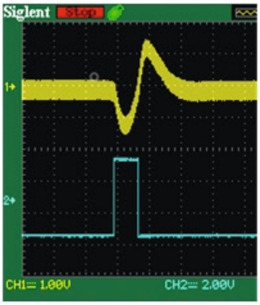
where:
I – the current generated by the sensor;
P – the sensor pyroelectric coefficient;
a – the area of the lens;
σ – Stefan-Boltzmann constant;
y – the lens efficiency;
h – the lens thickness;
c – the specific heat of the sensing material;
b – the effective surface area of the subject;
T_a – the sensor temperature;
T_b – the surface temperature of the subject;
L – the distance between the subject and the sensor.

The model is based on parameters that are difficult to measure experimentally, and information regarding these parameters is not available in PIR sensor datasheet. This model does not account for the Fresnel lens' effect and the subject speed of movement. Additionally, it does not address the simulation of analogue sensor response (as a function of time) when a subject moves through the FoV of the PIR sensor.

The researchers move from the acknowledgement of such criticalities and base the work on exhaustive experimental processes, i.e., focusing only on the theoretical and experimental results for the variation of



a)



b)

Figure 11. Sensor activation a ~ b, (forward triggering – positive first half cycle) and b ~ a, (reverse triggering – negative first half cycle)

the output voltage in the distance between the sensor and the subject, and its speed. Assuming a capacitive load and a power supply of 3 V, the sensor activation results in a dual blip, where a forward motion is indicated with a positive first half cycle response (indicatable as a positive blip), while reverse motion is indicated with a negative first half cycle response (see Fig. 11).

The study of the PIR sensor characteristics and field test produces a look-up table that utilises as input:

a) the objects direction (Fig. 12);
b) the peak to peak amplitude between the two blips (Fig. 14);
c) the peak to peak time delay.

Data processing through the look-up table produces the estimation of the object size/shape and speed (Fig. 14).

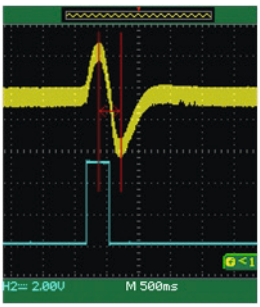


Figure 12. Time delay

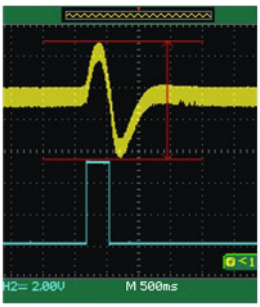


Figure 13. P-P amplitude

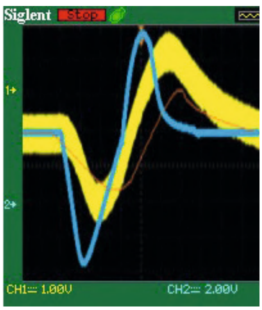


Figure 14. Look-up table estimation

8.2. Realisation

The PIR sensor is essentially split into its two substrates and in this configuration allows bi-directional reading plus two readings of radiation sensed (a positive followed by a negative) and is mounted on the vertical axis (Fig. 17b). Simplistic monitoring is achievable with a standard 32-bit low-cost industrial microcontroller (MCU) with an integrated 12-bit successive approximation register (SAR), analogue-to-digital converter (ADC). Usually, such kind of MCU offers a single ADC channel with an internal multiplexer with a sampling frequency in the range between 500 kbps and 1 Mbps. This implies a physical limitation on the speed detection of the object. In fact, as the object speed increases, the time between the two blips decreases. This imposes the requirement to use high sampling rates, which results in the effective number of bits (ENOB) deterioration. Therefore, a critical element of the product industrialisation is data processing management. A large number of required ADC samples may introduce software overheads and signal distortions due to several physical factors. In order to increase the detection accuracy and estimated speed range, it is considered to use a dedicated 14-bit ADC capable of 2.5 Msps (LTC2313-14) controlled by a low-cost FPGA integral circuit, which is capable of managing higher operational digital processing frequencies and digital information pruning.

9. Current research progress on radar type sensors

Originally developed for military purposes, radars are found today in a variety of military and civil applications, since they open up wide opportunities for identifying objects moving in space, determining their direction and speed, and relative sizes, as well as other object parameters.

The radar capabilities are extensive, the principles of their operation can be radically different, but the basic principles remain the same. In simple words, the principle of radar operation can be described as follows: with its transmit (TX) antenna, it radiates electromagnetic energy into space, part of this energy is reflected in different directions from an object (usually called a target), which is at a distance from the radar, then part of this reflected energy (echo) returns back to the radar receive (RX) antenna, the receiver amplifies this signal and after processing this signal, decision is made at the receiver output about presence or absence of an echo from the object and other target information acquired (Skolnik, 2008).

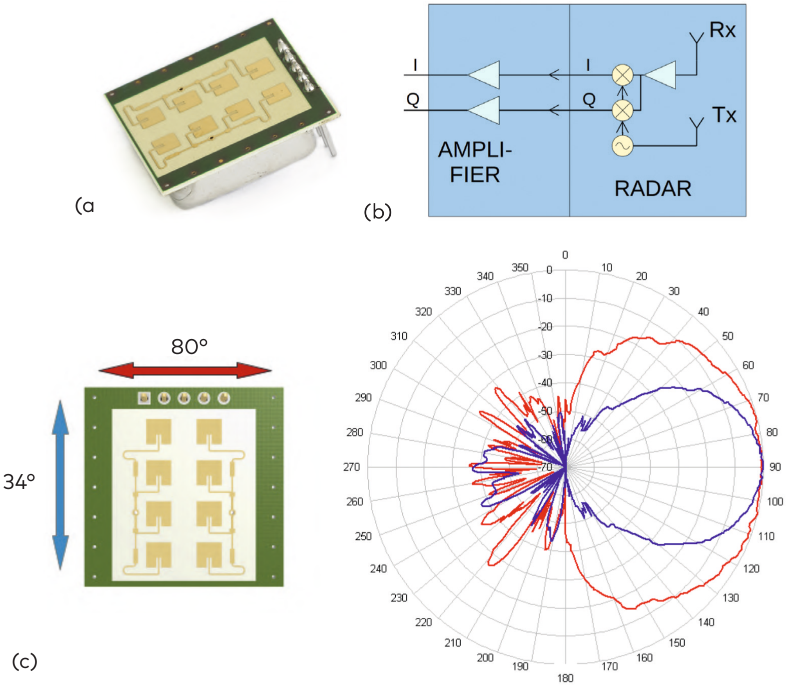


Figure 15. Selected transceiver for radar sensor: (a) appearance; (b) block diagram; (c) antenna system diagram (K-LC2)

As described above, we consider the radar to be a cost-efficient short-range sensor due to several circumstances: 1) compact, low cost and simple radars have recently become readily available on the market; 2) detection range of such sensors is of the order of several tens of meters; 3) there are no problems with making the housing, no special lenses are needed, ordinary (opaque) plastic can be used. Thus, the decision was made to build our radar sensor on 24 GHz K-band miniature I/Q transceiver with 2 · 4 patch antenna configuration (Fig. 15).

Here the "radar equation" is written as the product of three factors to represent physical processes:

$$P_r = \frac{P_t G_t}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \times A_e, \qquad (14)$$

where:
P_r – a portion of an echo power reflected from the target;
P_t – power radiated from antenna;
G_t – TX antenna gain;
R – distance to the target;

σ – radar cross-section (RCS) of the target (reflectivity of the target);
A_e – effective area of RX antenna.

Maximum range of the radar detection R_{max} can be found, when minimum detectible signal of the radar S_{min} is inserted in radar equation (Skolnik, 2008):

$$R_{max}^4 = \frac{P_t G_t A_e \sigma}{(4\pi)^2 S_{min}}. \tag{15}$$

For the selected microwave transceiver, inserting all the necessary parameters from the datasheet (module sensitivity −111 dBc and carrier frequency 24.125 GHz) we get a maximum range of detection:

$$R_{max} = 0.0167 \times 10^{\frac{-S_{min}}{40}} \times \sqrt[4]{\sigma}. \tag{16}$$

Using this equation and approximate values of RCS of the object, we can obtain indicative values of detection range: approximately 10 m for pedestrian and 26 m for moving cars [K-LC2].

9.1. Interpretation of transceiver I/Q data

To take all the advances of I/Q radar transceiver, real-time digital signal processing of these two signals (Fig. 14a) is necessary – by using complex Fast Fourier Transformation (Fig. 14b). Then direction and speed of a target can be determined in an easy way using this type of digital signal processing, frequency at a peak in the frequency domain that represents the speed of moving target, while the positive or negative sign in frequency domain represents movement direction of the target – approaching or receding (Fig. 14b). In terms of acceleration of experimental verification, the producer of such radar transceivers offers the ready solution of complex FFT for some of their products (K-LD2).

It also means that the radar in relation to the road must be installed in a special way, directed by the antenna in relation to approaching and receding targets, not perpendicular to the carriageway. This must be considered when installing a sensor of this type (Fig. 15).

For such a sensor with implemented complex FFT, the speed of target is proportional to the Doppler frequency shift $f_{Doppler}$ Eq. (17) according to the following equation:

$$f_{Doppler} = bin \times \frac{f_{sample}}{N_{FFT}} = bin \times \frac{f_{sample}}{256}, \tag{17}$$

where:
bin – FFT output value proportional to Doppler frequency; f_{sample} – FFT sample rate; N_{FFT} – FFT width, bits.

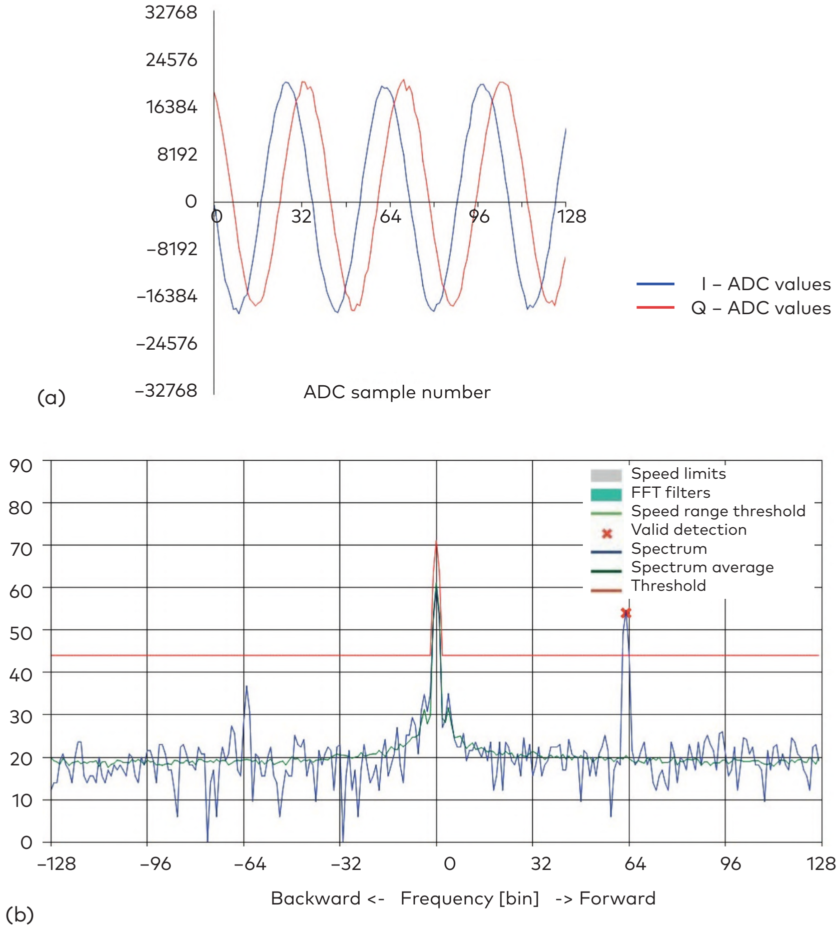


Figure 16. Radar transceiver signals: (a) I/Q signals; (b) complex FFT derived from I/Q signals (K-LD2)

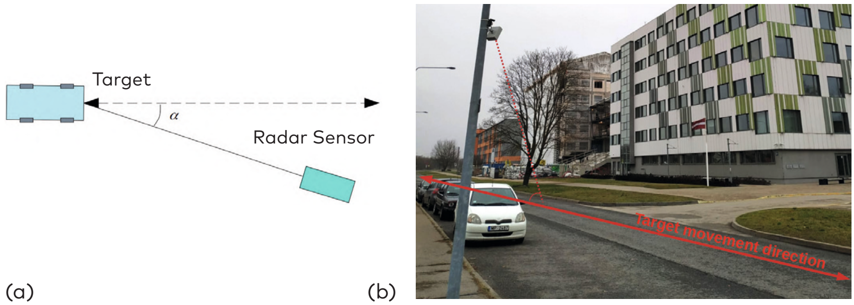


Figure 17. Influence of the radar towards moving object position on the measured speed: (a) schematically (K-LD2); (b) position of the experimental sensor at the installation site

Then the target speed Eq. (18) in km/h can be found from the modified previous equation, considering the angle between the radar and moving object trajectory cos (α) (K-LD2):

$$v = \frac{bin \times f_{\text{sample}}}{256 \times 44.7 \times \cos(a)}. \quad (18)$$

9.2. Setup for experimental radar sensor verification

First of all, it should be noted that experimental verification of the sensor requires its installation in real conditions with existing infrastructure of lighting system. There are two reasonable possibilities where to install the sensor: on a street lamp itself or on a street light pole (it is true not only for experimental verification but also for final sensor installation as part of the whole system), as shown in Fig. 18. Therefore, the configuration of test setup (and final setup) may vary, especially the housing.

In our case, the available option was installation on a street light pole. The experimental setup was installed on light pole opposite the Faculty of Electrical and Environmental Engineering of RTU, Azenes Street 1 (Fig. 17b). Thus, there are particular requirements for this experimental

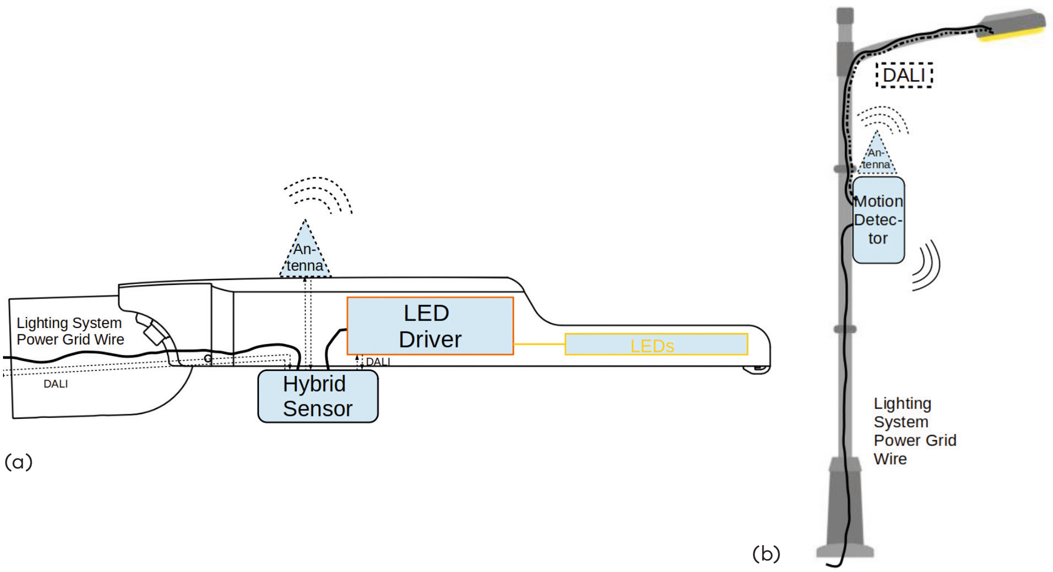


Figure 18. Two reasonable sensor installation possibilities: (a) on a street lamp itself; (b) on a street light pole

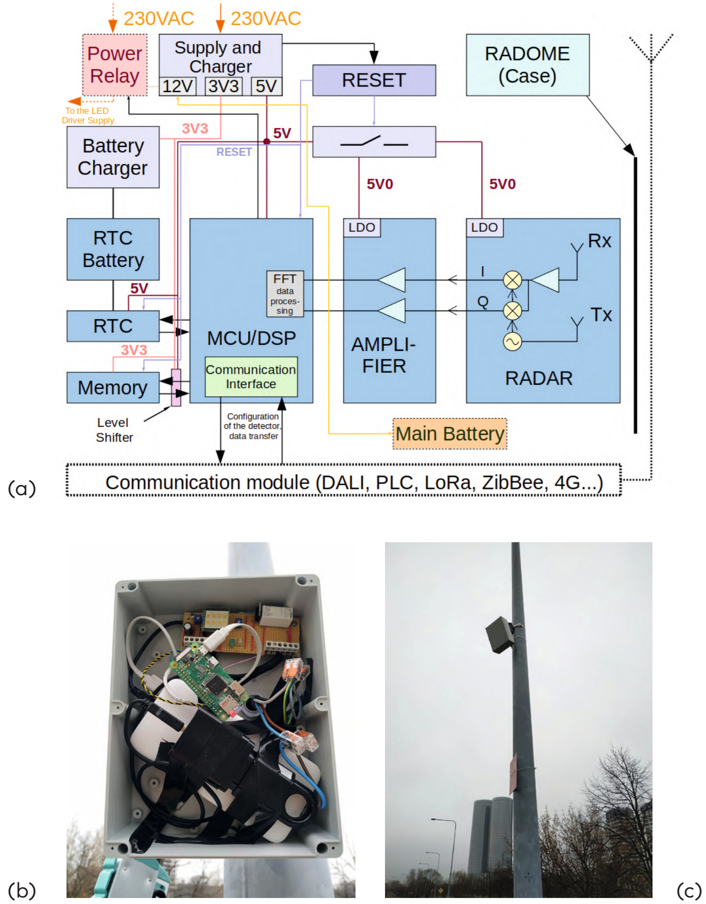


Figure 19. Radar sensor for experimental verification: (a) block schematics; (b) and (c) practical realisation

setup, such as independent or integrated grid power supply, battery and charger, autonomous operation for event statistics collection (grid supply is interrupted, when lamps are switched off). Also, the sensor must be able to commutate grid voltage (equipped with power relay); it must be equipped with more complicated communication module/s for the data transfer to the central management unit. In fact, this sensor should act as a lamp controller (in case of installation on the lamp with the ballast for smart ready solutions many of these additional blocks are not necessary). The block schematics for possible realisation of such an autonomous sensor is shown in Fig.19a, but the practical realisation is shown in Fig. 19b and 19c.

In order to speed up the construction of an experimental prototype, many control units and a communication module from Fig. 19a was replaced with the so-called single-board computer Raspberry Pi Zero W. This solution greatly simplified the work with the prototype, at first, as it made it possible to quickly organise remote access to the collected data, as well as provided the possibility of remote reprogramming and reconfiguration to study the capabilities of the sensor and test different configurations.

9.3. Analysis of the obtained experimental data

During these early experiments, it was possible to configure the sensor to obtain data on the direction of movement of objects. Unfortunately, it was unable to configure the sensor for the speed readings during these early experiments. However, this sensor supports speed detection function. The data were stored in the memory of Raspberry and periodically downloaded by connecting via Raspberry Wi-Fi module.

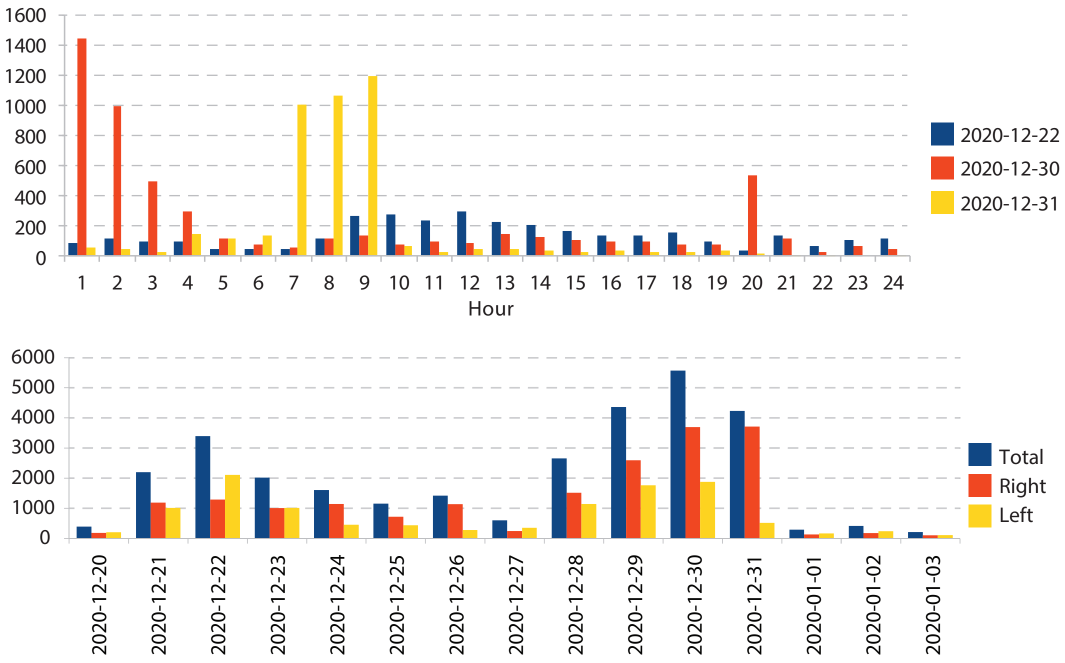


Figure 20. Summary of the experimental data obtained by the sensor: (a) accounting direction; (b) accounting time of the day

Information about the traffic flow along this street for a short period is summarised in the charts that are provided in Fig. 20. Even this small dataset allows making some conclusions: on such a small street, traffic intensity strongly depends on the time of day, day of the week, holidays and other factors. For example, in Fig. 20a, we see significant overall traffic intensity drop during New Year holidays starting from 1 January. For this period, street lighting could be optimised lowering the light level, thus reducing power consumption. We can also find significant traffic intensity rise during specific hours and specific days (Fig. 20b).

Such a low-cost short-range radar sensor can effectively keep records of traffic flow, counting vehicles, direction, and speed (will be verified in further experiments) – an ideal candidate in place of agent for MAS discussed above. Additionally, in future experiments it is necessary to carry out the verification of cyclist and pedestrian detection by this sensor.

9.4. Dynamic road lighting class detection algorithm using new functionality sensor data

Necessary amount of light on the road surface for the selected classes M or C and initial parameters is obtained during software (Dialux Evo or similar) modelling, when selecting the LED luminaire and its rated power value P_{max}. After LED luminaire installation works, lighting measurements in certain road spots can be performed to ensure maximum energy efficiency and lighting quality, and if necessary also correcting the initial set values of real control system (or luminaire controller). Selection parameters of Class M are defined in the introductory part, and for existing systems each time period has Class M corresponding to luminaire power (P_{min}) or the dimming level that is pre-programmed and stored in luminaire agent or gateway. The actual time is determined from the cloud management system, or from built-in clock. According to the algorithm (see Fig. 21), the time and actual time zone are checked every 10 minutes. If $t > t_{\mathrm{n}}$ it must be checked if night has ended and lights must be switched off (city calendar plan); otherwise, the variable n is increased by 1, and the cycle repeats in the next time zone.

The developed radar and PIR movement sensor enable a zero vision approach, as it detects the event and time-stamp and by Eq. (19), necessary parameters of Class M can be obtained: the traffic movement speed (V_{v}), traffic intensity (V_{i}) and maximum traffic capacity (C_{max}), traffic direction (NL – left; NR – right) and the number of each direction movement events or the number of vehicles N over the respective time frame T (one hour). N_i is an i-th measurement in succession over a

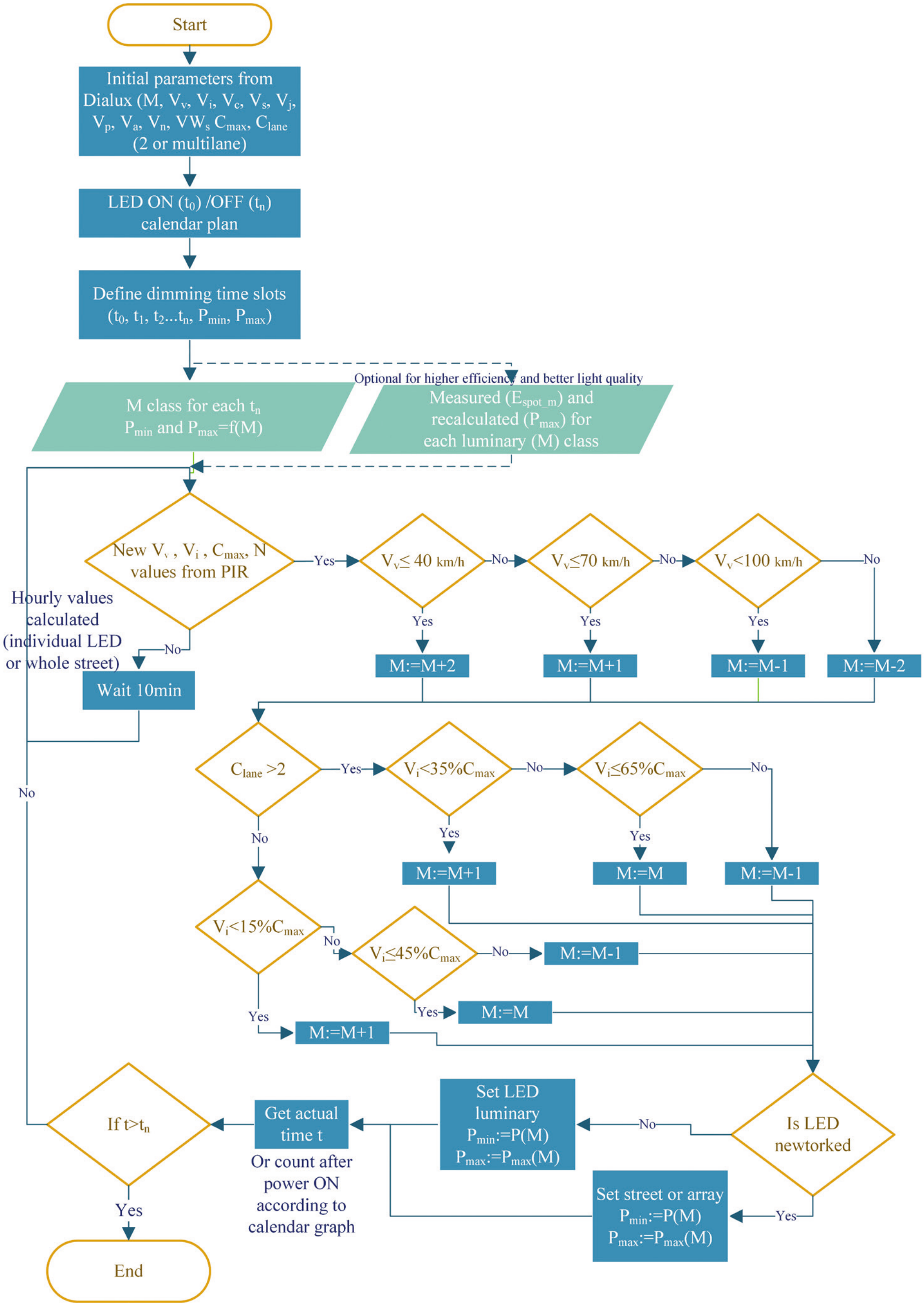


Figure 21. LED luminaire dynamic ME class control algorithm for the proposed sensor system (standalone or networked regime)

specific time period (one hour), regardless of the movement direction, i.e., N_i = NL + NR.

$$C_{max} = \sum_{T-24}^{T} (N) V_i = N = \sum_{T}^{T+1} (N_i) \quad . \tag{19}$$

C_{max} is expressed as the number of vehicles per day, assuming that the maximum value of traffic capacity can increase unexpectedly only in force-majeure situations (weather, exhibitions, concerts, etc.).

Traffic intensity (V_i) is the number of vehicles at one spot – close to lamp sensor placement. Traffic speed (V_v) initially is the maximum speed limit determined by a road sign, and later it is dynamically calculated from actual sensor readings. Class M requires calculating average V_v values (20) once in an hour (t = 0 up to t = 60 min) or once in a minute (t = 0 up to t = 60 s), depending on the needs of dynamic algorithm accuracy.

$$V_v = \frac{\sum_{t=0}^{t=60} v_i}{i} . \tag{20}$$

Further on, the algorithm checks in which range V_v is at the moment, consequently changing Class M ($V_v \in \{2;1;-1;-2\}$), and determining the impact of V_i parameter on Class M ($V_i \in \{1;0;-1\}$). Then, it is determined whether the luminaire has to be individually regulated or the entire group has to be regulated, consequently changing the set P_{min} and P_{max} values. The actual time is obtained, and it is checked whether it does not exceed t_n, in this case, turning off the lighting. If not, the cycle is repeated after the delay of 10 minutes.

Conclusions

Smarter elements and additional functionality approach for road lighting systems are essential to ensure safer operation of these systems. The data accumulated for statistical, analytical or probability analysis are crucial as outlined in the paper. Cloud computing with the inclusion of MAS control becomes a technology concept that may be adopted to run such systems. The system does not have to operate faster than the real-time one, as the data results collected at the MAS will not generally be used to control individual agents. Moreover, the MAS will be proactive in the assimilation of data, yet can maintain control of the system as a whole.

Communication (load) balancing of the road lighting control system is quickly reduced and synchronization between MAS and gateway may be extended from milliseconds to minutes, without detriment to the system, negating the need for synchronization across the agents. The multi-layered architecture of the system proposes increased accuracy over time, providing more accurate energy, traffic, pedestrian, weather and area-specific trends.

Preliminary guidelines for modelling the control architecture for the smart street lighting micro-array grid as a Cloud Computing Service have been presented herein. The guidelines address and identify the critical factors, on which the design is based. The developed dynamic Class M detection algorithm, using data from the new movement detection sensor functionality, allows for much smarter control of LED luminaires with appropriate light output quality when it is needed, thus making it also safer for road users.

During our experiments, we have found that long-range hybrid PIR sensor and radar type sensors can be used as zero vision elements for traffic flow detection and analysis, as all road users have been detected that are crucial elements for MAS agents described above. However, further experimental verification and improvements are necessary to obtain precision in various situations.

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Appendix 3

A. Avotins, O. Tetervenoks, L. R. Adrian and A. Severdaks, "Traffic Intensity Adaptive Street Lighting Control," IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society, **2021**, pp. 1–6

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Traffic Intensity Adaptive Street Lighting Control

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***Abstract*— This paper focused on energy efficiency increase for Smart street lighting systems with movement detection sensors. The measurements on Pilot Sites show a high potential to reduce energy consumption in the first years after installation, primarily if good quality LED luminaires are in use. In the third chapter, a new approach for movement detection sensors presents. It enables a data sensing dimension, enabling a new traffic intensity adaptive control algorithm that assists in regulating the lighting to required power values according to actual traffic intensity and M or C class during the whole night-time. It keeps maximum power when traffic is present and minimum when there is no traffic, thus achieving maximum energy efficiency while at the same time maintaining lighting quality and maximum safety.**

Keywords—LED, Smart lighting, energy efficiency, safety, adaptive control, movement detection sensors.

I. Introduction

Due to advancements in Light Emitting Diode (LED) technology, street lighting systems have continuously evolved during the last ten years. This evolution was going through several steps: 1) simple light source retrofitting, replacing high-pressure sodium vapor lamps with new LED luminaries (gives 40-60% energy savings); 2) further, upgrading lighting systems with a luminaire controller (with distant control or standalone regime working) operated on a pre-programmed calendar graph basis, with defined power levels per day or various power levels with specific time slots during the night. This approach enabled extra energy savings, but the actual savings typically were lower than expected as a higher light output (power) value was defined during the installation in the case of unplanned traffic increases.

The next logical step was to 3) introduce movement detection sensors, similar to the LITES project [1],[2], where the sensor detected a movement event and instantly increased LED luminaire power output to a maximum value of a specific time slot. Thus, we can say that this was the start of a smart or intelligent lighting system, as it was aware of actual traffic intensity events. As in the ZigBee network, the luminaire control nodes send maximum light "ON" signals through nearby lamp control nodes, illuminating the road in advance for 150-200 m. It is a common approach at the moment.

Through analysis of scientific literature, we could distinguish two types of further advancements, where one direction is to embed additional optimization or prediction models for systems without movement detection sensors. One such research [3] proposes actual lighting-class selection exploiting Greenshields Traffic Model and traffic data from other methods we can call virtual or context-based" sensors [4]. It is an interesting approach, as it makes the lighting system truly adaptive by selecting appropriate M or C classes according to the lighting standards [5] for a certain daytime period. Such an approach is precise and suited for large city areas, as traffic typically is monitored on highways or some central streets with a much higher M class. Also, it can be improved if traffic flow and traffic intensity distribution models are added, like [6],[7]. The disadvantage is that such models need high computing capacity.

The second direction exploits data from actual movement detection sensors. In this case, regulation depends on traffic changes. Accurate traffic intensity data can be used to embed the Brute-Force Energy optimization model [8] or some other traffic detection systems already installed [9] to use CIE (International Commission on Illumination) rule-based M class change [10]. The disadvantage is that the commonly used PIR (Passive Infrared) sensors are not advanced or functional enough [11] to measure both – the speed, direction, and traffic intensity data to enable full parameter scope for dynamical selection of appropriate lighting class. So the solution to this problem could be an advanced PIR sensor discussed in this paper and [12] that can deliver this functionality to provide an 80-120m detection range. Another way is frame capturing by advanced video camera and picture analysis, adapting it for street lighting control [13].

Further, we should also consider that LED luminaire stability [14], output power, and output light amount are not perfectly linear. Thus measurements with accurate reference data are needed, as variations arise due to thermal or dimming UP or DOWN parameters [15]. This way, we can make a more precise luminaire power selection.

II. Case Study Findings

A. Riga city

A Pilot Site was created in Riga during the LITES project implementation on Zunda Krastmala street. 29 pcs of existing HPS luminaires (3450W total installed power) were replaced with LITES system using Thorn Dyana LED luminaries (71.22 Lm/W efficiency, 2215W total installed power). The arrangement of luminaires was simulated in Dialux v4. Table I compares simulated results with in-situ measurements for three different points M1, M2, and M3 at different dimming levels.

In most cases, we can see that the simulation shows less light (@MF 1.00) to be given by this LED luminaire if comparing measurements of the years 2014 and 2020. The energy savings of the LITES Smart lighting system using sensors was 72-73% on average per year, and we can observe that during 7-year work (4400 hours per year), the lumen depreciation (light loss) is up to 20%. However, the actual values are still above the simulation results.

A. Daugavpils city

In this city, a Smart lighting control system with LED luminaires and microwave radar sensors (each 3rd pole or conflict zone) was installed in three city regions. One is central (higher traffic, 33 ME3/ME4/ME5 class streets), and two are in sub-urban areas (lower traffic, ME4/ME5, and ME5/ME6). The lighting system was retrofitted from HPS (High Pressure Sodium) lamps to LED system.

TABLE I. DIALUX MODELLING RESULTS OF LITES LED LUMINAIRE AT REAL SITUATION POWER/LIGHT OUTPUT RATIO (DIMMED) REGIME

Illumination Points		Measured 2020	Measured 2014	Simulated 2014	Difference %
E(80%), Lux	M1	25	28	20	+19%
	M2	7	10.7	8.19	-17%
	M3	24	17	20	+17%
E(60%), Lux	M1	20	-	10	+50%
	M2	6	-	4.49	+21%
	M3	20	-	10	+49%
E(40%), Lux	M1	14	-	6.24	+56%
	M2	4	-	2.92	+33%
	M3	14	-	6.24	+56%
E(20%), Lux	M1	8	7.1	3.12	+61%
	M2	3	3	1.35	+49%
	M3	8	7	3.12	+59%

Overall more than 1300 lighting poles were measured, using one Lux measurement in the middle of the street at dimmed regimes (20% dimming step), consumed power, including luminaire control node and radar sensor consumption (P, W, Lux, Candela). Luminaire power (W), type, and conflict zones were calculated in Dialux for all the streets, confirming that the selected luminaire will fulfill the minimum quality criteria of the chosen M or C class according to standard [5].

It is seen from Fig. 1 and Fig. 2 an accurate and stable dimming profile (power and light output consistency) is a challenging task due to the efficiency of LED driver changes in the dimmed stage and temperature impact.

From Fig. 1 we can see the relation of active power consumed and dimming step. We see regulation variance is ~10% at maximum power, leading to potential energy consumption or light output quality losses.

The relation of light output (Lux values at E_{spot}) and active power seems more linear (Fig. 2), but we see a 6% deviation between the same luminaries of the same street profile and a 22-25% difference between the same luminaire power in different streets. It clearly shows the need for "look-up table" type adjustments after performed measurements for finished system installation works.

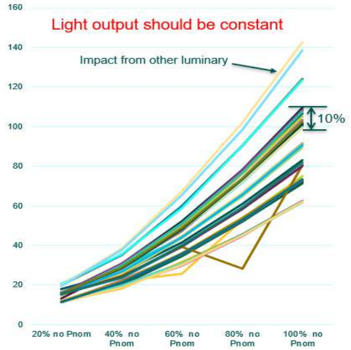


Fig. 1. Graphical relation of active power consumption and dimming step value.

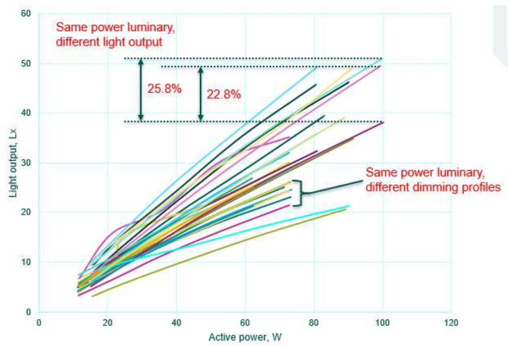


Fig. 2. Graphical relation of power consumption and measured light output values.

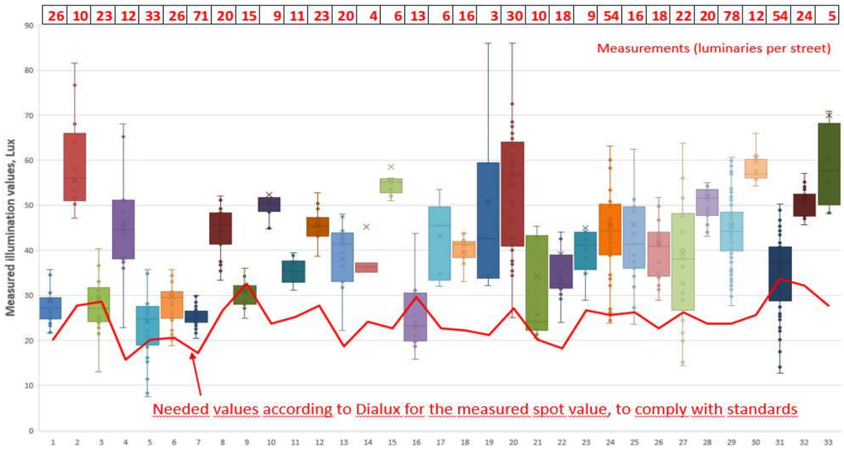


Fig. 3. Measured illumination vale distribution per street and needed minimums, according to Dialux.

Fig. 3 shows illumination level (Lux) value distribution per street graphically. The red line represents the needed minimum value of the Dialux calculation of the specific measurement point to fulfill the M class criteria. The red numbers above show measurement points performed (luminaries per street). The bars show the median analysis of all measurements (min to max). We can also see how many light points are outside the median. The median (bar in the graph) considers as the normal distribution according to simulation results. There are many points above average or outside the median, which proves the quality and safety issues.

The extremely low (minimums) of illumination level E_{spot} (Lux) values relate to the impact of surrounding obstacles, like the trees. For streets that were not affected by trees or other obstacles, the light deviation is still substantial.

III. Core Element of Adaptive System

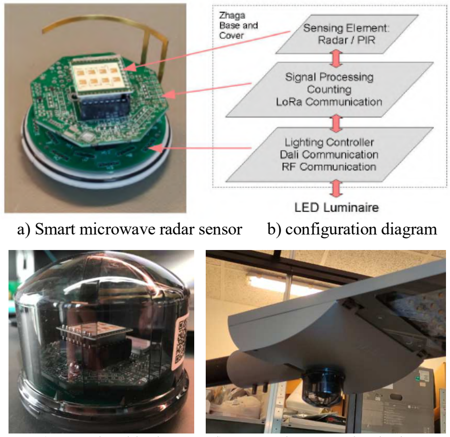
In our case, we want to create a fully adaptive control system that can work in both cases: 1) in a standalone regime, where a single luminaire is controlled, or in the case where a city doesn't have a central management and communication system or wants a simple and robust design; 2) in a networked regime, where one sensor can control several nearby LED luminaries. In both cases standalone regime proves invaluable. Therefore, we propose to add advanced movement detection sensors to each pole, or at least each third, when installation costs have to be reduced.

Our proposed solution to facilitate the configuration of various smart motion sensors is a stackable PCB (Printed Circuit Board) configuration (Fig. 4). Stack: 1) the base is lighting controller PCB; 2) radar / PIR processing PCB stacks above the base lighting controller PCB; 3) radar transceiver itself or PIR module is stacked above processing PCB (Fig. 4). Stackable configuration does not include the Long-Range PIR sensor (LRPIR) because it is a standalone item for specific requirements. The device is configured so that it may split into individual modules.

A. Smart LRPIR Sensor – Long Range detection

Although still under development, the LRPIR represents a very promising addition to the system. The LRPIR requires only an algorithm part to correctly analyze the inherently smaller signals and the addition of a specially modified lens adaptor allowing the unit to sense at greater range. Essentially, the circuitry of both the long and short-range sensors is equivalent, requiring only the algorithm and the lens apparatus, Fig. 5, to be adjusted.

Although repeatedly referring to a lens apparatus, the adaptor for the LRPIR does not have any magnifying capability. Adding a "magnifying lens" to the system reduces the device's receptivity and, therefore, reliability. The primary reason for this is an equivalent decrease in received infrared radiation for every barrier, glass, or plastic placed between the object and the sensor. A "magnification lens requires a precise focus point relative to the Field of View (FOV). Due to the varying distances required for placement of the LRPIR, and from an economic perspective, it is not feasible to adjust for each situation. Fig. 6 reflects an interpretation of the adaptor. For the purpose of this paper, it is sufficient to realize that an increase in "L" will give a proportionate decrease in "FOV" combined with an increase in "WD".



a) Smart microwave radar sensor b) configuration diagram

c) Completed look d) mounted on LED luminaire

Fig. 4. Configuration of intelligent movement sensor

The specific features of the LRPIR revolve around the need for long-range detection of vehicles, whether departing or approaching a long street or highway section, where no other sensors are required. The purpose is defined as controlling the light dimming process to a distance of approximately 100 meters in advance to alleviate disorientation to the driver due to luminaire brightness or road reflection blindness. This relates entirely to safety with the added benefit that if the road is congested with many vehicles traveling in the same area, the sensor will maintain a constant dimming process on that section of roadway and represents further energy efficiency. Additional investigation is ongoing to evaluate speed detection calculated from the waveform patterns, as denoted in Fig. 7. Where direction (approaching) is indicated by a positive first half cycle on Channel 1 and (departing) is characterized by a negative first half cycle on Channel 1. Speed may be calculated by an "ON" time value from Channel 2 for either direction.

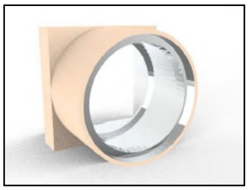


Fig. 5. Modeling of Short Range Adaptor.

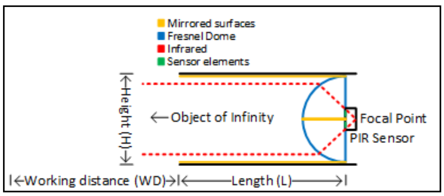


Fig. 6. Lens adaptor long and short-range configuration.

A further advantage of the LRPIR is vehicle counting. A good example would be that every city has entry and departure points. LRPIR's set at those points represents a data set to analyze the vehicle count to and from the city on a time basis allowing for far more accurate traffic analysis, routing, and control. A robust system emerges when combining these features and the sensor's compatibility with most existing lighting schemes.

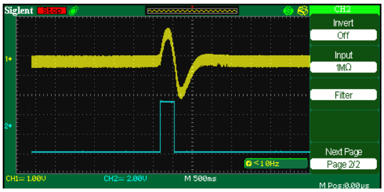
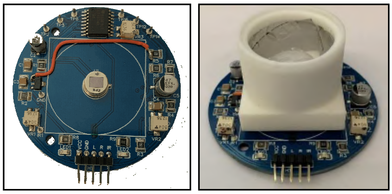


Fig. 7. Association between received waveforms.

B. *Smart SRPIR Sensor – Short Range detection*

The SRPIR is in the final stages of development, requiring connection to the stackable PCB described at the beginning of this chapter. As seen in Fig. 8 at the heart of our SRPIR sensor is the dual pyroelectric sensor incorporating modification to its sensitivity elements and other amplification/separation architecture, allowing the clear division of directional logic. The approximate detection distance is 20m for humans and cars.



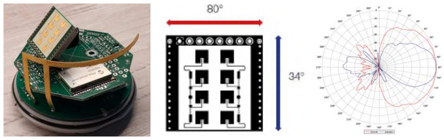
a) PIR Sensor mainboard. b) prototype with lens adaptor.

Fig. 8. SRPIR hybrid sensor prototype

C. *Smart Microwave Radar Sensor*

The base of the Smart microwave radar sensor is a 24GHz K-band miniature I/Q transceiver with a 2×4 patch antenna and 80°/ 34° beam aperture (Fig. 9). The approximate detection distance is 15m for humans and 30m for cars. However, the maximum range for Doppler movement depends on many parameters, mainly on module sensitivity, carrier frequency, and radar cross-section (RCS) of the object (object "reflectivity"), so experimental validation is necessary. This microwave sensor has powerful FFT (Fast Fourier Transform) signal processing and many parameter configuration options, sensitivity adjustment features, and plenty of filtering possibilities to adjust at different mounting heights and positions. It is capable of detecting movement, determining the direction and speed of moving objects.

This type of radar sees moving objects as approaching or receding. The higher precision for speed readings achieves when the angle between the moving object trajectory and the radar is minimal (13.7deg angle on Fig. 10). When the radar sensor is mounted on LED luminaire for the best performance radar sensing element should be tilted (Fig. 9 a) so that the moving object remains in the radar sensing area as long as possible (with the broader radar antenna aperture side). It is the main conclusion from the in-situ experiments.



a) Transceiver itself b) antenna beam aperture.

Fig. 9. 24GHz K-band miniature I/Q transceiver

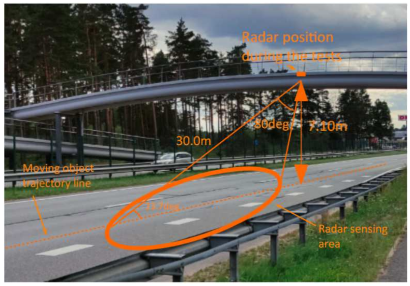


Fig. 10. In-situ experiments with radar module, sensing area, and angles.

IV. Traffic Intensity Adaptive Control Algorithm

"Lighting upon request" [6] or traffic-adaptive [16],[17] lighting management systems remain a topical issue. According to the LVS standards [5], it is already allowed to create four time zones (Δt_n) during the night, applying each M or C class, increasing or decreasing the lighting respectively, and P_{max}/P_{min} power levels. If PIR [18],[19]or radar [20], or sensors are used [21], the number of zones can be higher.

Standard 13201-1 [5] provides selection principles of road lighting M class and C class conflict zones, considering geometric and traffic data. Standard 13201-2, in its turn, provides minimum requirements for each class, where key quality parameters are average lighting (L, $cd \cdot m^{-2}$), regularity of horizontal lighting (U_0), irregularity of longitudinality (U_l), dazing coefficient (f_{TI}) and background lighting (R_{EI}), and for C class average horizontal lighting (E, lx) and regularity (U_0).

Comparatively, the lux values of the C class are higher than the M class, and approximate conversion from the candle to lux units can be achieved through a linear coherency (1). In the management software, such an approach would simplify the E_{spot} value obtained in Dialux software and actually measured, allowing to determine more accurate required power to comply with the requirements of lighting-class [22].

$$E(lx) = 1.027 \times M^2 - 13.7 \times M + 52 \qquad (1)$$

The lighting class M (or C) is determined by applying the formula (2) where the varying weighted sum (VWS) is used, or individual parameters that create the sum are analyzed, where dynamically varying parameters from the standard [5] "Part 1", taking into account also specific conditions: traffic speed ($V_v \in \{2;1;-1;-2\}$) and traffic intensity ($V_i \in \{1;0;-1\}$), and the constant parameters are the content of traffic participants (V_c), the density of crossings (V_s), presence of parked vehicle (V_p), surrounding lighting (V_a), the complexity of navigation (V_n), considering that it is night time. The sum of constant parameters can vary between the whole value range from +8 to -1. If the VWS sum is less than 0, the value "0" is used for calculations. If $M \leq 0$, the M1 class is applied.

$$M = 6 - VWS \tag{2}$$

$$M = 6 - \left(V_v + V_i + V_c + V_s + V_j + V_n + V_a + V_n\right) \tag{3}$$

LED luminaire management algorithm for the option without movement sensor is provided by Fig. 11, where the luminaire can operate independently or receiving management command from the central management system. Controller memory defines initial parameter values (E_{spot}, M, V_v, V_i, V_c, V_s, V_j, V_p, V_a, V_n, C_{max}), the calendar lighting schedule for every day or applying (4), as well as the number and duration of dimming time zones are determined.

$$T_d = 24 - {}^{2}/_{15}\left(acos\left(min\left(max(-\tan(\varphi)\tan(\delta), -1), 1\right)\right)\right), \tag{4}$$

$$where\ \delta = 23.45 \times \sin\left(\frac{360}{365}(284 + n)\right)$$

According to the Dialux model, the M class of each zone is determined and the value of P_{max} power that provides it. To ensure energy efficiency and improve lighting quality, after installing luminaries, it is possible to conduct lighting (E_{spot}) measurements once in five years, correcting the initial set values. The actual time is determined from the management system, built-in RTC (Real-Time Clock), or counting time-based on the calendar schedule, according to which the appropriate M class is selected.

Afterward, the actual time and actual time zone are checked every 10 minutes. If $t > t_n$, it is also checked whether it has not exceeded the turning off time when the luminaire is turned off, otherwise the variable n is increased by 1, and the cycle repeats in the next time zone.

Fig. 12 provides LED luminaire dynamic, traffic adaptive management algorithm for the option with movement sensor data for local and network connected mode, where one sensor can manage the nearby luminaries. The beginning is identical to the independent mode algorithm. Still, its Smart movement sensor detects the traffic movement speed (V_v), traffic intensity (V_i) and maximum traffic capacity (C_{max}), traffic direction (NL – left; NR – right), and the number of each direction movement event or the number of vehicles N over the respective time frame T which in this case is one hour. N_i is an "i" measurement in succession over a specific time period (in this case, one hour), regardless of the movement direction, i.e. Ni=NL+NR.

$$V_i = N = \sum_T^{T+1}(N_i); \qquad C_{max} = \sum_{T-24}^{T}(N) \tag{5}$$

C_{max} is expressed as the number of vehicles per day. It is assumed that the maximum value of traffic capacity can increase unexpectedly only due to extraordinary circumstances or planned events (exhibitions, concerts, etc.).

Traffic intensity (V_i) is the number of vehicles at one spot, i.e., near the lamp post. Traffic speed (V_v), according to the standard, is the maximum speed limit that is determined by a road sign for a specific street section (or time of the day) because the actual speed data have not been obtained so far. Therefore, this parameter can be changed dynamically, taking into account the fundamental values obtained from the movement sensors described above and in [19].

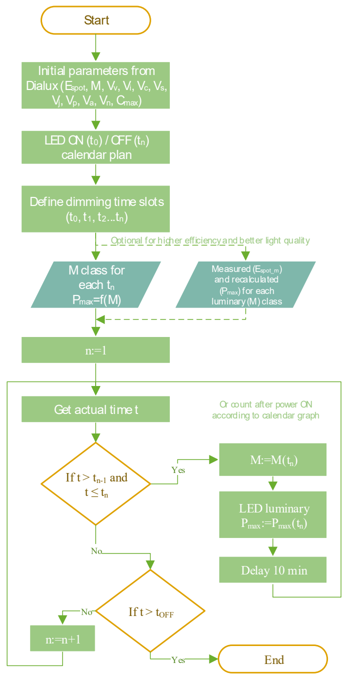


Fig. 11. LED luminaire control algorithm for the scenario without sensor data (standalone regime).

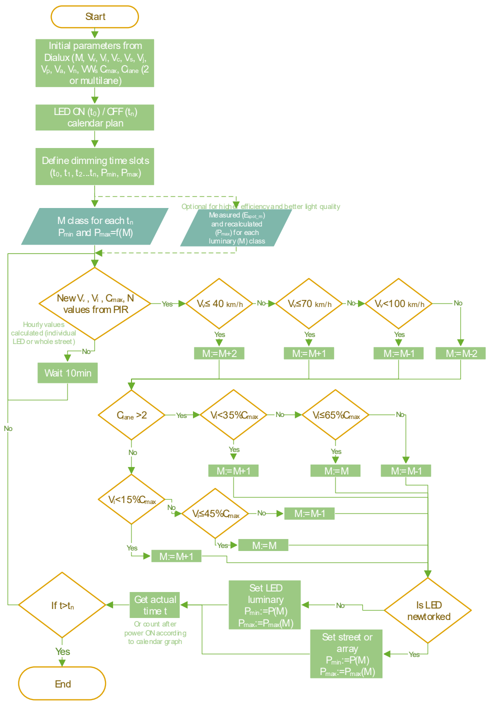


Fig. 12. LED luminaire adaptive control algorithm for the scenario with smart sensor data (standalone or networked regime).

M class requires average V_v values are calculated once in an hour (t=0 up to t=60min) or once in a minute (t=0 up to t=60sec), depending on the needs for accuracy.

$$V_v = \frac{\sum_{t=0}^{t=60} v_i}{i} \quad (6)$$

Further on, the algorithm checks in which range V_v is, consequently changing the M class ($V_v \in \{2; 1; -1; -2\}$), and determining the impact of V_i parameter on M class ($V_i \in \{1; 0; -1\}$). Then it is determined whether the luminaire has to be individually regulated or the entire group has to be controlled, consequently changing the set P_{min} and P_{max} values. The actual time is obtained, and it is checked whether it does not exceed t_n, in this case, turning off the lighting. If not, the cycle is repeated after the delay of 10 minutes.

V. Conclusions

The created dynamic management algorithm allows us to manage lighting based on traffic intensity and historical data. Moreover, individual luminaire management and the centralized system can be provided — for the entire street or groups of streets, over the ranges of several time zones of the day, therefore obtaining maximum efficiency and not reducing the traffic safety from the point of view of lighting.

Also, the core elements (Smart PIR and radar sensors) of the proposed adaptive system were discussed in this paper. With the inclusion of the working algorithm, the system as a whole is becoming increasingly robust. Any shortfalls in the PIR system are being alleviated by the radar system and vice-versa. The Smart microwave radar sensor considered in this paper seems ideal for small and medium-sized streets. For the higher traffic flow streets, a more advanced radar sensing module is necessary or a more comprehensive algorithm part of dealing with the PIR side of the system. A couple of sensors were assembled and are ready for mounting on the Pilot Sites. Further research is planned to implement the algorithm on a real street Pilot Site to determine system behavior, quality issues, and energy consumption reduction of this approach, which will be published in further articles.

Acknowledgment

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Appendix 4

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MAS Concept for PIR Sensor-Based Lighting System Control Applications

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***Abstract*—Focusing on the design, architecture, and monitoring of Smart LED Street Lighting control, this paper investigates the use of a Cloud-Based Multi-agent System (CMAS) as a possible framework. The work centres upon previous developments by the authors in Close and Long Range Hybrid Pyroelectric Infrared (PIR) motion detection sensors. It also introduces the advances in radar type sensors that can be used in intelligent street lighting system control applications. The proposed sensor solutions can detect the traffic user (car or human) and determine its movement direction and approximate speed, which can be used both for dynamic lighting control algorithms, traffic intensity prediction, and increased city street safety. Furthermore, the street lighting system infrastructure can also monitor city environmental parameters like temperature, humidity, and CO2 levels, and many more, creating new services for smart cities.**

Keywords—Multi-Agent System, PIR, sensors, lighting control, smart LED lighting

I. INTRODUCTION

The expanding use of cloud computing services in all forms of application control lends itself well to incorporating Multi-agent Systems (MAS) into existing and developmental structures. This paper explores its inclusion into smart LED street lighting technologies [1, 7] and control mechanisms for the use of long-range hybrid pyroelectric sensors [1, 2] within those lighting systems. The adoption of energy-efficient and smart LED street lighting is increasing at an exponential rate. Further, with the increase in the implementation of Photovoltaic Assisted Street Lighting (PVAL) we must also consider the addition of a Distributed Energy Resource (DER) being added to the emerging list of microgrids requiring intelligent control systems and tools, like solar optimizers [3], storage elements [4]. However, this paper is not intended to specifically review the potential for inclusion of PVAL's as a part of the system, nor at this stage as a DER Micro-grid. Though MAS Cloud control of DER's may be found at [5] and indeed the energy evaluations of the street lighting may be monitored and controlled using MAS.

An MAS has been selected as a distributed control architecture and described within [6] as a collection of autonomous computational entities (which in this scenario are individual LED street lights with hybrid long-range control sensors) (*the agents*) [1], which perform tasks based upon predefined goals. The agents are granted remedial intelligence (*currently fuzzy logic architecture*); they pursue goals to optimize given performance measures in an environment which can be challenging to define analytically. An agent can act upon its environment or its workspace envelope (WE) and interact with other agents with conflicting goals towards a common goal. Agents can be imbued with limited or global perception of situational variables, and likewise, each Agent's ability to affect the system environment is dependent entirely upon implementation.

The merging of MAS with cloud computing for the purpose of street lighting control is novel. In the Author's opinion, it has not been previously considered, primarily due to the requirement that lighting systems will be illuminated, darkened and or dimmed at specific or predefined times without the need for further consideration. Incorporating the long-range hybrid sensor system within each Agent [1] brings with it a completely new range of data sets that lend themselves to MAS control. The logical solution for data transfer when considering the sheer volume projected for the future LED illumination is the relatively new cloud computing solution.

Cloud computing architecture will also permit and extend the diversity of control services for Smart LED street lighting technologies. If successful will represent a significant increase in public safety (Refer Agent Capabilities; Hybrid Sensor) and may significantly reduce the deployment costs across the whole system.

II. MAS DEVELOPMENT FACTORS

A definition of the actors is required to describe the system. Within Fig. 1, a micro-array (*Array A to Array…n*) may be defined as a road, street, walkway or any other area designated for installing the system and having defined as its (*agents or actors*) the intelligent streetlights complete with their sensory systems.

An agent (*Agent_1 to Agent_n*) may be interconnected or islanded from the network and is composed of two distinct states. The Agent is ascribed asynchronous communication. The sending and receiving of message and control data are independent of a coordinated clock signal between agents due to the requirement for each to operate within a unique and dynamic environment. In this way, a single agent can react to unpredictable event triggers yet maintain information transfer to the network simultaneously. Utilizing this approach, the Agent becomes separated and decentralized, dependent on individual event triggers that may not affect other agents within the array. Within the distributed MAS, the micro-array management must adapt to changing conditions within the framework of each state.

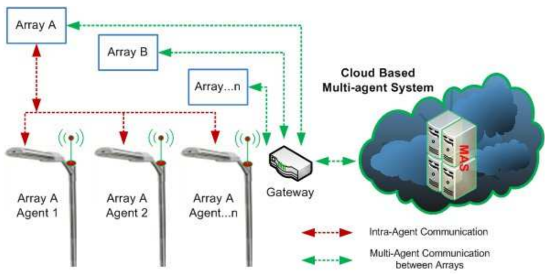

Fig.1. Remedial model indicating micro-arrays and agents.

An interconnected micro-array in cooperation with its agents must manage switching, illumination levels, energy consumption analysis, and data transfer to and from the CMAS, which maintains constant analysis of the combined network of micro-arrays. An example might be the various management modes under the decision algorithm of the CMAS, which may affect shared intersections of (micro-array A and micro-array B) due to any number of location-specific incidents which may vary significantly across a town or city.

When islanded, or when an agent has entered standalone mode due to a specific event trigger, all Agent systems may become autonomous yet continue to transmit data between its brother agents. Therefore, the CMAS relying upon its decision-making process, will become actively involved or remain silent. Regardless of the Agent state, the CMAS will seek the most favourable solution to allocated objectives where necessary.

III. NON-SYNCHRONOUS SYSTEM

Unlike many MAS systems, a synchronization strategy holds little importance due to the dynamic nature of the *Agents,* as described in Section II. Operation as a distributed system requires that all Agents operate in a synchronous manner and the various Agents and the synchronization within the system are a primary and necessary objective. Without this synchronization, complex software modelling and simulations applications fail to function. For example, in a pedestrian counting simulation, the physical area where targeted pedestrians are located may be segregated into various parts and monitored by an *Agent*. However, those pedestrians may wander from one physical location to another. Without a mechanism for synchronization, pedestrians walking from one *Agent* to the next would be misplaced in real-time where one *Agent* is ahead or behind in the model simulation. Therefore, uncontrolled synchronization would invalidate the simulation process due to overlapping past, present, and future tense events or triggers. It should be apparent that even a non-synchronous system dealing specifically with random data collection may be synchronous after an event when collated in date/time format.

Therefore, the main goal is to achieve data transfer to the CMAS, the primary decision-maker at the heart of the operation. The problems associated with synchronization are system overhead, requiring more complex data retrieval and processing algorithms.

Within the proposed system, there is a view to total removal of synchronization overhead which does not trade accuracy or performance.

IV. POWER MANAGEMENT AND SMART POWER

An exciting facet of creating a data collection system that also doubles as a decentralized Micro-Grid and Power Management scheme is the breadth of the possibilities for control algorithms. Power management is, as stated, controlled by the CMAS decision algorithm and may be refined over time. However, the primary triggers are initially within the control loop of each *Agent* designed to respond to environmental or physical changes within its WE. As may be seen in Fig 2, the Author's preferences lie in the fuzzy logic arena. However, the system, built primarily on non-proprietary software, lends itself to a whole array of possibilities regarding the choice of protocol and subsequent proprietary software. In this respect, the hardware of the system can become the main focus of the proposal.

Hybrid Long Range Sensor consists of one quad PIR sensor (incorporated Lens), 4x static IR sensors, temperature sensor, ambient light sensor, humidity sensor, and moisture sensor.

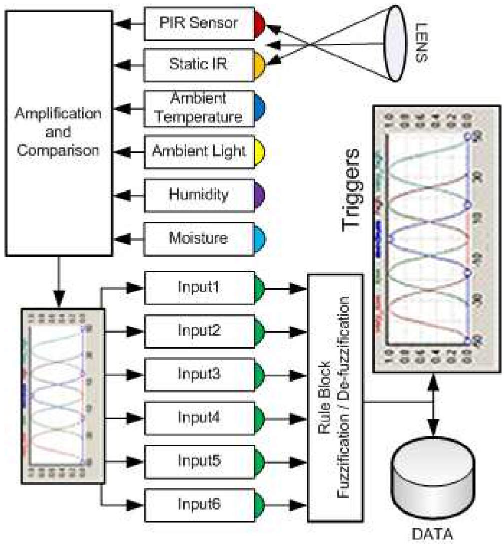

Fig.2. Current fuzzy logic system model.

V. AGENT CAPABILITIES

One challenge facing distributed MAS with DER systems has been the vast diversity of different components connected to the many micro-grids involved. Interoperability is key to a successful MAS deployment. Therein, the reasoning makes intelligent street lighting systems ideal and very capable in the processes of agent classification without extensive additional programming and, therefore, an ideal solution for a hybrid Cloud/MAS. Currently, the LED Street Lighting system with hybrid sensors (*the Agent*) in Fig.3 and 4, are in the production process or presently capable of the following functions:

Hybrid Sensor (*operating under fuzzy logic architecture*)

- Long and close range vehicle and human detection.
- Movement direction (L/R or R/L) detection, including detection of approaching or departing vehicles.

- Vehicle counting and in a lesser degree, pedestrian counting.
- Approximated vehicle velocity and vehicle headlight recognition.
- Ambient temperature sensing, ambient light sensing and wet weather detection.
- Compatibility with most existing lighting systems.

LED Street Lighting System (*using hybrid sensors*)

- Increased energy efficiency – light delivered only when and where needed (less light pollution).
- Exact lighting-class determination on actual traffic data according to EN13201.
- New services and functionality added to the system (improved Return of Investment values).
- Introduction of new Prediction, Maintenance and Control algorithms.
- Decentralized control, the system can analyze and make decisions – the system becomes smart.
- Context data application to enable participation in energy price markets (like Nordpool) or adjust consumption according to current price forecast.

Fig.3. Long-range PIR hybrid sensor prototype.

Fig.4. Standard range PIR hybrid sensor prototype.

VI. GENERAL PRINCIPALS

Figs. 5 and 6 show that Chanel 1, with a positive first half cycle, indicates direction, and Chanel 2 represents the square wave equivalent of the signal in Chanel 1 in real-time. The square wave pulse represents an approximate peak to peak value of the waveform.

It can be seen that Ch.1 is incremented in a 1-volt measurement. This is the PIR reading amplified from mV to approximately a 2V peak to peak and will require further filtering to remove parasitic frequencies. Ch. 2 is clean and is running directly from the 5V rail.

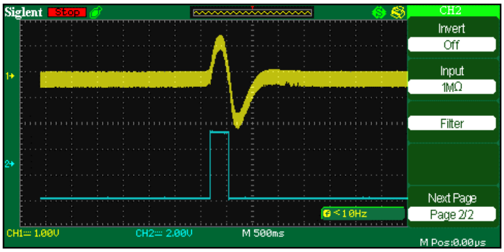

Fig.5. Demonstrates the combination of the two signal types and their association.

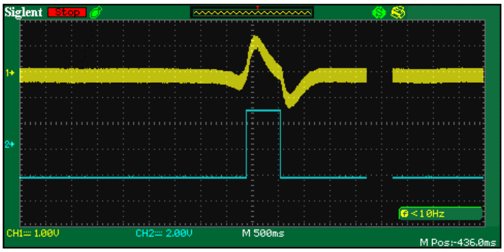

Fig.6. Slower movement can be indicated by overshoot or undershoot of the waveform.

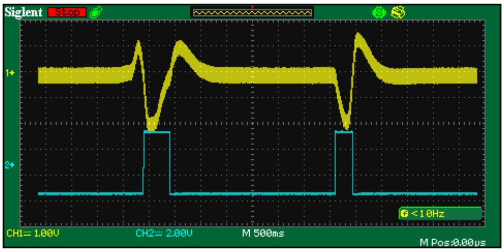

Fig.7. Snapshot 2 Vehicles passing in the opposite direction.

As seen in Fig. 7, the first waveform exhibits the characteristic positive first-half-cycle, indicating right to left movement. The second waveform shows the opposite (negative first-half-cycle) as is expected in the left to right direction. Also seen intuitively is an approximation of vehicle speed. The second square wave pulse is approximately 1/3rd less than the span of the first, indicating the higher velocity of the vehicle passing from the left.

VII. FUZZY LOGIC CONTROLLER

The authors' preference for a "Fuzzy Logic" controller is the outcome of a careful evaluation of several controller techniques within several projects. The decision process shows an advantage when used with the parallel computation capability and the possibility to integrate the Fuzzy Logic controller into a more comprehensive, self-adapting and self-learning system [21], with the ability to utilize the shared information between Agent and Cloud.

The previous sentence is of paramount importance for establishing a robust design for the Long-Range Hybrid PIR Sensors within a Smart LED Street Lighting System. This specific application is heavily influenced by environmental variables. The system's ability to use the shared information between the Agents and the Cloud is highly beneficial, primarily because the transferred information may also be used for self-training purposes and allow the system evolution to environmental variables. Additionally, this functionality may help minimize the effects of faults within local Agents.

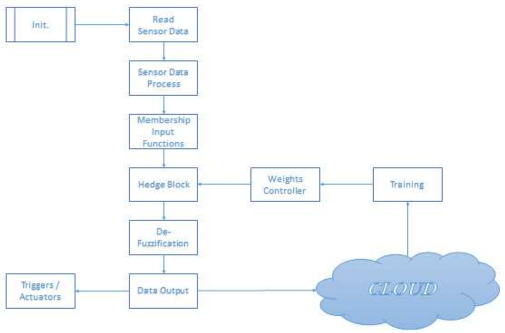

Fig.8. Decentralized Controller Flow Chart.

Therefore, a relevant approach to the research goal becomes the design of an adaptive fuzzy logic *Rule Block* capable of accepting and utilizing weight change commands from the "Cloud".

For this framework and the Author's license, the controller implements a small form factor, cost-effective FPGA for the physical implementation of the decentralized controller. A dedicated Paper [22] explores the decision process, which generates the outcome as described herein.

VIII. DATA TRANSFER

Adjustments to the control approach are implemented as a Cloud Computing Service. This approach can be easily extended with new functionalities without modifying the internal logic of the gateways. The Cloud is used to store the data related to the different points of the grid. The proposed architecture provides neighbourhood management as a service. A MAS may maintain the grid's stability by using only local area information (distributed control) of the luminary grid. Cloud-Based Multi-agent System (CMAS) architecture is shown in Fig. 8.

System Connectivity should and can be a user-customizable variable, which will be essentially defined by the application's specific environmental and technical requirements. In other words, the ideal MAS systems should be capable of being easily adapted to utilize any of the commonly used Data Transfer Methods as examples:

- ST LORA - LPWANs.
- Wireless.
- GSM/3G/4G/5G internet connection.
- ZigBee.

This is easily achievable, adding to the "Agent" one specific, or more, communication modules, where 5G [12] and NarrowBand and LoRa IoT are some of the promising technologies nowadays. The fuzzy logic parallel computational capability increments the system performance, especially if using FPGA based gateway, which is capable of parallel interaction parallel with all system agents' within an array (as in Fig.1 and Fig.9).

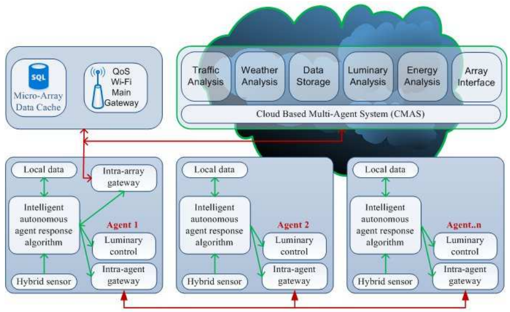

Fig.9. Cloud-based multi-agent system model.

The study case requires that the Agent covers a wide area and shares an amount of relatively small information, usually one or two Bytes for each parameter to be transferred. Data transfer speeds between agents is not an essential parameter in that the communication range capabilities are privileged. ST LoRa technology is the perfect solution for the study case because it is a Modular / Plug-in unit able to deliver, in optimal conditions, data at speeds up to 300Kbit/s, however, a 56 Kbit/s communication speed has been selected to be RS232 compatible, and which is larger than the minimum communication speed calculated with the Equation 1.

$$Com_{min} = (2 \times Sen_{refresh} \times Param_{max} \times Data_{res} \times Agents_{max}) \mathrm{T_{learn}} < \left(\frac{\text{(MOB in Mb)} \times 2e20}{\left((\mathrm{Sen_d} \times 1) + (\mathrm{Sen_a} \times 2) \right) \times \mathrm{S_{ps}} \times \mathrm{S}} \right)$$

$$= (2 \times 6Hz \times 8 \times 16bit \times 32) = 49.152 Kbit/s \quad (1)$$

where $\mathrm{Com_{min}}$ is the minimum communication speed; $\mathrm{Sen_{refresh}}$ is the sensor refresh cycle frequency; $\mathrm{Param_{max}}$ is the maximum number of parameters; $\mathrm{Data_{res}}$ is the parameter data resolution; $\mathrm{Agents_{max}}$ is the maximum number of agents per array.

IX. MULTI-AGENT CLOUD SIMULATION

Some problems generally relate to MAS systems and simulations requiring the evaluation of and impact of data packet arrival at the Cloud/MAS and relate specifically to the time synchronization departure/arrival on the MAS or gateway side of the system. Due to the truly "agent" nature of each streetlight, the intrinsic ability to enter "standalone" mode upon receipt of specific "triggers" provides the system with the added advantage of stability. Each part of the system, CMAS, Main gateway, Inter-Array and Agent Array, is designed with standalone algorithms to operate their own component of the system with data transfer secondary to the MAS if a trigger has occurred. In this aspect, the MAS may be viewed as a data collection distribution centre that can override all other systems when required. The main priorities of the system are that the MAS collect all transmitted data, providing instruction to *Arrays* (Streets), which control the *Agents* (Streetlights). The *Agents* (Streetlights) maintain control of their own *Workspace Envelope* (WE), reacting individually or in unison with other agents to received triggers.

X. CONCLUSIONS

The arena of intelligent street lighting administration is essential to the controlled operation of these systems as they emerge in our cities. The accumulation of data for statistical, analytical, or probability analysis is crucial, as outlined in the paper. Cloud computing with the inclusion of MAS control becomes a technology concept that may be adopted to run such systems.

The system doesn't have to operate faster than real-time as the data results collected at the MAS will not generally be purposed to control individual agents. Moreover, the MAS will be proactive in the assimilation of data yet can maintain control of the system whole.

Though theoretical in nature, the paper demonstrates that the system's load balancing may be easily reduced, and matters of synchronization between MAS and Gateway may be extended for milliseconds to minutes, without detriment to the system negating the need for synchronization across the *Agents*. The multi-layered architecture of the system proposes increased accuracy over time, providing more accurate energy, traffic, pedestrian, weather and area-specific trends.

Preliminary guidelines for modelling the control architecture for the intelligent street lighting micro-array grid as a Cloud Computing Service have been presented herein and address and identify the critical factors on which the design should be based. Commencement of algorithm functionality has commenced intended to foster an intelligent street lighting system to introduce the market.

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Appendix 5

R. Porins, P. Apse-Apsitis and **A. Avotins**, "PIR-Sensor Based Street Lighting System Control," 2020 IEEE 8th Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), 2021.

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PIR-Sensor Based Street Lighting System Control

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***Abstract*—The article deals with short-range PIR motion sensors' application into the intelligent street and walkways lighting illumination control for energy saving and better human experience needs. Future research of illumination level ramping profiles to achieve maximum energy efficiency and not downgrading human comport feeling must have an experimental setup, including discussing several possible and implemented simple control systems.**

Keywords—event detection, infrared sensors, control equipment, lighting control

I. Introduction

Obviously, by higher conversion efficiency from electric energy to visible light energy, LED light-based illumination has also become popular in street lighting. It is possible to save even more energy by implementing intelligent luminaries control based on street occupancy by people or traffic, and according to the LITES project [1], it can give 70% energy savings if existing high-pressure sodium lamps are retrofitted to LED technology. A lower lighting level for empty streets increases the energy efficiency through light source dimming and increases traffic safety at full illumination level otherwise.

The problematic question is - how to detect pedestrian or car presence on the street? Typically, one is looking for a long-range movement sensor like a long-range PIR [2], long-range laser, or microwave/radar [3] sensor. Some of the sensors are just prototypes, but some of them are available as on the shelf products, like Steinel PIR [4] or Citintelly radar sensors (cost around 70EUR), or Bosch Tritech long-range sensors (up to 200 EUR), but laser technology even exceeds the costs of the LED luminary itself. PIR sensor technology at the moment is the cheapest solution if comparing prices in Farnell, Digi-Key, or similar electronic component catalogs, and their application potential is not yet fully explored, as various layouts and combinations can bring enough precise detection results [5], especially in streets with walkways and not-so-busy traffic intensity. Here the LED luminaires are low power and thus have also a lower cost in EUR, therefore appropriate sensing technology requires less expensive variants.

Industrial and well-known brand PIR movement (occupancy) detectors have a short detection range - in most cases, less than 12 meters. At the same time, luminary pole height is in the range of 7–10 meters, in general close to the PIR movement sensor detection range. Another disadvantage is the delay or saturation cooldown time, which disables obtaining fast detection signal "time-stamp", if two PIR elements are used as additionally it can help to determine also approximate traffic speed and direction information. Having such hourly info can help dynamically select appropriate ME lighting-class according to existing lighting standards [6].

The further article describes a new possible approach for LED luminary control according to traffic or pedestrians' presence, based on short-range PIR sensors.

II. Background of the Task

Street illumination typically is made from several to tens of luminaries placed on poles in distances 20…30 m. Regardless of the type, luminaries are switched OFF during the daytime and switched ON over the night to keep overall illumination acceptable for human eye lighting-recognition conditions. Such an approach is technically easy to install but today becomes less satisfactory due to energy waste if there are no humans or vehicles in the illuminated area.

Another approach for new lighting installations is to pre-set the initial LED luminary power value in a range of 20%… 40% from max illumination if there are no humans and relatively slowly ramping it up to 100% when humans enter the detection zone or move in the illuminated area. This is a common approach for smart indoor lighting control (train stations, supermarkets, airports, etc), as installation height is relatively low, and sensor detection range is the same as lamps spotlight zone.

The best and most acceptable ramping profile isn't clear at the moment due to the human eye's extensive adoption to illumination level (also glare effect), especially if driving a car, as speeds can be different. Today well-known linear, exponential, parabolic, or some similar custom-defined profiles are used. Any ramping and 100% (max) luminary light emission must follow several standards [7]. Road minimum illumination level depends on the road pavement, and by R1–R4 classification difference for the same street geometry, it can be in the range of 30% [8].

Dimming or lighting output profiles typically don't include environmental conditions like rain, snow, fog, moonlight, locally detected by additional sensors, but as such conditions, like wet road affects minimum lighting values (in Lux or Candelas), it should be considered for the future improvement of the system control.

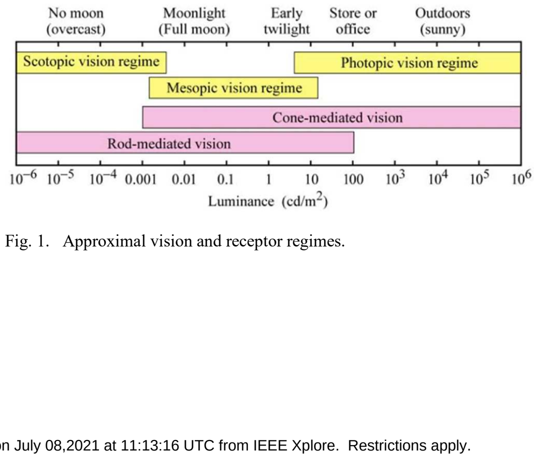

Fig. 1. Approximal vision and receptor regimes.

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In traffic conditions, illuminated roads and environments are sensed by the human eye, not by some physical sensor. The human eye is a complicated and complex biological sensor. Eye retina includes the light-sensitive rod cells (rods) and cone cells (cones). Rods are more "light-sensitive" than cones. Rods are sensitive over the entire visible spectrum opposite to cones, sensitive to RGB wavelength accordingly - see Fig. 1 [9].

"Photopic regime" relates to human vision during daylight conditions) and the cones mediate the image. "Scotopic regime" relates to the human eye at night and vision relay on rods, in this case also less light is needed. "Mesopic regime" relates to light levels between the photopic and scotopic vision regimes. Rods are more sensitive than cones, but cones determine light color sensing. However, the sense of color practically is lost in the scotopic vision regime - at low illumination, objects only appear in different grey levels.

Street illumination falls in the mesopic region where both - rods and cones - are involved in light reception, so small spectrum changes during the LED dimming create a negligible influence on visual recognition.

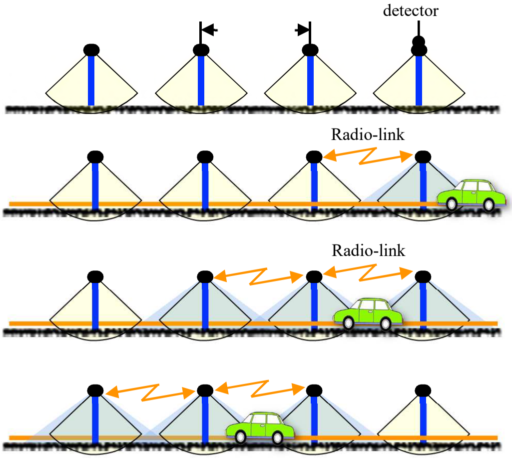

Fig. 2. Luminary and detector position on the street or the walkway and "wave" operation.

The illumination must ramp up in advance of entering the zone. Thus, the whole system must "predict" entering the zone and movement direction. Luminaries ON-OFF must follow the object movement and the street along with luminaries – "wave" or "train of light" operation in any movement direction (Fig. 2). Luminaries dimmed down to preset level if there is no movement of more than 15–30 seconds.

The proposed design will allow the test, measure, and tune-up of inexpensive PIR sensors to enable a dynamically adaptive and innovative street and/or walkways illumination system, based on described background information.

Finally, the test system estimates the amount of electrical energy consumption/savings by installed an electricity meter in all luminary poles (power supply) and/or street line feeder point. The human satisfaction estimation method isn't defined yet; probably some cellphone app could be used in the future.

III. The Detector

The detector includes a PIR motion sensor and detection ON-OFF information radio-link modules. Due to the included Fresnel lens and high sensitivity, VZ series Panasonic EKMC1603112 PIR motion sensor for human (or vehicle) detection is chosen:

- power supply: 3VDC…6 VDC, <1 mA;
- detection distance: up to 12 m;
- detection range (horizontal×vertical): 102°×92°;
- the difference in temperature between the target and background: > 4°C;
- detection object movement speed: >1 m/s;
- detection object size: 700mm × 250mm.

Radio-link utilizes simple 433 MHz short-range (up to 100 m) transmitters and receivers (Fig. 3), applied in security systems. The communication protocol is based on Amplitude Shift Keying (ASK). Radio-link modules also are chosen from previous experience [10], [11].

a) b)

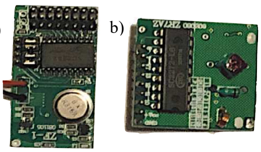

Fig. 3. Radio-link transmitter (a) and receiver (b).

Such a simple link sends just its pre-decoded number (by choosing jumpers combination), and typically it is possible to select one from 59049 numbers. It's good to set detector serial numbers in the same numbering order and the same manner as lighting poles are numbered. Setting a detector number into hardware isn't expensive or complicated, but this isn't a good option if one thinks about all system upgrade/downgrade requesting number changes in all detectors. In such a case, it could be costly.

IV. Illumination Control Functional Description

Fig. 4. show the luminary and the detector position on the pole and corresponding illumination and detection areas and dimensions. The system functional diagram is shown in Fig. 5.

Control of the luminaries "wave" operation isn't complicated (Fig. 2.):

- let's assume that moving objects enter the pole **A** PIR sensor detection zone. Luminary **A** will ramp up to full illumination (100%), and transmitter **A** sends a signal to the receiver on pole **B**, and luminary **B** also ramps up to 100%.
- by continuous object movement, objects enter into the PIR sensor detection zone of pole **B**. Regardless of the dimming level of the pole **B** luminary, it ramps up to 100%. And, again, the transmitter **B** sends a signal to receivers on pole **C** and pole **A**.
- on object enter into the PIR sensor detection zone of the pole **C**, regardless of the dimming level of the pole C luminary, it rump up to 100%. Again, transmitter **C** sends a signal to receivers on pole **D** and pole **B**. Luminary on pole **A** dim down to pre-defined level.
- sequence continuous till the end of the luminaries line.

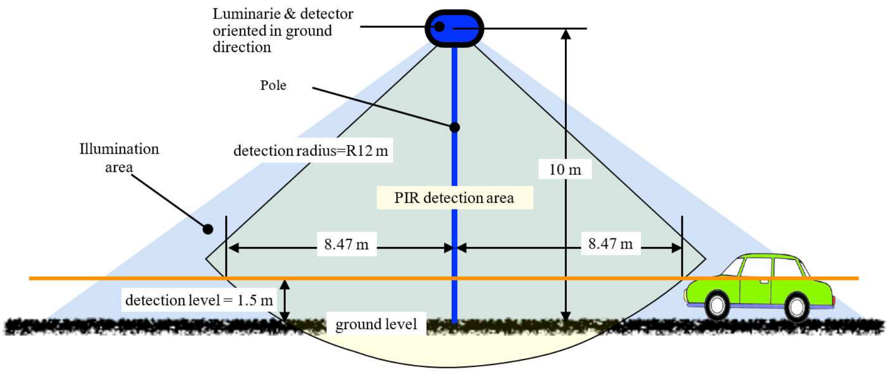

Fig. 4. Luminary and detector position on the mast and corresponding dimensions, illumination and detection areas.

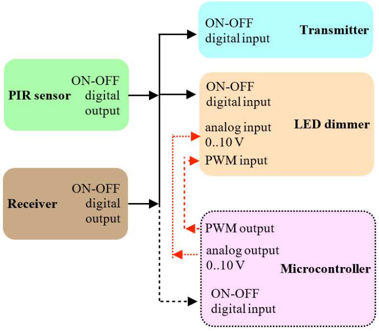

Fig. 5. System functional diagram.

The described process also relies on intelligent LED luminaries' ballast, providing possibilities for automatic dimming up and down by one PIR output digital control signal (Fig. 6.).

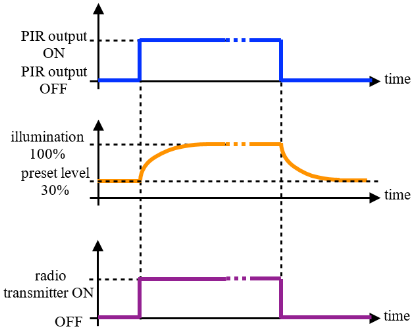

Fig. 6. Process diagrams.

A low-cost microcontroller (ATtiny 45/85, for example, or similar)) and additional low-pass filter is included in the detector (Fig. 7.) in case if less intelligent LED dimmers are in design without programmable dimming profile actuating on ON-OFF signal to replicate the processes shown in Fig. 6.

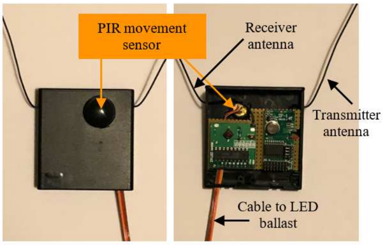

Fig. 7. Detector prototype.

V. Detector Prototype and First Tests

Three detector prototypes (Fig. 7.) make a test setup to test movement sensor, transmitter, receiver, and information transfer according to the "wave" process shown in Fig. 2 and the dimming process shown in Fig. 5.

LED ballast includes an automatic dimming option by one PIR output digital control signal.

The authors did initial tests in a large hall. Dimensions of the space allow placing the detectors and simple luminaries at a distance of 22 meters and 10 meters in height. Achieved experimental results are comparable to planned and expected, thus such sensors can be used for lighting system control. The results also show that antenna positioning design must be changed from flexible wire to hardwired or even PCB antenna could be used. Another design modification that must be implemented - is easier detector alignment against the road surface, or it could be also NEMA socket-based if added to luminary housing directly.

VI. Control Algorithm

According to CEN-TR standard 13201-1 [6], for each specific situation, road lighting class (M) and thus also minimum average illuminance values (E_{av}), is determined by the sum of weighting values (VWS) of several parameters. The traffic speed (V_v) and traffic volume/intensity (V_i) are dynamic parameters and traffic composition (V_c), separation of the carriageway (V_s), junction density (V_j), parked vehicle presence (V_p), ambient luminosity (V_a), navigational task (V_n)

are mostly constant parameters, especially if considering night time. If VWS<0, then 0 is applied, if M≤0, then M1 class is applied.

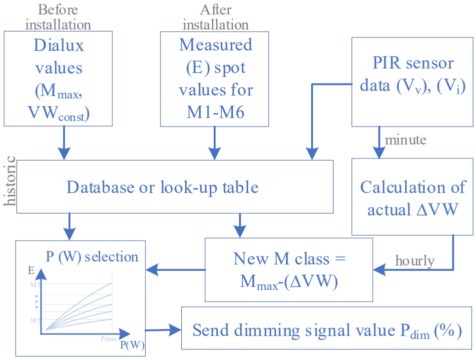

Fig. 8. Simplified control algorithm block diagram of a single luminary.

$$M = 6 - VWS \tag{1}$$

$$M = 6 - (V_v + V_i + V_c + V_s + V_j + V_n + V_a + V_n) \tag{2}$$

Where dynamic parameters $V_s \in \{2; 1; -1; -2\}$ and $V_i \in \{1; 0; -1\}$ and a sum of constant parameters variates between +8…–1 range. Thus, we can see, those dynamic parameters have the most impact on potentially lowering the M or C class in night-time hours selecting (E) values according to Table I or applying linear approximation (3). Fig. 8 depicts the control algorithm for centralized or decentralized individual luminary control based on close-range PIR sensor obtained data and selection of proper luminary power output (dimming %) value and lighting M class according to traffic and standards to have maximum safety and energy efficiency.

TABLE I. MINIMUM ILLUMINATION VALUES FOR C AND M CLASSES

M class	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
E, cd·m^{-2}	2	1.5	1	0.75	0.5	0.3
C class	**C0**	**C1**	**C2**	**C3**	**C4**	**C5**
E, lx	40	30	20	15	10	7.5

$$E(lx) = 1.027 \times (M)^2 - 13.7 \times (M) + 52 \tag{3}$$

TABLE II. PARAMETERS AND VW SELECTION CRITERIA

Parameter	**Description**	**Weight value VW**
Speed (V_v)	v ≥ 100 km/h	2
	70 < v < 100 km/h	1
	70 < v < 100 km/h	–1
	v ≤ 40 km/h	–2
traffic volume / intensity (V_i) for two lane routes	> 45% of maximum capacity	1
	15-45% of max capacity	0
	< 15% of maximum capacity	–1

VII. CONCLUSIONS

Developed PIR sensor was able to detect movement within 10m range, thus implementing simplified control algorithm, it is possible to have locally controlled luminary network. Future work is to update the detector design and set up the whole system with 10 to 15 luminaries on the street, for more detailed tests in the system-level scenario and measure energy consumption while the system is operating.

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Appendix 6

Apse-Apsitis, P., **Avotins, A.**, Graudone, J., Porins, R. RGB based sensor for semi-spherical light measurements. Engineering for Rural Development, 2020, 19, pp. 1242–1247

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RGB BASED SENSOR FOR SEMI-SPHERICAL LIGHT MEASUREMENTS

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Abstract. Different light sources emit light in various directions in a different spectrum, making this a complex task in real application environments. In the case of a greenhouse, evaluation of spherical lighting must be carried out to understand how much power the plant is getting at the top, inter, and bottom layers. Part of the light is both absorbed and reflected by plant leaves, and the greenhouse elements themselves. Determination of received μmol amount from sunlight and/or artificial lighting is vital for plant growth and also the energy efficiency of the total greenhouse system. For best results, this parameter needs measurements over time by a specific sensor for this application. The article deals with a new design of the RGB light sensor - RGB sensor matrix in spherical form, where obtained raw data are processed on the controller and through communication network sent to the IoT database. The article deals with the initial measurement design, and tests for the proof of the concept and later overall discussion. The conclusion at the end is that such an approach can be applied for light parameter monitoring in greenhouse systems.

Keywords: RGB spectrum, light measurement, IoT.

Introduction

The demand for fresh vegetables and healthy food is increasing, thus also many industrial greenhouses, vertical farming, hydroponics and other growing facilities emerge more and more frequently. The tendency in greenhouse automation also asks for more control/sensor options, such as quality parameter measurements for feedback, in order to control greenhouse heating, ventilation, climate equipment in more precise and energy-efficient way. Nowadays systems with Internet of Things (IoT) become more and more popular for such applications.

The article deals with a lighting measurement system that is able to count micromoles from semi-spherical directions, thus in a greenhouse it is possible to detect light amount that hits the sensor from top, from sides and reflected light from the floor. The proper lighting system management can save a lot of electrical energy, due to fact that greenhouse lighting system is the main electrical energy consumer. This is due to the fact, that greenhouse has top lighting, typically High-Pressure Sodium vapour lamps (400W-600W) or equivalent LED lamps (120-200W), placed at the ceiling level in single array. Then there are also interlighting systems, having one, two or even three LED lamps in one array, that are placed in the crop level, to have more light (micromoles) in the leaf and fruit (tomatoes, cucumber, etc). These artificial lights are switched ON or OFF, depending on sunlight availability during the day or according to specific algorithms used by the greenhouse system or managing person. Currently for micromole measurements, relatively expensive quantum based sensors, like Li-COR LI-190R [1] are used to measure photosynthetically active radiation (PAR) values, typically placing single sensor in the greenhouse centre, controlling the whole greenhouse system (0.5 hectares). If the greenhouse is growing different varieties of tomatoes, and under different artificial (mixed) lighting systems, then the feedback value from such lighting mix will be different in each place/height, as tomato leaves are growing very differently in each sector, having various leaf coverage area, etc. SI-NDVI sensors [2] would be introduced into evaluation and greenhouse system control algorithms, as they have potential to monitor plant water stress detection in greenhouses [3], according to [4], spectral reflectance by vegetation in ranges of 0.4μm to 2.5 μm can indicate healthy, stressed or severely stressed vegetation. From [5] a single image NDVI (SI-NDVI) gives a new way to derive spectral character from a single RGB image, thus it can be applied to indoor greenhouses using artificial lighting such as LED. Furthermore, RGB distribution and micromole value could help improve the precision of SI-NDVI values that are affected by various light source spectrum, by implementing corrective coefficient [2] that is reflecting blue, red and far infrared distribution.

The article deals with development of a novel IoT based light sensor that can detect light distribution from semi-spherical direction, same time showing also RGB distribution, could improve precision of the lighting system switching ON/OFF algorithms, thus saving extra energy or provide more precise light amount to the plants, thus increasing the yield of crops.Application of RGB sensors that are able to obtain also energy values $W \cdot m^{-2}$, is promising, due to potential to decrease of the overall costs of such light sensor, as quantum sensors have the cost of 400-1000 EUR, the RGB sensor setup in the range of 100-200 EUR.

The semi-spherical RGB sensor design

If there is just one luminary (light source), the sensor development or placement is more comfortable. In essence, oriented into the direction of luminary reliable state RGB light sensor must be or concentrating light lens must be applied. If there are several luminaries, as well as many reflective surfaces, the measurement is very complicated and sometimes impossible – light at a point in space comes from surrounding 360 degrees.

A matrix of 14 RGB light sensors, positioned in the semi-spherical form (Fig. 1), allows estimating a level of light power and light spectrum at one point in the environment. Measured RGB data are sent wirelessly by WiFi or cellular network to the database, as well as to the light controller.

The proposed matrix consists of 14 RGB light sensors positioned in two circular vertical planes in the right angle to each other, and on each side of the circular plane, 3 or 4 sensors' printed circuit boards (PCB) are placed (Fig.1.). All sensors are enclosed into a transparent spherical bulb (ball) to protect the sensors' surface from dust and other particles. At the same time, plastic reduces the amount of light by 3-5 %. For precise measurements, a plastic enclosure (bulb) is not applied.

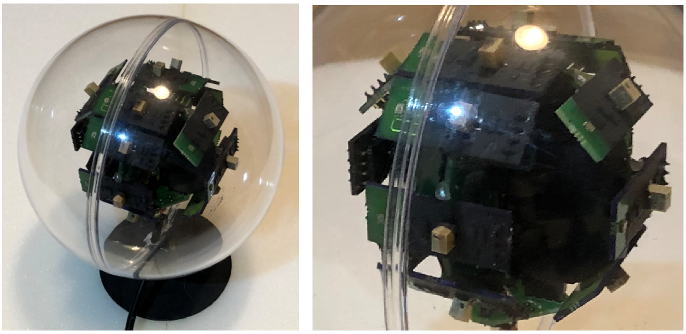


Fig. 1. **RGB semi-spherical light sensor:** overall image (left), closer look (right)

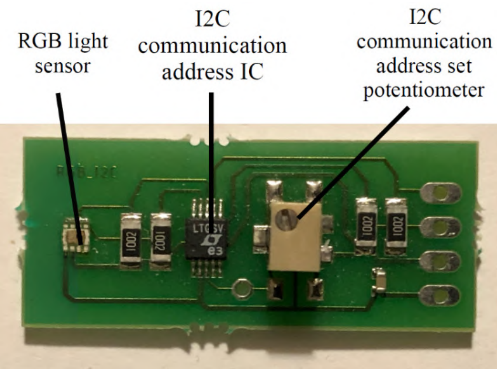


Fig. 2. **Individual RGB light sensor**

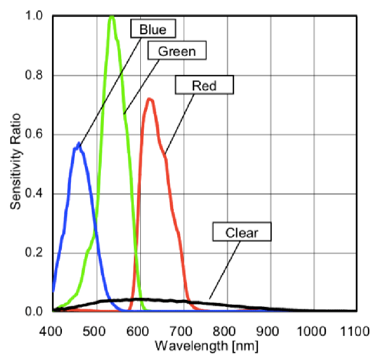


Fig. 3. **Sensor sensitivity-wavelength relationship graph**

Each RGB sensor printed PCB (Fig.2.) includes an RGB sensor (RhomBH1745NUC), I2C communication address set integrated circuit (IC), address set potentiometer, and additional elements. The RGB light sensor sensitivity – wavelength graph is shown in Fig.3. Sensor output allows calculating watt per square centimeter ($W \cdot cm^{-2}$) at corresponding red (R), green (G), blue (B) wavelength, and overall "clear" received light value (C). The obtained light of R, G and B channels has an IR filter (passes visible light and blocks infrared light), but the clear "C" channel has no filter, thus it obtains light in full spectrum. Watt per square centimeter is the derived SI unit of illuminance and luminous emittance. Units $W \cdot cm^{-2}$ approximately can be recalculated to μmols by the expression [6]: $1\ W \cdot m^{-2} \approx 4.6\ \mu mole \cdot m^{2} \cdot s^{-1}$

The spherical view angle is approximately 30 spherical degrees in standard 3 dB sensitivity area for each sensor, measured at a right angle against the sensor surface. Sensor data output is a 16-bit digital value for each RGBC channel (covering 0-65535 decimal values). According to the data in Fig.4, it is possible to calculate the received $W \cdot cm^{-2}$. Fig.4 values in the box represent the digital reading average value correspondence to $20 \mu W \cdot cm^{-2}$.

Red Data Count Value	D_{RED}	3400	4000	4600	count	MODE_CONTROL2(42h)=12h, EV = 20μW/cm² (Note 3)
Green Data Count Value	D_{GREEN}	2847	3350	3853	count	MODE_CONTROL2(42h)=12h, EV = 20μW/cm² (Note 4)
Blue Data Count Value	D_{BLUE}	2014	2370	2726	count	MODE_CONTROL2(42h)=12h, EV = 20μW/cm² (Note 5)
Clear Data Count Value	D_{CLEAR}	128	160	192	count	MODE_CONTROL2(42h)=12h, EV = 20μW/cm² (Note 4)
Dark Count Value	S_{0_0}	0	0	3	count	MODE_CONTROL2(42h)=12h, No input light

Fig. 4. **Sensor output data for calculations according to sensor datasheet**

Fig. 5. shows the sensors, marked as S0 to S13, positions on the spherical surface. Sensors S0, S1, S2, S3 and S7, S8, S9, S10, are located on one vertical plane but sensors S4, S5, S6 and S11, S12, S13 on another vertical plane. The planes are in a right angle to each other.

The overall data receiving and commands sending scheme are shown in Fig.6. Electric imp device [7] communicates with each sensor by the 2-wire I2C protocol. The communication clock frequency is 10 kHz. Data are received sequentially from sensor to sensor.

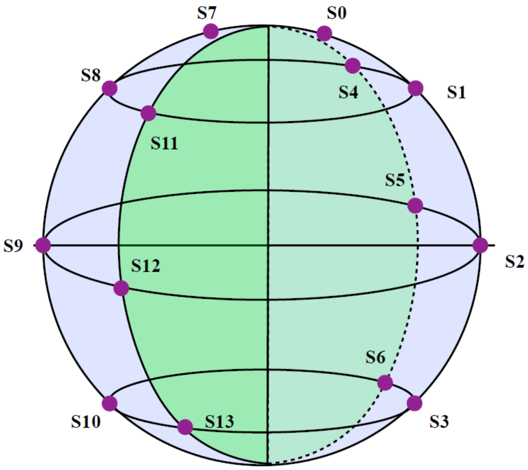


Fig. 5. **Sensors' positions on the spherical surface**

When data from all sensors are received, an electric imp device wirelessly by WiFi or cellular network sends them to a web server in CSV format where data are stored (see Fig. 6). Data processing to control the light system is an option. The data rate is set as 1 minute. This way we can obtain both instantaneous values and later also cumulative values can be obtained per day.

This article deals with the proof of concept evaluation of this sensor system, using rather simple testing method and environment. As the sensor is planned to be installed in the real greenhouse environment, then a cover must be applied to the sensor, to ensure appropriate IP rating (IP67 would be target), due to fact that real environment with high temperature and moisture values is very challenging for electronics. The cover will decrease the precision, but will prolong the lifetime of the sensor. At the moment tests will be performed for both cases –with cover and without cover, to see the impact of cover material to the results, and further also other types of materials will be tested in the same manner.

As next step of the research, testing in the controlled environment is planned, where 3 types of lighting will be used, same time also measurements from the spectrometer will be analysed, to compare the precision and enable calibration parameter calculation. Further the tests in industrial greenhouse will be performed to evaluate results of light parameters in real conditions, affected both by sunlight and greenhouse glass cover properties.

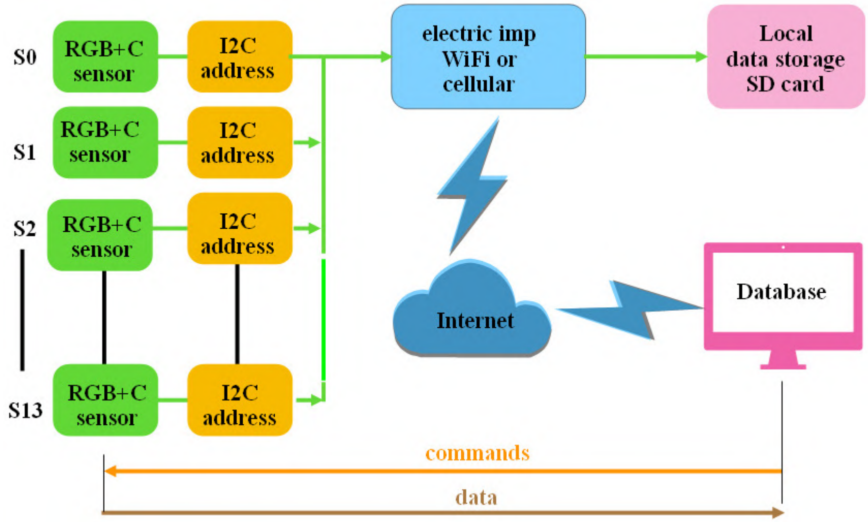
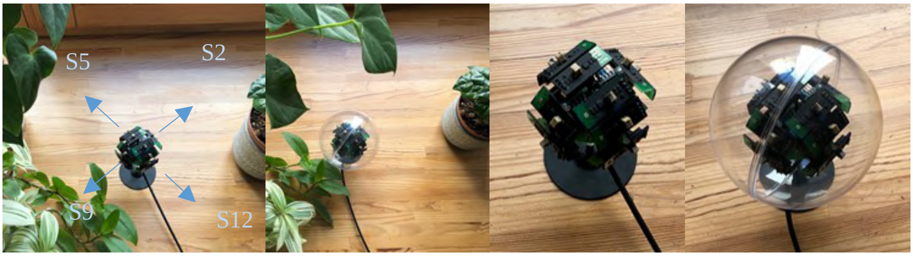


Fig. 6. **Data receiving and commands sending scheme**

In overall the RGB sensor system is similar to the described before systems [8; 9].

Experimental results in the interpretation of data

Each measurement contains 56 values – 4 from each sensor multiplied by a count of sensors (14). This article deals with the main results from the first tests for proof of the concept. Due to a large number of table columns and rows, it is not possible to reflect all data here. Tests were provided in 4 conditions (Fig. 7). Table 1 includes raw data values from sensors S2, S5, S9, S12, for example. In all condition cases the natural light was used, using the same plant and room configuration.



condition 1 - without transparent bulb, with some reflection from houseplants	condition 2 - with transparent bulb, with some reflection from houseplants	condition 3 - without transparent cover and direct sunlight, and no reflection from houseplants	condition 4 - with transparent cover, direct sunlight, and no reflection from houseplants

Fig. 7. **Test conditions and description**

Table 1

Raw data values from sensors S2, S5, S9, S12

Cond	R2	G2	B2	C2	R5	G5	B5	C5	R9	G9	B9	C9	R12	G12	B12	C12
1	2786	8899	3763	1793	3283	10027	4409	1900	11	693	183	242	87	1266	351	433
2	2232	7628	3122	1580	3543	9652	4148	1842	126	798	232	259	35	1215	338	404
3	3237	10026	4311	1955	3633	10482	4584	1984	235	973	268	308	609	1693	542	511
4	2794	8649	3665	1725	3786	9927	4264	1895	279	1379	429	327	603	1711	565	498

In order to calculate each channel energy value, the corresponding coefficient (given at 20 $\mu W \cdot cm^{-2}$, see Fig.4) must be used. Further the radiant energy value can be multiplied by 4.57 (for sunlight) to obtain the PAR ($\mu mole \cdot m^{-2} \cdot s^{-1}$) value.

Table 2

Calculated PPFD values from sensors S2, S5, S9, S12

Con.	R2	G2	B2	C2	R5	G5	B5	C5	R9	G9	B9	C9	R12	G12	B12	C12
1	6.37	24.28	14.51	102.43	7.50	27.36	17.00	108.54	0.03	1.89	0.71	13.82	0.20	3.45	1.35	24.74
2	5.10	20.81	12.04	90.26	8.10	26.33	16.00	105.22	0.29	2.18	0.89	14.80	0.08	3.31	1.30	23.08
3	7.40	27.35	16.63	111.68	8.30	28.60	17.68	113.34	0.54	2.65	1.03	17.59	1.39	4.62	2.09	29.19
4	6.38	23.60	14.13	98.54	8.65	27.08	16.44	108.25	0.64	3.76	1.65	18.68	1.38	4.67	2.18	28.45

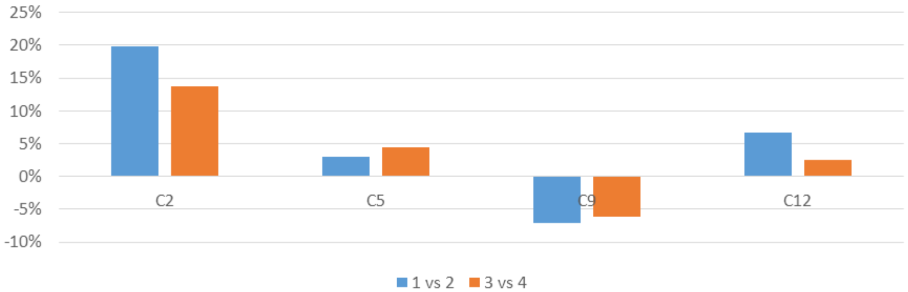


Fig. 8. **Difference between conditions ½ and ¾ for "clear" channels**

In Fig. 8, we can observe that there is impact of the cover, ranging from 3 % to 20 % for condition 1-2, and 3-14 % for condition 3-4 comparison. Also, the results show that with more light, also the readings are with less difference. The values also show from which side the most of light came (S2 and S5), corresponding to the placement towards the sunlight. S9 values have the least values, as the least amount of light was received, probably only the reflected light.

For further analysis, also R + G + B and/or C values should be compared, as it would be a good indicator for light distribution (or luminary type) ratio detection, that can be used further in SI-NDVI sensors.

Conclusions

1. Light measurements typically reflect some luminaire emitting light and illumination on known distance or in sphere [10].
2. The article deals with another look – receiving the light (and light RGB components) on the spot from the surrounding 360º environments and a proof of the concept for such measurement device.
3. The described 360º spherically placed sensor matrix shows good results for each sensor, but the overall received light power calculation method is still on the discussion. The work continues.
4. The received data rate from sensors can be up to 1 sec, and such rate can reflect received light changes very effectively.

Acknowledgements

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Appendix 7

Tetervenoks, O., **Avotins, A.**, Fedorjana, N., Kluga, A., Krasts, V. Potential Role of Street Lighting System for Safety Enhancement on the Roads in Future. No: 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2019): Conference Proceedings, Latvija, Rīga, 7–9 October, IEEE, 2019, pp. 349–353. e-ISBN 978-1-7281-3942-5.

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Potential Role of Street Lighting System for Safety Enhancement on the Roads in Future

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***Abstract*—This paper is an attempt of authors to consider most likely scenario of the further development of street lighting systems, based on current trends in sensors, telecommunication technology and auto industry. Street lighting system previously already was considered as the element of the Smart City by researchers, however, the precise functionality, role and the importance of such a system was considered rather mediocre (ordinary). This article is a holistic view of the Smart Street management system with the street lighting system, which plays great importance of whole transportation and mobility infrastructure functionality and safety enhancement.**

Keywords*—*advanced driver assistance systems, lighting control, traffic control, vehicle safety.

I. Introduction

Nearly 1.25 million people die in road crashes each year, on average 3287 deaths a day [1]. This statistic shows, that car is a dangerous type of transport, therefore safety enhancement is top priority in modern auto industry. Most accidents occur as a result of the human factor. The human factor should be kept to a minimum, therefore different driving assistance systems were developed and implemented in modern cars during last years, like car self-driving system, human tiredness monitoring, however, the introduction of such a system requires changes in legislation. One of the issues why the self-driving cars are not yet allowed on the streets, is lack of tests and doubts about the behavior of the system in ambiguous situations.

The solution can be borrowed from the most reliable transport type – aircrafts [2]. Aircrafts are equipped with complicated pilot assistance systems, systems for the prevention of dangerous flight conditions and the detection of dangerous actions of a pilot, as well as a warning systems for prevention of dangerous situations and flight conditions. This practice could be applied also in self-driving cars.

Also there are multiple problems related with increased mobility of the people during the last years. The traffic flow capacities of existing roads and streets are limited, heavier traffic leads to a big impact on fuel consumption, and on the amount of emissions [3]. Although there is no clear evidence about relationship between the traffic flow and number of accidents [4], [5], the studies shows that red light running on signalized intersections is affected by heavier traffic [4], thus increasing accident risks.

There were many papers about smart city concept [6]-[8]. However, these papers usually describe general idea, and more detailed consideration of "smart" functionality of particular infrastructure types of smart city in these articles is omitted. This paper is focused on the particular description of potentially possible functions of the street lighting system which can be a key element of transportation and mobility infrastructure of the smart city.

The next sections of this article consider not only standard function of street lighting system, but also highlight potential role of the use of its infrastructure for traffic flow control and distribution, enhancement of self-divining function of future cars and increase of reliability for traffic flow distribution system.

II. The Role of Street Lighting System

Of course, safety enhancement is the main function of street lighting system (it is vital to provide sufficient lighting level in accordance with existing standards and at the maximum possible efficiency). In future there will be self-driving cars, but the driver still will be the essential part of the car, the self-driving ride will not be possible without driver. Therefore comfortable conditions for driver on the road (also lighting) should be kept at a high level also in future smart city.

Street lighting system is the well suited infrastructure for the further development of street management system, which could provide wide functionality including smart traffic flow distribution and assistance functions for self-driving cars. Existing street lighting system already have its own infrastructure near the road. The mounting position of the lamps in respect to the road also is advantageous, the lamps always are above the road or few meters from the road – ideal location/position for different sensors, communication nodes.

The great part of investment in the development of new street management system can be saved by using this existing infrastructure. Also the installation costs can be significantly reduced and the possibilities for the further development increased by using new street lamps equipped with special sockets for the connection of additional control elements. As

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the warranty lifetime of the modern LED lamps is 5-10 years, but the real lifetime can be up to 20 years, it is good idea to foresee option for easy replacement of the control modules without lamp dismantling and disassembly of the lamp for flexible system upgrade possibilities.

There are already standardized socket types for street lamps (Zhaga and NEMA/ANSI sockets), which provide opportunity to gain this advantage in a great extent, as shown in Fig. 1.

Also with the development of 5-th generation cellular network (5G) street lamps may become an ideal place for installation of 5G small cells. 5G is designed to work in conjunction with existing 4G networks, using a range of macro cells, small cells and dedicated in-building systems. In this concept 4G provides control signaling and 5G provides fast data connection. Small cell is a key element of 5G network to achieve higher data transfer rates using higher radio frequencies. Higher frequencies also means shorter data transfer rates (in range of few tens of meters to a few hundreds of meters) [9]-[11]. The height of street lamp poles also meets minimal antenna installation height requirements in accordance with standard [12] to keep human out of hazardous exposure of antenna [11]. A concept of 5G network architecture is shown in Fig. 2.

III. Holistic View of the Smart Street Management System

Smart street management system can be a core of traffic flow distribution system, including the following functions:

1) *Traffic flow control/traffic distribution*

   a) *Car precise positioning on the road, street, in car lot, - alternative positioning system of GPS/DGPS.*

   b) *Priority function for public transport and high priority function for emergency transport*

   c) *Connection to network and data interchange between system server for further processing and optimal traffic flow formation*

2) *Environmental monitoring, pollution control.*
3) *Street visual control (safety, warning system, fast reaction on accidents)*

   a) *Street lighting control*

   b) *Video monitoring*

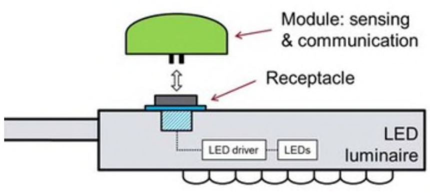

Fig. 1. LED street lamp with socket for external modules [13]

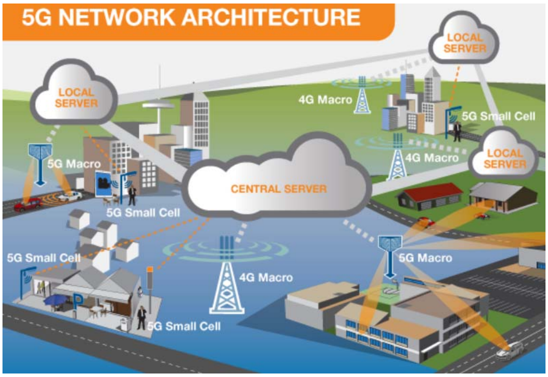

Fig. 2. Concept of 5G network [9]

IV. Assessment of Energy Efficiency for Condition Dependent Dimmable Street Lighting System

Modern lighting systems must fulfil two main requirements: 1) it must provide illumination level in accordance with current standards; 2) it must utilize electrical power with the high efficiency (high efficiency of the electrical power conversion to the light). The development of LED lighting technology allowed considerably improving the system efficiency. While the LED efficacy itself does not give significant vantage over some traditional light sources (low and high-pressure sodium lamps, fluorescent lamps and induction lamps), the construction or LED gives significant benefits. LED can be considered as point light source which facilitates the development of compact efficient optics for uniform light distribution. Therefore, less light is necessary to provide the same illumination level as in case of traditional light sources. Also, LEDs are driven by energy efficient driving techniques [14]-[15] and dedicated current control power supplies [16], and thus are more convenient for the dimming, in this way they open new opportunities for even greater energy savings and/or lighting quality improvements.

Dimming is an essential function for smart lighting system, which is the latest tendency in lighting industry. To get maximum efficiency, each energy conversion part (light source, optical part and electrical part) of the luminaire also must have highest possible efficiency. As mentioned previously, the control approach may have a great impact on the efficiency of whole system. It is shown that distributed control approach among other control approaches allows to improve light uniformity for moving objects.

The performance of whole system in a great extent depends on the functionality of the separate nodes. The luminaires for smart lighting systems must be equipped with sensors and communication modules to provide motion or presence sensing and data transfer between the nodes [17].

V. Real-Time Locating Systems (RTLS)

As the future street lighting systems (5G, car on-board sensors, RFID tags, etc) will be adopted after various tests, standardization, therefore it will take time till its implementation in real life. Thus we could ask what to do with existing systems or how to improve performance of the existing systems? As we know that most of the systems use Power Line (PLC) or wireless data transmission (ZigBee, radio, etc), realized by communication control node added to the luminary, this way controlling LED power supply through DALI, PWM or 0-10VDC signals. Addition of movement detection sensors to the system [18] actually enables decentralized dynamic street lighting control system, that is capable to adopt to changing traffic intensity during the time of the operation thus actually calculate the appropriate ME class [16] parameters needed for the safe traffic. It means we could get maximum safety with minimum energy consumption in same time if we store such traffic data on each street during the night hours. To calculate analytically the potential savings, two case studies were performed.

A. Case Study 1. "Dienvidu tilts" Bridge in Riga City

In this case the bridge is equipped with Schreder ONYX2 (reflector #1419) 250W High Pressure Sodium vapor lamps (HPS), therefore it could be a good place for renovation to LED based smart lighting system. It is a 3-lane street with pedestrian walkway (Fig. 3.). Currently it is designated with ME2 class lighting parameters, as a typical approach of the municipality agency "Rigas Gaisma" class selection according to road maintenance classes. To assess the lighting quality and potential light output, a Dialux model was created of the site, using maintenance factor 0.75, tarmac: "R3, q0: 0.070".

TABLE I. DIALUX CALCULATION RESULTS

Values	*L_{av}[cd/m²]*	*U0*	*Ul*	*TI[%]*	*SR*
Calculated	*2.21*	*0.57*	*0.74*	*10*	*0.52*
Required	≥ 1.50	≥ 0.40	≥ 0.70	≤ 10	≥ 0.50

Measurements were obtained using "luxmeter BEHA 93408", where measurement points, geometrical distances and measured values (Lux) can be seen in Fig.4. and they are compatible with the Dialux calculation results.

Traffic intensity data (Fig. 5.) is obtained from measured statistics of state funded company "Latvijas Valsts celi", with peak value of 3068 cars per hour in one direction. According to standard [19], high intensity is above 65%, normal is 35%-65%, and low is below 35% of maximum value (100%=3068). Accordingly we can obtain M-class number for each hour, as it is shown in Fig.5. Here selected M2 class is needed only 5.5

Fig. 3. "Dienvidu tilts" bridge and ONYX2 luminary.

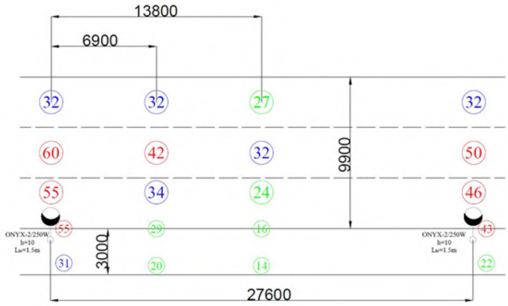

Fig. 4. Practical luminous (Lux) value measurments on site.

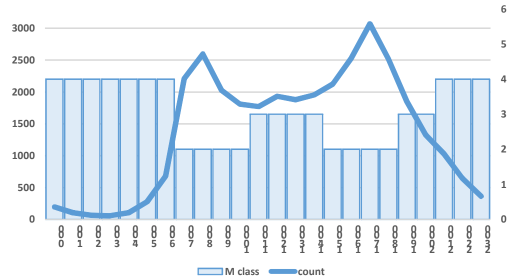

Fig. 5. Traffic intensity data and according ME class for one day.

hours from 17.5 hours of that particular day. Interesting that during summer we shouldn't use M2 class at all, in the rest of time the class is lower – M3 and M4, which means also decreased light output, thus less consumed power (W). If we recalculate the M-classes according to obtained traffic intensity and combine it with yearly ON/OFF schedule of Riga city lighting system, we can see that M2 class is needed 454 hours (11.5%), M3 - 401.5 hours (10.2%) and M4 class – 3093 hours (78.3%) of total lighting system working hours. This result shows that in this particular case – system is working **88.5%** of time in wrong regime, causing energy losses and creating lighting pollution.

As HPS luminary is not possible to regulate in full range, a LED luminary would be needed. Thus by modeling same scene in Dialux, and to fulfill all parameters of M2, M3 and M4 classes, we can select "Schreder AMPERA MAXI" with 154W for M2 class and 117W for M3, M4 class. So to obtain energy saving potential of the individual luminary dimming – we will compare situation "1" when only M2 class is applied (no regulation) and situation "2", when we change the classes from M2 (154W), M3-M4 (117W) accordingly. As a result we get yearly consumption of 608.0715718 kWh for situation "1" and 478.7713718 kWh for situation "2", enabling energy savings of **21.26%**, just by applying dynamic dimming function.

B. Case Study 2. “Jaunciema street”, Riga City

This is a main traffic street located at the lake “Kisezers”, it is also equipped with 171 pcs 100W LED luminaries of Photon-L company. In order to obtain traffic intensity data, two sensors were developed basing on Arduino platform, Velleman motion sensor VMA314 and memory card module VMA304. Sensor 1 was installed at the beginning of street (closer to Vecmilgravis), Sensor 2 – at the end of street (closer to Jaunciems), at 1.7m height on the luminary pole. Thus two week measurement data of period 25.03.2019. – 08.04.2019. were obtained. Sensors are developed to register detected motion period (time), it means if motion (sensor voltage) is detected, an instant value “TurnON” is written in memory, when no motion is detected “TurnOFF” is written. In case of more than one car in the row, “motion” is still detected, therefore time of 3 seconds is added to the motion detected period value. In this way we get data about “motion” detectors triggered event count each 20 minutes (Fig. 6.), as well as “motion sensor” summed ON times each 20 minutes, representing more intensive traffic if time value is higher (Fig. 7.).

Sensor values differ, as Jaunciems street has a T-type junction with another street, dividing the total traffic direction and thus also intensity value. Further we could apply two

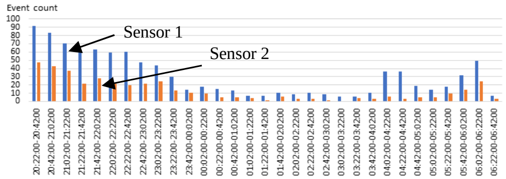

Fig. 6. Sensor event count each 20 min during 03.04.2019.-04.04.2019.

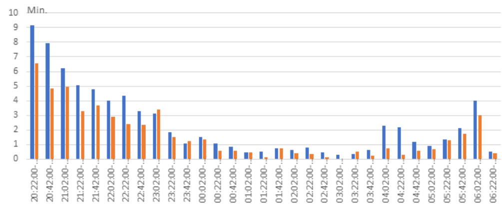

Fig. 7. Sensor ON times each 20 min during 03.04.2019.-04.04.2019.

regulation stages 100% and 20% of light output representing maximum and minimum traffic intensity and ME road class parameters.

In order to calculate the energy consumption for each junction, when sensor is triggered, thus 100% light output needed, and it means also maximum power consumption, then we use formula (1).

$$E_{100\%} = T_{\Sigma 100\%} \times P \times N_g \quad (1)$$

Where $E_{100\%}$ – total daily energy consumption (kWh);

$T_{\Sigma 100\%}$ – luminary ON time (h);

P – luminary power (W);

N_g – luminary count in the street.

Energy consumption of the system with luminary control based on sensor (traffic) data is given in formula (2).

$$E_{vad} = (T_{\Sigma 100\%} - T_{\Sigma 20\%}) \times P_{100\%} \times N_g + T_{\Sigma 20\%} \times P_{20\%} \times N_g \quad (2)$$

Where E_{vad} – total daily energy consumption (kWh);

$T_{\Sigma 100\%}$ – luminary ON time (h);

$T_{\Sigma 20\%}$ – luminary ON time (h) with 20% power (no traffic detected);

$P_{20\%}$ – luminary at 20% dimmed power (W);

$P_{100\%}$ – luminary at full power (W);

N_g – luminary count in the street.

After applying these formulas for each day, we can obtain total energy consumption values of the 14 day period, where $E_{100\%}$ = 2485.77 kWh, and E_{vad}=1222.06 kWh. This means we can reach up to **50.84%** energy savings in such situation.

VI. Assessment of Motion Sensors

Motion detectors by their operation principle can be distinguished on two different types:

1) *active motion sensors,*
2) *passive motion sensors.*

Active motion sensors continuously emit energy in surrounding area or part of this area in the form of infrared light, sound waves or electric waves. They combine two circuits: energy emitting circuit and reflected energy receiving circuit. Any changes in surrounding cause changes in received energy amount, therefore also output of receiving circuit.

Active motion detection sensors consume more energy, as they continuously emit some energy in surroundings.

Main active motion sensor types are 1) microwave sensors (operation is similar to the Radar, operation on Doppler effect) [20]; 2) ultrasonic sensors which use ultrasonic waves for movement detection and to detect changes in surroundings, 3) tomographic sensors for precise movement detection on large areas (can be used for detecting motion even in hidden areas) [21], [22].

Passive motion sensor operates by detection of infrared radiation of human or object, radiated by the human or object itself. Passive infrared (PIR) or pyroelectric sensor consumes less energy as it is not necessary radiate any energy for operation. It consists of two halves such, that the infrared radiation of surrounding objects causes the same signal in both halves, canceling these signals [23]. The only limitation is that it cannot detect stationary or very slow motion objects.

Usually the additional optics is required for PIR sensors to cover specific sector of surroundings [21], [22].

Microwave sensor has one important benefits over other movement detection approaches: 1) microwave sensor operates through existing optics (plastic), therefore it can be integrated (hidden) in luminaire without visible changes in luminaire appearance [23], no additional optics is required as in case of PIR sensor.

VII. Conclusion

Potential role of street lighting system in enhancement of self-divining function of future cars and reliability of this system were described in this article. Also holistic view of the future smart street management system was presented in this paper.

Despite the fact that this concept looks too futuristic, the implementation of this idea would allow to achieve a lot of positive effects - controlling traffic flow and increasing the capacity of city streets and roads (which is especially important during peak hours), improving traffic organization and safety, transport distribution by priorities and the allocation of separate lanes for public/emergency transport if necessary (rest of the time is available to all modes of transport).

Furthermore, it also shows the high potential of LED smart lighting systems and movement detection sensor application in various places of the city streets, where much higher lighting classes are applied as needed, reaching up to 88% of total time, therefore during night time energy savings from 20 – 50% can be reached.

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Appendix 8

Tetervenoks, O., **Avotins, A.**, Apse-Apsitis, P., Adrian, L., Vilums, R. Movement Detection Sensor Application for Traffic Direction Monitoring in Smart Street Lighting Systems. No: 2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2018): Conference Proceedings, Latvia, Riga, 12–13 November, 2018. IEEE, pp. 1–5. e-ISBN 978-1-5386-6903-7.

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2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)

Movement Detection Sensor Application for Traffic Direction Monitoring in Smart Street Lighting Systems

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***Abstract*— a lot of studies are spent on the smart lighting systems, particularly on street lighting systems. There are two fundamental ideas which substantiate this invention: 1) enhancement of the efficiency of separate system elements, improvement of system algorithms, as a result more rational use of Earth resources and energy sources; 2) improvement of the environment for human habitation. Majority part of these studies consider term “smart” as the ability of the system to provide the necessary amount of the light in accordance with the existing norms, lighting standards when it is necessary and where it is necessary. In other words, the system is considered “smart” from point of view of the main end users: drivers, cyclists and pedestrians, in the same time forgetting about system service staff: installation technicians and system administrators. This paper endorse studies of smart lighting systems in this extended meaning: considering system “smart” for all the system users. Therefore some low cost solutions with extended functionality are considered in this paper.**

Keywords—Automatic control; infrared sensors; LED lamps; radar detection; sensor systems.

I. Introduction

The implementation of a smart lighting system is quite expensive. However, recent studies and calculations show that smart lighting systems have fast ROI (Return of Investment) time [1]. Moreover, these systems are constantly improved to enhance efficiency [2], functionality [3], [4] as well as reduce initial and maintenance costs [4], [5], in this way also ROI period. Efficiency is improved either by the separate elements - different type LEDs: Chip-on-Board (COB) technology [6], chip scale package (CSP) technology [7] and flip-chip technology [8], [9] and etc., LED drivers [10], optical system [11], or by improving control algorithms [4], [12], [13]. So the reconstruction and renovation of lighting systems are popular in recent times. However, it is worth keeping in mind that the pursuit of reducing the cost should not adversely affect the functionality of the system, when its separate elements support reduced set of functions and the system remains “smart” only for the end user, making a headache for service staff with complicated and expensive installation and work on the maintenance of the system. For instance, [5] describes the benefits of prognostics and health management (PHM) techniques (based on observation of the state of the system by processing of real-time data) reduce unscheduled maintenance events, extending the duration of maintenance cycles of the system and reducing ROI period.

One another important point for consideration is compliance with the existing lighting standards. Standard allows using of 4 dimming zones per day, but the use of sensors with extended functionality allows create dynamic lighting system control algorithm that adjusts to required lighting class in accordance with actual daytime, traffic flow, user types and average speed and etc. Thus with such type of sensors it is possible to create more dynamic control system with maximum savings at maximum lighting quality. This paper gives a brief analysis of potential possibility of lighting system to perform such functionality with considered sensors.

So, the structure of the paper is following: first a brief description of a configuration of smart lighting system in general is given. Then the requirements of the street lighting standard are analyzed in order to determine the parameters, which affect lighting class selection, in this way providing necessary light amount “on demand” in conformity with given standard. The most appropriate sensor types are discussed using this analysis. Then the motion/presence detection methods and sensors are briefly considered. After that the implementation methods are considered. In the following sections simplified traffic count devices based on microwave motion detection and passive infrared (PIR) sensor is described. Received data is analyzed to verify initial testing results of these movement detection sensor prototypes and potential for the use of these sensors (with extended functionality) in smart lighting system.

II. A Brief Description of a Smart Street Lighting System

Although the idea of this concept is not new, a brief description as an introduction is given in this section. There are

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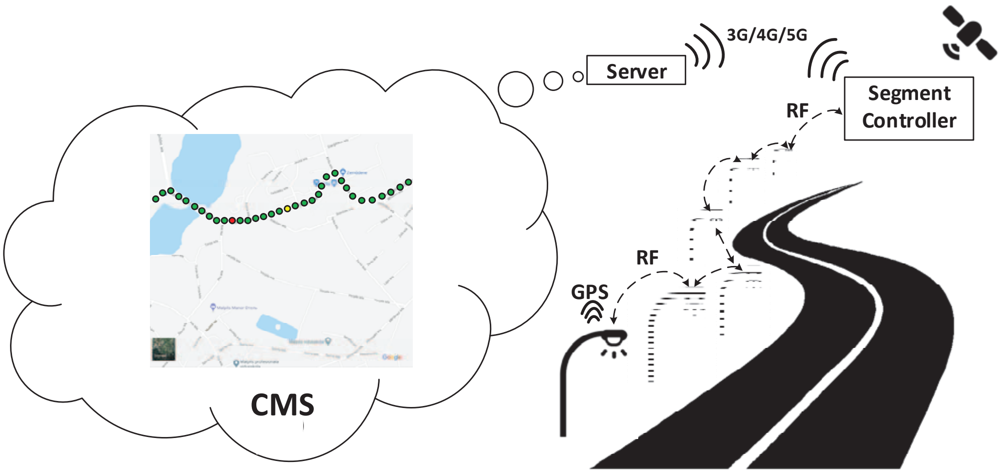

Fig. 1. Configuration of the system for proposed approaches

several considerations and rationales about the configuration of the concept of proposed system:

- Rebuilding of existing infrastructure of street lighting systems is time consuming and costly process, therefore new system elements (luminaires, sensors, communication interfaces), as far as possible, should be less demanding of the need to change the existing infrastructure.

- The following communication types allow using existing infrastructure: 1) power line communication (PLC) and 2) wireless communication (either optical, radiofrequency)

- Power line communication has significant limitations (therefore, also limited application possibilities), as the transformers significantly reduce or totally block signal.

- In case of wireless communication data transfer rate should be considered.

- The versatile solutions are the most appropriate for the mass production: high production volumes allow reduce price on components, there are possibilities to optimize (reduce) technological processes and no necessary to reconfigure production line.

- The installation and initialization of the system elements should be as simple as possible to reduce time and cost of field works.

- The user interface of the system should be as simple as possible and must provide data collection and visualization possibilities, convenient system management possibilities.

Fig.1 shows the concept of the system discussed above. In accordance with the considerations described above, the communication is provided via wireless network between the nodes (luminaires), nodes operate also as repeaters. There is at least one node, which is connected to the global network and provides communication of other nodes with the server and interaction with central management system (CMS). Depending on the requirements the luminaires can be equipped with different type sensors, detectors and modules.

III. Identification of the Necessary Parameters

The lighting standards [14], [15] have been studied to identify the parameters, which should be monitored by the system to comply with these standards.

First, the parameters described in the standards can be divided into two main groups: constants (or very slowly changeable parameters) and variables. Table I summarizes these parameters.

TABLE I. SUMMARY OF THE PARAMETERS, WHICH ARE PLAYING ROLE ON THE SELECTION OF LIGHTING CLASS

CEN/TR 13201-1, CEN/TR 13201-2	
Constant (or very slowly changeable parameter)	***Variable***
- road type and speed limit - separation of carriageways - junction density - navigational task - facial recognition - lightness of the road surface *Q0* - luminaire location	- actual mean speed of users - traffic volume, use intensity - traffic composition - parked vehicles - ambient luminosity - ambient light

IV. Considerations on the Reduction of Installation Work

The proposed concept may allow to reduce time and costs on the installation work and system initialization in the following way: 1) it should be possible to set all the constants from the Table I through CMS (group luminaires and set the parameters simultaneously for all the same group elements); 2)

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as the graphical interface of CMS is based on the real map, luminaires should be equipped with Global Navigation Satellite System (GNSS) module (including Global Positioning System GPS, BeiDou Navigation Satellite System BDS or other regional positioning systems) for automatic registration in CMS, when connected to CMS server through wireless communication between the lamps and segment controller; 3) variables shown in Table I should be obtained from luminaires equipped with appropriate sensors, detectors and measurement modules (different type detectors, easily attachable to the luminaire - conveniently configurable system); 4) there must be a way to replace this variable with constant, if the relevant sensor is not presenting in the system or it is not capable to take this measurement.

V. Discussion on the Problematic System Parameters

So, the variables from Table I are problematic parameters, as in general they should be obtained from sensors and detectors. The rest part of this paper describes one of the most problematic issues - low cost solutions for motion detection, in particular, solution for traffic volume measurement, actual mean speed calculation, use intensity and traffic composition determination. Detection of the ambient light level is not problematic with the modern on-chip low cost light sensors available on the market. But the discussion on the detection of parked vehicles and ambient luminosity is expected in the further papers.

There are plenty of motion detection possibilities: active and passive sensor types. Main active motion sensor types are 1) microwave sensors (operation is similar to the radar – on the Doppler effect); 2) ultrasonic sensors which use ultrasonic waves for movement detection and to detect changes in surroundings, 3) tomographic sensors for precise movement detection on large areas (can be used for detecting motion even in hidden areas) [16], [17]. Passive infrared (PIR) sensor cannot detect stationary or very slow motion objects. Usually the additional optics is required for PIR sensors to cover specific sector of surroundings [16], [17].

As mentioned previously some low cost solutions with extended functionality are considered in this paper. It is expected to obtain additional information from low cost motion detectors - not only detection of motion event, but also the speed of object, direction and maybe even type of object.

VI. Experiments with Radar Type Sensor

The prototype of movement detector was built for the experiments with the radar type sensor described in [18]. Basic block diagram of the detector is given in Fig. 2. (a), but the pictures of device are given in Fig. 2. (b), (c) and (d). As shown in this block diagram, it is planned to use this detector with autonomous power supply for convenient placement possibilities on the field. Detector is equipped with the real time clock and SD card, where each detected movement is saved as a Unix Timestamp (amount of seconds since 1 January 1970). Slow moving objects are detected as a series of timestamps, as shown in Table I, where data of several initial experiments is shown as a sample (some pictures of these experiments are given in Fig. 2. (e) and (f)).

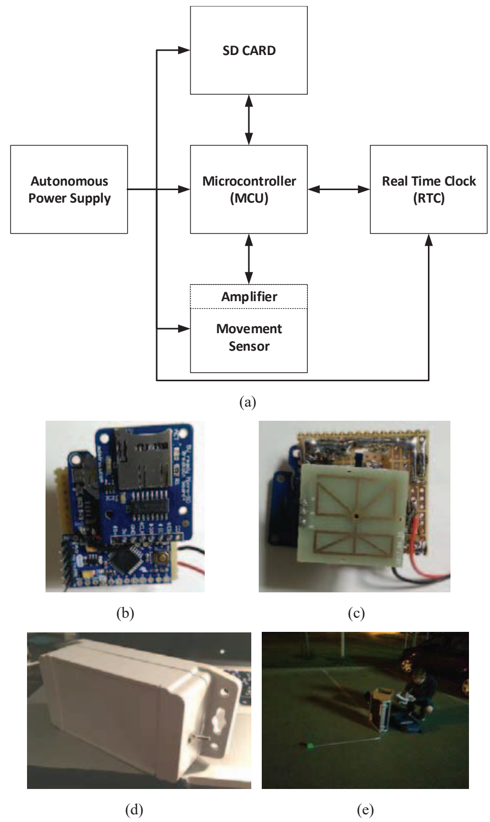

Fig. 2. Prototype of the simplified autonomous traffic flow detection device: (a) block diagram; (b)and (c) pictures of the prototype; (d) placed in case for field experiments; (e) picture from field experiments

TABLE II. Summary of the data from several initial tests with the radar type sensor

At a 2.5m distance from detector			**At a 5m distance from detector**		
Unix Timestamt	***Converted time***	***Descrip -tion***	***Unix Timestamt***	***Converted time***	***Descrip-tion***
1526257827	00:30:27	Sensor ON	1526258786	00:46:26	Sensor ON
1526257859	00:30:59	Slowly moving object - pedestrian	1526258818	00:46:58	Slowly moving object - pedestrian
1526257860	00:31:00		1526258819	00:46:59	
1526257860	00:31:00		1526258820	00:47:00	
1526257861	00:31:01		1526258821	00:47:01	
1526257861	00:31:01		1526258824	00:47:04	
1526258218	00:36:58	Slowly moving object - pedestrian	1526259000	00:50:00	Slowly moving object - pedestrian
1526258218	00:36:58		1526259000	00:50:00	
1526258219	00:36:59		1526259001	00:50:01	
1526258219	00:36:59		1526259002	00:50:02	
1526258220	00:37:00		1526259002	00:50:02	
			1526259003	00:50:03	

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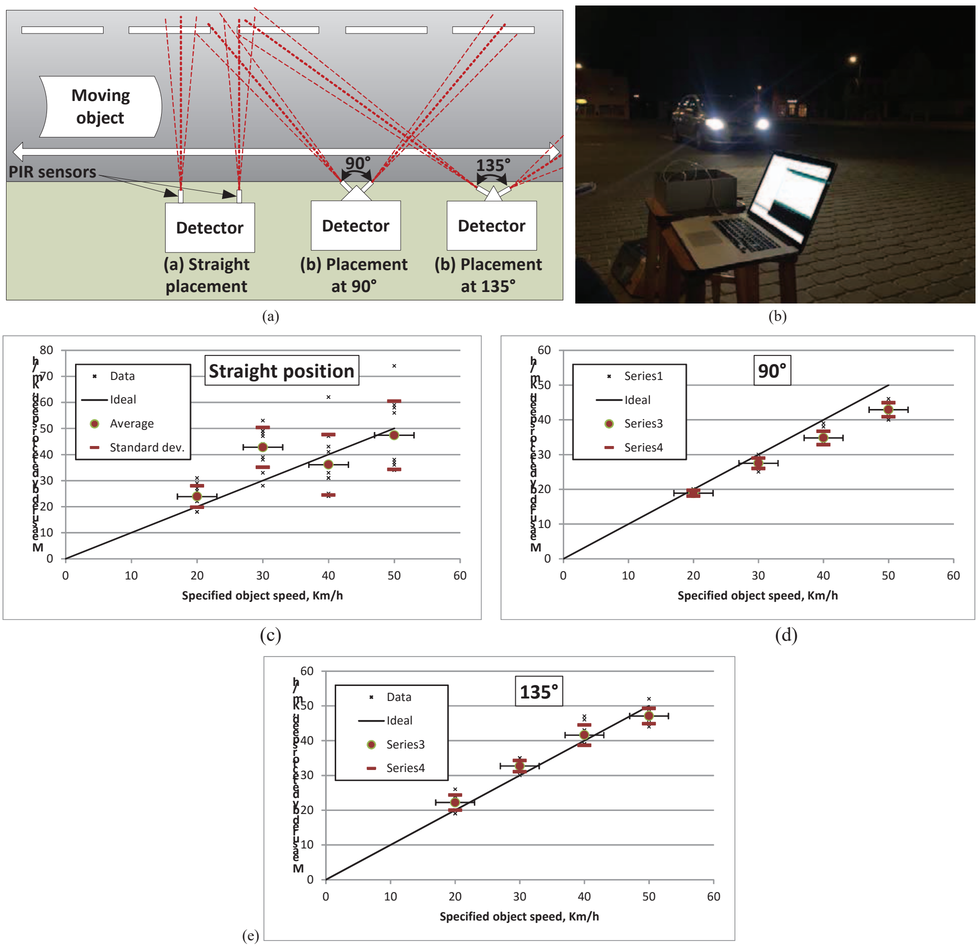

Fig. 3. Tests on the considered PIR detector prototype: (a) block diagram; (b) field tests; (c), (d) and (e) summary of the test results.

Several this kind detectors can be used for experiments on the traffic flow detection with simple radar sensor in different situations, road configurations, junction types. Autonomous power supply gives flexibility and freedom of choice for detector installation. Saved information in timestamp format gives possibility for further complex data processing from several detectors and estimation of collective operation of simple sensors. The analysis of these experiments is expected in next paper.

VII. Experiments with Pasive Infrared Sensor

One of ideas to extend functionality of the motion detector based on PIR sensor (get additional data about the speed of moving object) is use of two sensors with narrow sensing area, as shown in Fig. 3. (a). Three different sensor placement configurations are shown in this picture: 1) straight sensor position; 2) placement at 90° angle; 3) placement at 135° angle. Prototype of this kind detector was built on Arduino platform with two simple PIR sensors and several experiment were conducted (Fig. 3. (b)). The results of experiments are summarized in Fig. 3. (c), (d) and (e). Although use of several PIR sensors for motion detection is not a new idea [19], it looks better to use single PIR sensor for object speed calculations, taking in account PIR sensor operation principles: by assessment of the time between appearance and disappearance of the object in sensing area [20]. Detailed consideration of this approach is expected during further studies.

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VIII. Conclusion

This paper describes improved concept of smart lighting system and presents the discussion on the elements of the system with the practical suggestions for the reduction of field work time. Also several low cost motion detectors with extended functionality were considered in the scope of this paper: radar type sensor and PIR. It is expected to continue further studies on both detector types.

The use of sensors with extended functionality allows create dynamic lighting system control algorithm that adjusts to required lighting class in accordance with actual daytime, traffic flow, user types and average speed and etc. Thus with such type of sensors it is possible to create more dynamic control system with maximum savings at maximum lighting quality.

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Appendix 9

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Industrial DC Microgrid Analysis with Synchronous Multipoint Power Measurement Solution

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Keywords

« Microgrid », « Industrial application », « DC power supply », « Measurement »

Abstract

Paper is presenting application of synchronized power flow measurement system within 13 locations of DC microgrid installation in production plant with specific measurement equipment system developed for dynamic energy flow analysis. Insight into internal DC bus power exchange behavior and interconnected operation advantages with respect to energy efficiency improvement is provided. Future trends towards DC based manufacturing infrastructure are discussed. Presented results provide insight into electrical energy distribution behavior within DC microgrid system structure operated based of realistic industrial manufacturing tasks. Application of multipoint power measurement system provide real measurement data of various manufacturing technology tool load profiles that serve as important basis for future system modelling and dimensioning tasks.

Introduction

Presented paper is related to DC technology based electrical supply infrastructure integration effort within automotive manufacturing branch and obtained power flow measurement results with dedicated multipoint synchronized measurement equipment. High level European Union policies [1] are demanding investments towards more energy efficient production technologies. Also country specific initiatives such as Energiewende [2] in Germany present concepts toward intelligent DC power distribution in future. Such factors lead to development of highly automated manufacturing infrastructure modifications including DC microgrid as electrical energy supply concept as presented in Fig. 1. Elements of local PV generation, energy storage and consumers as well as ability to operate in islanding mode for certain periods allow to discuss presented electrical installation as microgrid. Green dots represent relevant power flow measurement locations within microgrid structure.

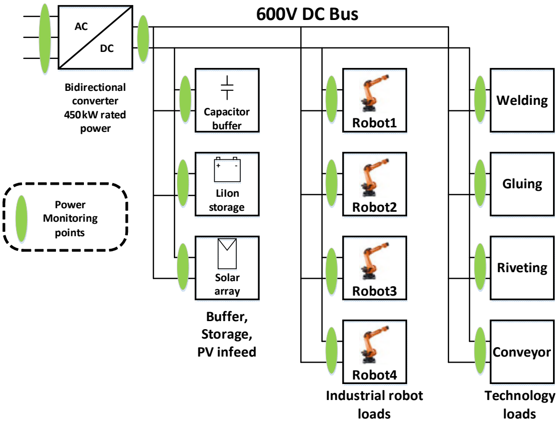

Fig. 1: Structure of examined DC microgrid for automotive manufacturing application.

Development of 600V DC electrical system for integration within existing factory infrastructure arise problems of less developed standard base and electrical component portfolios of typical suppliers with respect to state of the art AC electrical technology. However, future plans covering DC standards have been presented [3]. Insight of research activities covering both software and hardware modifications with focus on energy efficient robotic manufacturing has been presented by [4],[5]. Advantages of DC energy supply systems has recently been identified also in marine applications [6] and buildings [7]. Ideas of verified simulation model development of electrical components as well as parallel development of virtual software analogue of existing manufacturing infrastructure systems also known as digital twin concept has been considered [8]. Such concepts are demanding verified experimental data of power consumption as basis for new modelling and planning software development. Also control strategies of adaptive system operation with respect to energy prices, renewable energy production potential and energy storage options require experimental research. Realization of Fig. 1. presented DC microgrid structure has been built as operating production cell including industrial robot manipulators with related tools and technologies at Daimler AG factory in Germany as presented in Fig.2.

Fig. 2: DC microgrid realization as automotive manufacturing cell for experimental analysis.

System has central AC/DC bidirectional converter with rated power of 450 kW. Load group is combined of 4 industrial robots and related tools for material joining by spot welding, glue dispensing and punch riveting methods as well as rotating conveyor for part exchange. As auxiliary systems electrolytic capacitor bank of is directly connected to main DC bus as well as LiIon storage and photovoltaic panel array with respective DC/DC power converters.

Multipoint power metering system application

Scale of presented system and involved electrical components arise problem for power flow measurement realization. The approximate dimensions of cell are 8 by 8 meters with DC ring bus rail and electrical cabinets located along outer wall. In order to obtain power flow measurement data from 13 distributed measurement points with common sampling time reference power measurement devices combined with optical fiber data transfer system has been created and applied. Power measurement units has been built based on approach presented in [9] utilizing voltage to frequency method for voltage measurement and compensated hall effect sensor current measurement methods. Following Fig. 3 represent power measurement module designed for industrial robot cabinet connection and graph during measurement validation tests.

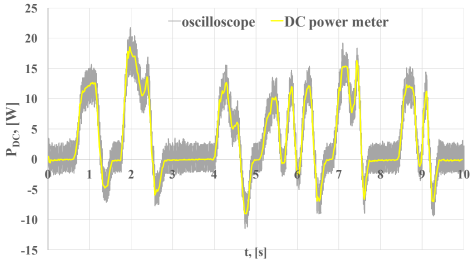

Fig. 3: Power measurement device prototype for DC industrial robot and measurement performance evaluation example against oscilloscope based power measurement.

The basic sampling frequency is 2.8 kHz and averaged values over 20 millisecond periods corresponding to 50Hz AC side power measurement are propagated via optical fiber network for central data logging as text file. The AC side power measurement device prototype is shown in Fig. 4. For installation in existing AC electrical system external current clamps have been preferred with ability to connect without dismantling the high power electrical wiring. All power metering devices have been designed for later integration within industrial automation infrastructure via Profinet communication standard for power monitoring capability. For the current scope of this paper bidirectional optical communication has been utilized enabling synchronized reading of all involved measurement modules to obtain single time base for 12 DC type and one AC type power measurement readings.

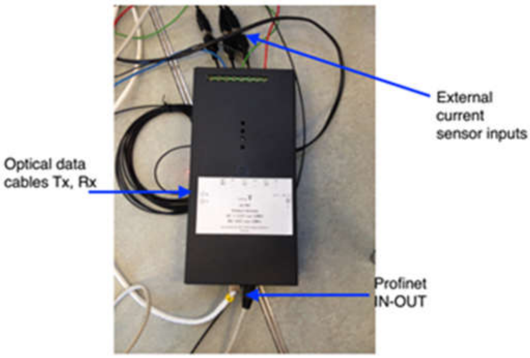

Fig. 4: AC side 3 phase power measurement prototype with external current clamps, bidirectional optical data transfer and Profinet communication module.

Synchronous Multipoint Power Measurement Data example

Based on application of aforementioned measurement setup power flow data has been obtained based on industrial manufacturing application operation of 110 second duration completely supplied via local DC microgrid. Following Fig. 5 represent 13 datasets with common time axis grouped according to similar magnitudes of power flow.

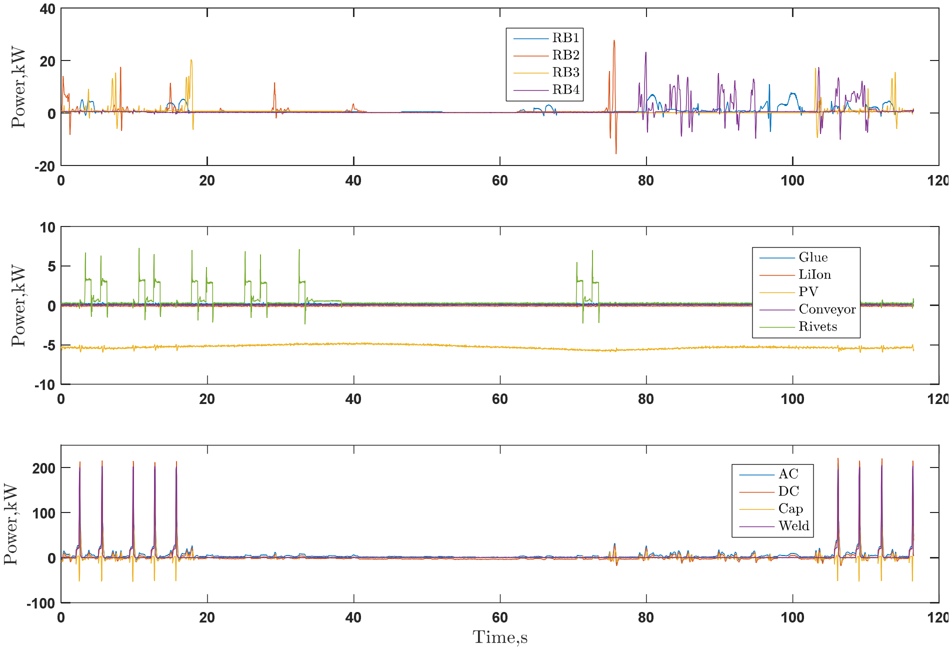

Fig. 5: Obtained synchronous power flow measurement data at 13 microgrid locations: 4 industrial robots (top), tool technologies, PV infeed and LiIon storage (middle), AC, DC, Capacitor buffer and welding (bottom).

Power flow direction is considered positive as consumption from DC bus or AC grid respectively. Alternative way to classify involved microgrid components regarding functional tasks can be addressed as already introduced in Fig. 1.

Industrial DC Microgrid Power Flow Analysis

By observing behavior of consumers it is possible to derive group of elements operating with bidirectional power flow in DC bus. In order to obtain insight about intermediate power flow behavior within DC network following calculation has been performed according to equations (1) and (2) calculating average positive P_{Pos} and negative P_{Neg} power flow within given 116 second operation period T and results have been summarized in Table 1.

$$P_{Pos} = \frac{\int_0^T P(t)}{T}; P(t) \in [0, \infty) \quad (1)$$

$$P_{Neg} = \frac{\int_0^T P(t)}{T}; P(t) \in [-\infty, 0) \quad (2)$$

Table I: The title of the Table I

	DC load group (4 robots, tools, capacitor buffer)	Robot 1	Robot 2	Robot 3	Robot 4	Technology tools (4 units)	Capacitor buffer
P_{pos}, kW	8.01	0.99	0.94	0.68	0.64	3.51	1.25
P_{neg}, kW	1.06	0.012	0.1	0.04	0.04	0.04	0.82
P_{neg}/ P_{pos}, %	13.23	1.21	10.64	5.9	6.25	1	66

Observing analytical results one of advantages of integrating industrial robots within common DC system is verified presenting reused braking energy utilization in range between 1.2% and 10.6% depending on programmed robot motions and tasks. All technology loads have been analyzed as group and also 1% of negative energy flow has been detected that can be explained by significant internal capacitance of welding technology converter. Main electrolytic capacitor bank buffer power flow yield to 66% ratio of supplied average power flow with respect to stored power flow and can be explained by internal losses of assembled unit. Analysis of combination of 4 technology load units, 4 industrial robots and capacitor buffer as common DC load group ratio of reused power flow with respect to fundamental consumptions power flow is 13.2%.
Another aspect of verification of experimental results has been presented in Fig. 6. Assuming that sum of all 11 DC bus end user elements (4 robots, 4 loads, 3 storages, buffer and PV) power flow should be a close match of one infeed power flow value DC respective difference has been calculated as value SumDC. Deviation of average value of SumDC over period is 180W. Higher deviation can be observed during rapid power flow change at welding process. It has to be noted that SumDC represent both internal DC bus conductor rail losses and measurement errors. Obtained value support confidence of experimental measurement dataset of 13 power flow locations. More in-depth analysis of measurement system dynamic response, particularly current sensor behavior at high current rate of rise is foreseen as future activity.

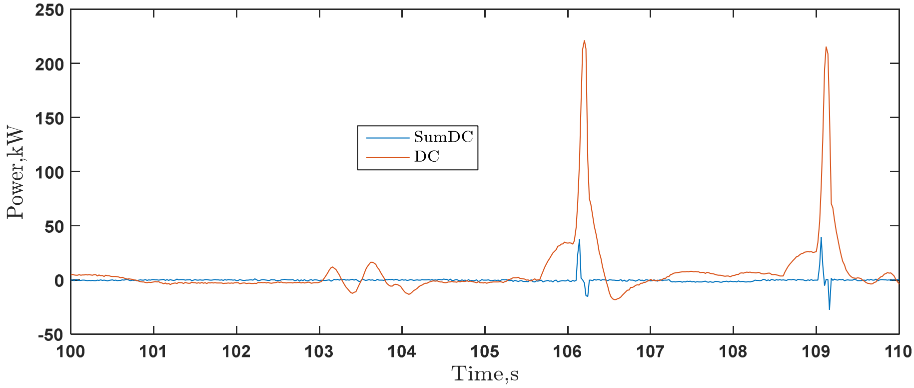

Fig. 6: Comparison of analytical calculation of DC bus component power balance: *SumDC* and measurement of main supply converter DC side power flow: *DC*.

Obtained results allow further analysis of such concepts like power peak shaving since welding process impose dynamic consumption on AC grid side. Also dimensioning of internal storage capacity considering accumulation of renewable energy during weekends or bridging of possible grid outages can be done based on experimental data.

Conclusion

Power flow measurement results covering industrial scale DC microgrid has been obtained in synchronized manner and based on real production equipment operation use case. Such data serve as important basis for validation of simulation models of both component and system levels. Application of experimentally verified electrical component models regarding dynamic power consumption is considered as one of key advantages for design of energy efficient manufacturing installations. Presented results support expected energy efficiency advantages of interconnecting electrical loads with regenerative energy potential within common DC grid. Further activities are foreseen towards analytical dimensioning of central AC/DC power supply converter regarding planned load group within DC microgrid supply area. Since demand for individual welding tool peak power and production cycle average power present large difference new approaches of intermediate energy storage with dynamic response are scope of further research. Also optimal distribution of capacitance within system is interesting topic and will be analyzed in order to reduce unnecessary energy exchange between loads during operation. All aforementioned topics has been considered during initial design phase of DC infrastructure but more detailed analysis covering all DC microgrid can be pursued with assistance of power flow measurement system introduced in this paper.

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Appendix 10

Apse-Apsitis, P., Vitols, K., Grinfogels, E., Senfelds, A., **Avotins, A.** Electricity Meter Sensitivity and Precision Measurements and Research on Influencing Factors for the Meter Measurements. IEEE Electromagnetic Compatibility Magazine, 2018, Vol. 7, No. 2, pp. 48–52. ISSN 2162-2264.

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Electricity Meter Sensitivity and Precision Measurements and Research on Influencing Factors for the Meter Measurements

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Abstract—Methodology, equipment, precision, immunity to electromagnetic emissions and reliable measurement results are important questions for electrical energy measurements. Widely used smart energy meters show good results under laboratory tests and in ordinary applications, but are not very suitable for industrial digital electrical energy supply environment. A different method and inexpensive equipment are used to overcome the above mentioned. The measured power balance between 15 robotized manufacturing cell measurement points (only power losses not measured are the ones in cables) varies in a range of 1,8% (measurement data rate- 20ms), despite the high level of electromagnetic emissions inside and outside of electric cabinets created by power converters.

Keywords— Electromagnetic Compatibility, Smart Meter, Electronic Meter, Interference, Power measurement

I. Introduction

One of the most used measurement devices is electricity meter. It is installed in almost every household and industrial enterprise, and all the electricity expenses are based on its measurements, so it is in everyone's best interests that these devices are as precise and sensitive as possible.

More, in order to increase energy efficiency, measurement device must be connected near each consumer or consumer - generator (smart home or smart robotized production, for example) to spot out inefficient energy consumption. As more electrical energy supply become digital (switch mode supplies) as more robust metering device must be in order to stand multiple wired and wireless electromagnetic influences.

Electricity meter is a measurement device that measures the amount of electrical energy consumed for any electrically powered device, residence or an entire household/enterprise. Every electricity meter needs to meet the IEC protocol standards. For most of the modern households digital electricity meters are used and their input signal is Ethernet frames according to IEC 61850 protocol, as it is communication protocol for digital substations [1][2][3].

In this paper different models of regular electricity meters which are used in regular households and are calibrated and meet the required IEC protocols were used for tests and measurements. Tests are provided in laboratory as well as in industrial applications. Calibration scheme is described in more detail in references [5] and [6].

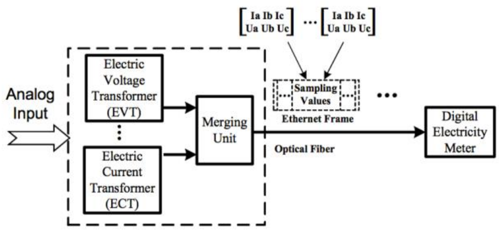

Fig 1. Electrical Energy Measurement in Digital Substations[4].

Suggestions about electrical energy/electrical power metering in digital power supply environment (unidirectional and bidirectional AC/DC, DC/DC, DC/AC converters and inverters) also are discussed.

II. Methodology

A. Electric Power and Electric Energy

Two main methods – C.I.Budeanu method (1927) dealing with non-sinusoidal signal harmonics power and instant power or instant power "p-q" theory (1983) dealing with instant voltage and instant current values (synchronized). Both require complex calculations.

In to microcontroller environment 3rd to 5th order voltage and current delta-sigma modulation and following multiplication and filtering also are widely applied today (*Analog Devices, Inc.* chips, for example).

As we can see – first we measure voltage and current and then calculate power value. Afterwards electrical energy can be obtained by multiplication by time period.

Another method - “non-even sampling method” (proposed earlier by article first author) [7] – where electrical energy are calculated in first and then average electric power are obtained by dividing by time period. Non-even sampling method shows good results in harsh electromagnetic environment in to industrial applications - (1,8% precision over 20ms time period in industrial digital supply environment)

B. Laboratory Tests

Laboratory tests are provided in rooms where low level electromagnetic radiation can be observed.

For all the sensitivity and precision measurements described in this paper, specific devices were used:

- Programmable power supply *PPS400.3*, made by *MTE*.
- Power supply control module *PCS400.3*, made by *MTE*.
- Portable electricity meter testing device *PWS2.3*, made by *MTE*. Testing device equipped with a scanning head *SH2003*.

Before all measurements each electricity meter and measurement device was warmed up for at least half an hour.

Programmable power supply was connected with the electricity meter and with the testing device using 4-wire system in case of a 3-phase meter, and 2-wire system in case of a 1-phase electricity meter. The testing device measured power shown by electricity meter using the scanning head, which fixed meter active powers light emitting diodes blink, also known as an impulse.

Electricity meter sensitivity measurements were made in 3-phase AC power supply voltage values: 253V, 230V and 207V.

Each individual meter measurement was started by applying phase current, which was equal to the minimum current that was shown in the meter’s data sheet. For accurate measurements of meter sensitivity, at least two impulses were fixed. As an additional measurement, meter accuracy was determined. If both impulses were received, then measured accuracy was fixed and appropriate phase current was lowered by the step not bigger than 5mA. If impulse was not received in time twice as nominal impulse receiving time:

$$t = \frac{3600}{SK*P}, [s] \quad (1)$$

then it was considered, that the meter cannot measure passing phase current anymore so the sensitivity limit was determined. In the equation (1) SK is a meter constant and P is the passing power.

Electricity meter precision measurements at different grid voltages were made with meter nominal current (Reference current), in 50Hz frequency, with purely active power. Measurements were made in phase voltage from 250V till 190V with a lowering step of 10V. For precise measurements, testing device was set up for 400 impulse counting mode in case of 3-phase meters and 100 impulse counting mode for 1-phase electricity meters.

Meter precision measurements in various grid frequencies were made in meter nominal current (Reference current), in 230V phase current, with purely active power. Measurements were made in grid frequency ranging from 45Hz to 65Hz with a step of 5Hz. For measurement calculations, a testing device was setup to perform 400 impulse counting for 3-phase meters and 100 impulse counting for 1-phase meters.

Electricity meter precision measurements in various sinusoidal forms were made in 50Hz grid, with voltage fundamental harmonic effective phase value 230V and current fundamental harmonic effective value equal to the meter nominal current given in the data sheet (Reference current). Measurements were made adding third, fifth and seventh harmonic to the main voltage and current signals. Each harmonic was added to each voltage and current signal and to both of them at the same time. For 3-phase meters harmonic percentage composition was set to 20%, but for 1-phase meters harmonic percentage composition was set to 30%. For measurement calculations, a testing device was setup to perform 400 impulse counting for 3-phase meters and 100 impulse counting for 1-phase meters.

For the electricity meter precision measurements in digital (switch mode) power supply working load additional impulse power supplies were used:

- Digital power supply Bestec *EA0061WEA*. The power supply output was set to such active power, so that the power from the network consumer would be approximately 6.3W.
- Digital power supply *S6/S10*. The power supply output was set to such active power, so that the power from the network consumer would be approximately 5W.
- Digital power supply Amigo *AMS3-0502500FV*. The power supply output was set to such active power, so that the power from the network consumer would be approximately 13W.
- Digital power supply *S-150-12.* The power supply output was set to such active power, so that the power from the network consumer would be approximately 100W.
- Digital power supply *VT-20150.* The power supply output was set to such active power, so that the power from the network consumer would be approximately 100W.

For these measurements faculty grid voltage was used. Measurable electricity meter was connected to the grid using 4-wire system in case of 3-phase meter, and 2-wire system in case of 1-phase electricity meter. In the meter output testing device was connected, and in the testing devices output one or more switch mode power supplies were connected. For meter testing one of the switch mode power supplies were connected to each phase. In case of 3-phase meter, one measurement was made, where switch mode power supplies were connected to the first and third phase, but second phase was without any load. The testing device measured power shown by electricity meter using a scanning head, which fixed meter active powers light emitting diodes blink, also known as an impulse. For power supplies with power less than 20W only 4 impulses were used, but for more powerful supplies 20 impulses were uses for each measurement.

III. Laboratory Test Results

The results for electricity meter sensitivity are shown on Figure 2. The minimal current which is detected by the electricity meters varies from as low as 0.008 A till 0.034 A for the electricity meters. Minimal detected currents were measured in different voltages. It is a very low percent from the nominal meter current I_{ref}.

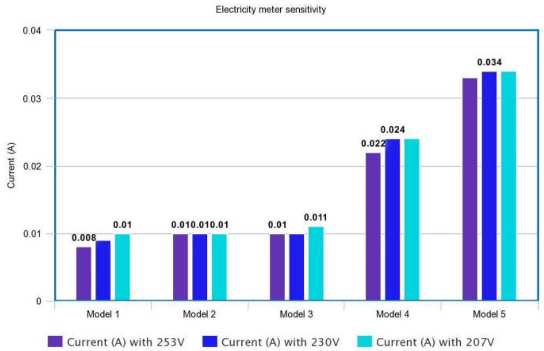

Fig. 2. Electricity meter sensitivity measurement average results for each model.

Electricity meter precision measurement at different grid voltages results are shown in Figure 3.

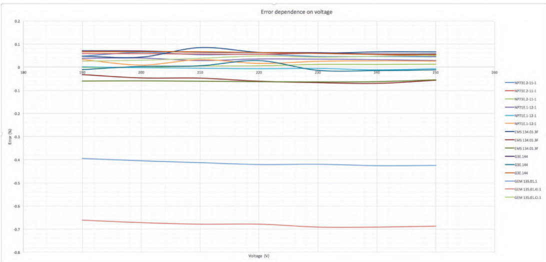

Fig. 3. Electricity meter error dependence on different grid voltage.

The results vary mostly in a range of 0,1 % error for the electricity meter measurements, with two exceptions, where it goes as high as almost 0,7%

For precision measurements in various grid frequencies for the electricity meters the results vary mostly in a range of 0,5 % error for the exact measurement, with few exceptions, where it goes as high as 1,15 % error. The biggest error appears at 65 Hz frequency, and the lowest errors appears in 50 Hz frequency. The results are shown in Figure 4.

In Table 1. the first column shows, which higher harmonic is added to the voltage signal. The second column shows, which higher harmonic is added to the current signal. The third column shows the percentage value of the harmonic added to voltage signal. The forth column shows the percentage value of the added harmonic to current signal. The fifth column shows the measured electricity meter error in %.

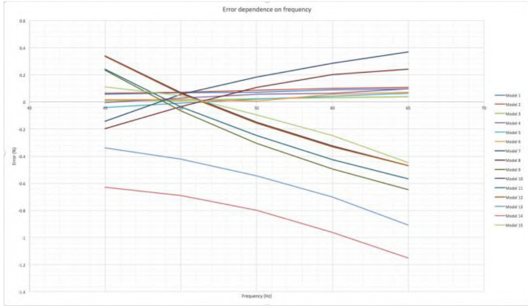

Fig. 4. Electricity meter error dependence on various grid frequencies.

Electricity meter precision measurements in various sinusoidal forms were measured in specific harmonics and order for each meter, with voltage fundamental harmonic effective phase value 230V and current fundamental harmonic effective value equal to the meter nominal current given in the data sheet (Reference current). The results (worst case between several the same model meters) are shown on the Table 1.

Table I. Measurement results, sinosoidal harmonics

Voltage harmonic	Current harmonic	Voltage harmonic value(%)	Current harmonic value(%)	Error (%)
3.	3.	20	20	0,1
-	3.	-	20	0,084
3.	-	20	-	0,095
5.	5.	20	20	0,11
-	5.	-	20	0,092
5.	-	20	-	0,093
7.	7.	20	20	0,113
-	7.	-	20	0,086
7.	-	20	-	0,09
3.	3.	20	20	0,1

As for the measurements in digital (impulse) power supply working load for electricity meters the results are sorted out in tables in Table II. The first column shows information about electricity meter load – DC power supply model, based on simple rectifier with filtering capacitor on AC side, the second column shows each meter's serial number. The second column shows the approximate load power value. The third column shows in which phase the load was connected. The fourth column shows the measured electricity meter measurement error in %. This table shows that for this test the maximum meter error for the specific model could reach more than 3 %.

Table II. Measurement results, rectifier-capacitor load

Load – DC power supply	Load (W)	Connected phase	Error (%)
Bestec	6,3	1.	-3,188
S6/S10	5	2.	-2,922
Amigo	13	3.	-0,555
S-150-12	100	3.	0,125
VT-20150	100	1.	-0,204
S-150-12 and VT-20150	200	3. and 1.	0,027

IV. Industrial Tests

Industrial tests show the uselessness of these energy meters in a dynamic power consumption-recuperation environment. Strong electromagnetic fields (field generating currents are up to 600 A) influence measurement devices in the similar way like open door electric cabinets cause several model laptop's touch pads "live on their own". At the same time measurement devices and corresponding current transformers must be installed in to the electric cabinets in order to use shorter power cables.

Typically dynamic current changes do not fit into standard defined frame: aluminum spot welding requires power jump from 1-2 KW during stand-by and up to 360KW during welding (Figure 5). Welding time is about 90 milliseconds and it is not known where it occurs over the measurement frame – at the beginning or at the end of the frame.

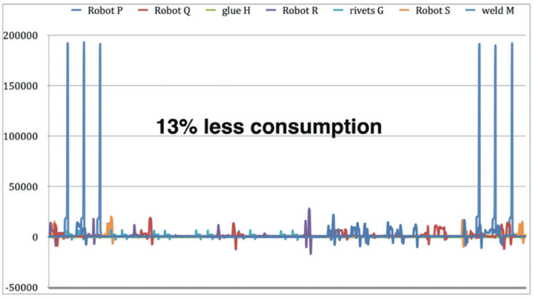

Fig. 5. Industrial production machines and tool power profiles , W.

Non-even sampling method based devices (Figure 6.) are used to synchronically measure multiple machine and tool power profiles in to an AC or DC digital environment. Currently this allow to record robotized manufacturing cell all electric equipment power profiles (consumption and recuperation) by implementation of 15-measurement point setup. Measurement and analysis allow observe and record 13% less energy consumption in to industrial 600 V DC power supply grid.

Fig. 6. Bi-directional AC/DC power / energy flow meter; 20 ms energy sampling rate.

V. Power / Energy Flow Measurement Tools - Discussion

The following must be taken into account in a discussion about electrical power / energy measurements in a digital environment:

- Converters generate emissions and thus influence voltage and current probes and high speed ADC's readings regardless of ADC conversion method (delta-sigma, multi-order delta-sigma or direct SAR conversion).
- Signal filtering/conditioning creates phase shift and filters cut-off frequency influence etc.
- Sensors mainly have a poor dynamic range.
- Blurring of ADC readings up to ±2-4 less significant bits (practical observation) exists due to inducted noise in wires and PCB. Noise typically is very similar to "white" or "rose" noise (definitions from audio engineering), especially if high speed ADC's are used or signal digital processing takes place (Figure 7). It exists regardless of applied shielding method.
- There are no knowns and unknowns in the measurement device processing method implementation. So it is difficult to predict where the attention must be paid more in order to reduce noise and increase precision.

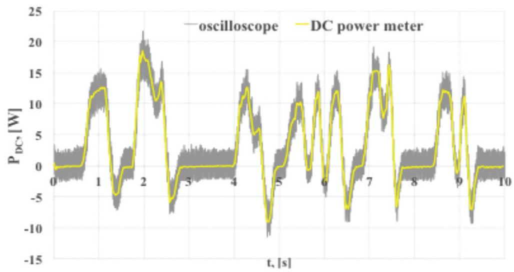

Fig. 7. Noise impact –Oscilloscope v.s. Bi-directional AC/DC power / energy flow meter (20 ms energy sampling rate).

Readings are typically logged or displayed in between of 3…5 seconds rate, however that is not applicable for fast processes. Higher rate leads to lower precision as observed.

Widely used [KWh] units are not applicable for fast processes. Standard SI unit [Ws] must be used.

VI. Conclusion

After various tests and measurements, we can conclude that electricity meter precision is not dependent on the grid quality (higher/lower voltage and frequency). It is also not dependent on the current and voltage load disturbances or interferences. This conclusion is mainly based on the fact that the electricity meter measurement error should be lower than 2%.

A different case is the low power switch mode power supplies, whose consumed current is close to the minimal current for electricity meter sensitivity. In these cases, electricity meters tend to exceed the error limit of 2%. In all the fixed cases it benefits the consumer as the measurements show a lower registered quantity of energy.

When observing or recording micro- or nano-grid energy flow in practice, it is complicated to get precise information about power balance. Noise level, switch mode power supply electromagnetic emissions and their character change under different processed power, depending on measurement point location. Wiring losses are not constant and sharp power consumption/recuperation change causes additional loses due to wiring inductance and capacitance. Practical observations always show 2-4% imbalance regardless of the precision of the involved measurement devices.

Electromagnetic compatibility always has analog signal character. Applying design principles and techniques from vacuum valve era, well known principles from audio engineering and correct PCB layout design, allows to achieve acceptable results without special measures to reduce noise and the influence of emissions.

However, the “typical and well known” devices do not allow to perform distributed multipoint synchronous measurements. Even multichannel data loggers are not applicable for 5-10-15 meter distances between the measurement points and the logger.

Acknowledgment

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EMC

Appendix 11

Pellicciari, M., **Avotins, A.**, Bengtsson, K., Berselli, G., Bey, N., Lennartson, B., Meike, D. AREUS – Innovative Hardware and Hardware and Software for Sustainable Industrial Robotics. In: 2015 IEEE International Conference on Automation Science and Engineering (CASE 2015): Automation for a Sustainable Future: Proceedings, Sweden, Gothenburg, 24–28 August 2015. pp. 1325–1332. ISSN 2161-8070.

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AREUS – Innovative Hardware and Software for Sustainable Industrial Robotics

M. Pellicciari, A. Avotins, K. Bengtsson, G. Berselli, N. Bey, B. Lennartson, D. Meike

Abstract— **Industrial Robotics (IR) may be envisaged as the key technology to keep the manufacturing industry at the leading edge. Unfortunately, at the current state-of-the-art, IR is intrinsically energy intensive, thus compromising factories sustainability in terms of ecological footprint and economic costs. Within this scenario, this paper presents a new framework called AREUS, focusing on eco-design, eco-programming and Life Cycle Assessment (LCA) of robotized factories. The objective is to overcome current IR energetic limitations by providing a set of integrated technologies and engineering platforms. In particular, novel energy-saving hardware is firstly introduced, which aim at exchanging/storing/recovering energy at factory level. In parallel, innovative engineering methods and software tools for energy-focused simulation are developed, as well as energy-optimal scheduling of multi-robot stations. At last, LCA methods are briefly described, which are capable to assess both environmental and economic costs, linked to the flows of Material, Energy and Waste (MEW). A selected list of industrially-driven demonstration case studies is finally presented, along with future directions of improvement.**

Index Terms— **Energy-Efficient Industrial Robotics, DC-grid, Computer-Aided-Robotics, Optimal Sequences, LCA.**

I. Introduction

The fierce competition within modern globalized markets requires high-performance, reconfigurable, adaptive and evolving factories based on robotic technologies. In parallel, it is necessary to reduce factories ecological footprint by achieving a more efficient use of material and energy resources. Henceforth, it is clear that Factories of the Future will have to be *smart* and *green* [1]–[3]. On one side, the extensive use of Industrial Robotics (IR) is finally leveraging smart manufacturing. Nonetheless, on the other side, IR is intrinsically energy intensive, and its massive adoption compromises factories sustainability, not only in terms of ecological footprint but also in terms of economic costs, associated to the increasing energy prices. The main challenges to be solved in order to enable a really sustainable robotic manufacturing are related to the lack of:

- Effective solutions for reducing the energy consumption, specifically optimized for multi-robot lines and cells (i.e. maximum energy efficiency);
- Methods and computer aided tools for the eco-efficient design of sustainable IR plants;
- Automated tools for the energy optimization of IR manufacturing processes (eco-efficient process scheduling);
- Life Cycle Assessment (LCA) methods for assessing both environmental and economic costs, linked with the flows of Material, Energy and Waste (MEW).

The AREUS project [4] (Automation and Robotics for EUropean Sustainable manufacturing) aims at solving all these challenges by providing an innovative set of integrated technologies and engineering platforms, intrinsically interdisciplinary, modular and configurable. In this paper, the AREUS approach will be described, with particular focus on four main innovations:

1) **Energy consumption reduction technologies**, based on a novel electrical power supply system to exchange, harvest, store and recover energy at factory level, improving the use of renewable energy sources;
2) **An IR integrated design and simulation environment**, specifically conceived for the eco-design of IR plants and focused on the simulation of the energy flow;
3) **An IR processes optimization environment**, specifically conceived for the energy-optimal production scheduling and the subsequent automated computation of robot code to be fed into the Programmable Logic Controller (PLC);
4) **LCA methods to assess/optimize both environmental and economic costs**, linked with the MEW flows of co-evolving products and processes realized with robotic production systems.

The realization of such building blocks, whose schematic is depicted in Fig. 1, is currently enabling the modular and scalable/progressive development of optimized sustainable IR applications (or the re-adaptation of existing production facilities). Moreover, a special focus herein is placed on reducing the IR ecological footprints and the total life cycle costs, as compared to conventional factories of similar productivity rates. The paper is simply organized as follows: Sec. II to Sec. V respectively describe the four aforementioned innovations; Sec. VI provides an overlook of the demonstration activities; Sec. VII provides general observations and final remarks.

II. IR Energy Consumption Reduction Technologies

Concerning the first AREUS innovation and regarding automotive manufacturing as one of most automated industries with a high degree of IR applications, several aspects related to energy efficiency have been previously examined in collaboration with the major automotive manufacturer

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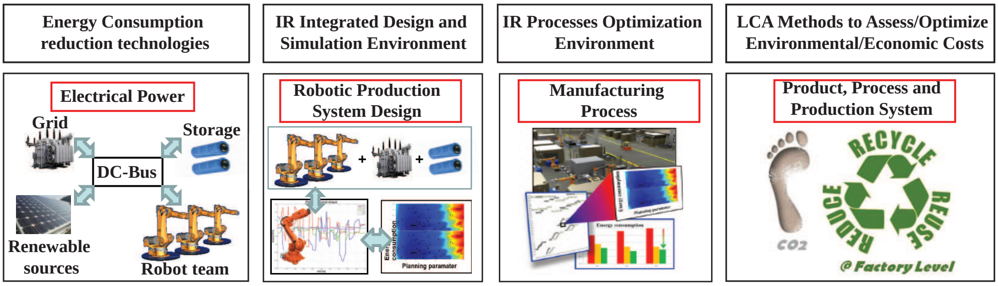

Fig. 1. Schematic of the four AREUS innovations.

Daimler AG, resulting in a doctoral thesis [5] and in experimental field testing within a real assembly plant located in Sindelfingen, Germany [6]. In addition, the vision of future manufacturing represented in the German national initiative - Industrie 4.0 [7], which promotes an individualised, adaptive and fast production based on digital communication technologies, would present new functionalities also from an energy utilisation perspective.

Within this context, the AREUS project is a logical continuation of previous research in a much larger scale and, at the same time, it is dealing with new technical challenges in industrial environments. In particular, IR Energy Consumption Reduction Technologies development is based on a DC-grid electrical power supply system and a new DC-Robot architecture. As explained in the following, envisaged benefits of these innovative AREUS concepts are:

- Simplified and more efficient integration of renewable power sources into factory power grid;
- Minimized loss of recuperative energy of electric drives at factory level;
- Reduction of power losses due to minimized power conversion stages and more effective energy transfer;
- Copper savings due to peak power reduction;
- Installation cost and material reduction by significantly less hardware;
- Practical enabler for realization of smart grid concepts.

A. DC-Grid Electrical Power Supply System

Nowadays, advances in power electronics enable to realize DC-grid also at higher voltages, thus promising additional power savings over conventional AC power grids due to fewer conversion stages needed and higher converter efficiency. On a factory level, which is the scale and scope of the AREUS project, similar power losses are present due to conventional AC-distribution. Furthermore, most of renewable energy sources (wind, photovoltaic, fuel cell) as well as power consumers are DC-based or have an integrated DC-link in the power converters. In addition, also energy buffer and storage devices mostly has DC-based elements, thus a more efficient choice is to use DC-DC power interface modules to connect to DC-Grid and also enable bidirectional power flow.

As a conceptual example, Fig. 2 depicts a conventional AC power system connected to a couple of AC loads (e.g. two AC electric motors). The supply of the first load requires three conversion stages (i.e. numbers 1-3 in the picture). Similarly, energy exchange among the two loads requires four conversions (i.e. numbers 4-7). On the other hand, Fig. 3 depicts the novel DC-based architecture. In such case, the supply of the first load requires a single conversion (i.e. number 1), whereas energy exchange among the two loads requires two conversions (i.e. numbers 2-3). As underlined in the same Fig. 3, the AREUS project DC-Grid voltage is selected to be 600V, to enable eased interconnection to existing AC grid, and to use cost-effective semiconductor materials for power interface module development.

Another issue is that electrical drives used in production may have short-time peak power requirement, up to 10 times

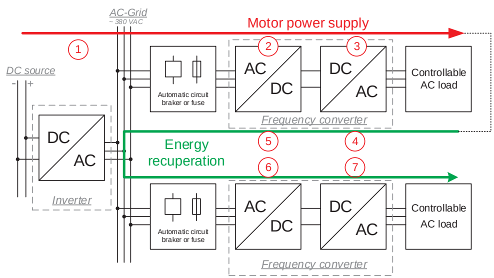

Fig. 2. State of the art AC power system (1-7 = AC/DC conversion stages).

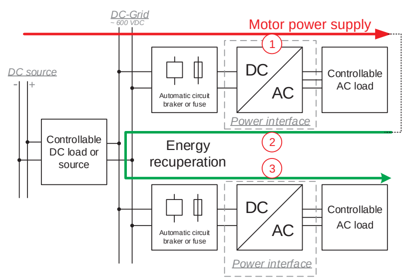

Fig. 3. DC-based power architecture (1-3 = AC/DC conversion stages).

higher than the actual base load, which leads to infrastructure over-dimensioning and waste copper use (keeping in mind that peak energy is typically also very expensive). Modelling results shows that using AREUS DC-Grid approach with fast high power energy storage systems, combined with appropriate DC-grid interface converters, can save up to 30% of peak power requirement locally in the industrial robot manufacturing cell.

B. DC-Robot Architecture

The conventional industrial robot architecture is based on permanent magnet synchronous servo motors that are AC driven, and typically have quick starts, stops and rapid direction changes in the time frames often less than a second. In the latter case, during manufacturing process, braking energy is typically lost in braking resistors as heat. Similarly as for an electric car, also here recuperative energy can be re-used. Nonetheless, in this case, an AC-robot system (as described in [8]) must be used, where energy savings between 2 robots are 5-20% with return-of-investment of 8 years.

Within the AREUS project approach, the industrial robot can be treated as either a load or even as an energy source. In the latter case, a new robot prototype, which can be powered directly from 600V DC voltage grid, has been developed, and preliminary testing results will be provided in next scientific papers and demonstration facilities of the AREUS project. As a mechanical basis, a KUKA high payload robot (Quantec 210R2700 Prime) is used, but new power electronics converter interfaces are developed, allowing DC-grid connection and bidirectional energy flow, enabling new control algorithms to be applied, that should increase energy efficiency for a given production rate.

III. IR Integrated Eco-Design and Simulation Environment

At the current state-of-the-art, IR plant design mainly focuses on product quality and production rate, robot tasks and idle configurations being developed under technological constraints only. In addition, the choice of the robot type and its positioning within the cell is based on optimal reachability and dexterity. In this context, although recent researches have practically proved that the IR power consumption can be partially reduced if energy optimality is introduced as a design goal [9], [10], most of the available Computer-Aided-Robotics (CAR) and Digital Manufacturing tools do not include energy computation/optimization as a part of the plant design practice. Within this scenario, as the second AREUS innovation, a novel simulation environment has been developed, which provides a direct computation of the IR energy consumption to be made readily available to the designer. Envisaged benefits of these innovative AREUS concepts are:

- Capability to assess energy consumption of novel IR plants already during the initial design stages;
- Eco-efficient re-design of existing plants, which are far from their life cycle end.

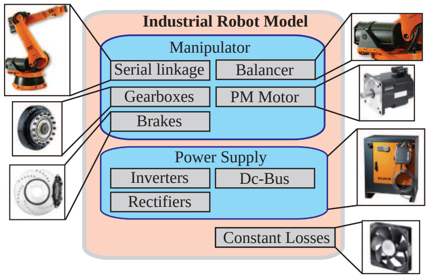

Fig. 4. Schematic of the Industrial Robot Model: Sub-system components.

A. Development of an Energy-Aware CAR tool

The new AREUS CAR tool is based on a white-box and modular model of the IR energy flow, firstly developed under a Matlab platform and then integrated into an external CAR product. For what concerns the IR mathematical model, as depicted in Fig. 4, the dynamic behaviour of all energy-significant sub-components is included, namely manipulator rigid-body dynamics, spring/pneumatic balancer, gearmotors (including normally-closed brakes), inverters, DC-Bus components, rectifier and load-independent power losses (due to cabinet's PC, cooling, and IR control panel). A detailed model derivation can be found in [11], whereas a detailed description of the parameter identification methods is presented in [12].

For what concerns commercial CAR tools, *Delmia Robotics V5* has been chosen as the preferred external platform, due to its wide spread use in the automotive industry. In particular, starting from a Matlab code, the *Matlab Compiler* ® has been used for the generation of a *.NET* Dynamic Link Library (DLL), and subsequently used by a Visual Basic software purposely developed for the interfacing with the CAR tool (*Delmia V5*). Then, the energy consumption of the various sub-system components is then readily computed

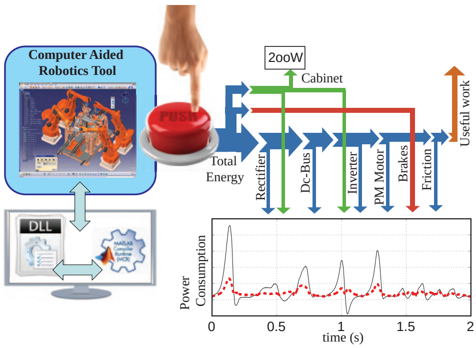

Fig. 5. Energy-aware Computer-Aided Robotics. A DLL library is interfaced with an external software (e.g. Delmia Robotics). The user can easily visualize the power losses in the various system components (i.e. rectifier/inverter/Dc-bus, Permanent Magnet (PM) electric motors, safety brakes, mechanical friction).

once the robot electromechanical parameters are set within the DLL.

As conceptually depicted in Fig. 5, this augmented, CAD-based and user-friendly, simulation environment allows to automatically visualize and highlight multi-robot energy signatures (i.e. energy consumption as a function of the main system design parameters such as cycle time, payload, DC-Bus capacitance, and other critical electromechanical components [8]). By noticing that industrial robots are typically programmed for applications of cycle times from several seconds to a minute or more, that are repeated millions of times during the whole production life cycle, it becomes clear that even a very little energy optimization of a particular robot application may achieve significant savings. In its future implementation, this energy-aware CAR tool will also provide information about energy-optimal robot base positioning and robot selection.

IV. IR Processes Eco-Optimization

Robot movements are often optimized focusing on time performance. More recently, energy consumption has also been an issue. The third AREUS innovation therefore focuses on

- Energy-efficient performance via optimal robot trajectories;
- Efficient computation of energy optimal sequences of operations (scheduling) for multi-robot systems, still keeping desired cycle times.

A. Energy-Optimal Trajectories

A simple but novel concept for generation of energy-optimal robot trajectories has recently been developed and presented in [13]. As a starting point, manually defined robot paths are generated by the normal robot programming language. The resulting robot trajectories, sampled (about 100 Hz) and recorded either from physical robots or a CAR simulation tool, are delivered to an optimization algorithm. The original equidistant sampling times are then adjusted by the optimizer to simply minimize a weighted sum of squared accelerations on each robot joint. At the same time the original robot paths are preserved, while velocities and accelerations are changed due to the modified sampling times. The resulting optimization problem is nonlinear and non-convex, but solved quite efficiently due to the good initial solution given by the manually defined robot paths. The optimized trajectories are converted to trajectory control code that is possible to directly execute by KUKA-robots.

A typical result is shown in Fig. 6, where the first joint for a real KUKA robot KRC30 is moving 110 degrees with 100% speed. The difference between the original trajectory generated by KUKA's standard robot commands (blue curves) and the optimal solution (red curves) is shown in this figure. After the initial acceleration and before the final retardation, the optimal solution generates a constant jerk (derivative of the acceleration), see the red curve in the acceleration diagram in Fig. 6, instead of the original constant speed, see the blue curve in the velocity diagram. This difference saves about 20% of energy for this simple

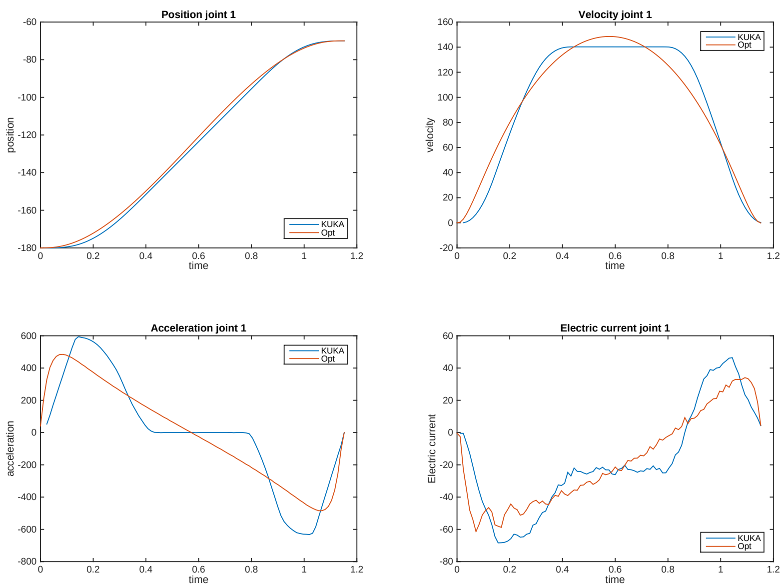

Fig. 6. Comparison of angular positions, velocities, accelerations , and electric currents before (blue) and after optimization (red).

scenario. Observe that the optimized trajectory has the same total execution time as the original one. The optimized trajectories have a higher jerk and sometimes also a higher maximum speed compared to the original motion, but it is within limits for what is possible with the robots. Generally the optimized motions looks and feels smother and less aggressive.

In another example a longer path has been optimized, including multiple points and both point-to-point and linear motions. The result for the optimized version is, in this case, an impressive 32% energy reduction, ones again the same total execution time for the original and the optimal trajectories.

B. *Energy-Optimal Sequences for Multi-Robot Systems*

The optimization strategy above can also be generalized to multi-robot systems, where robots also need to be coordinated to avoid collisions. This concept has been implemented in the new AREUS Sequence Planner (SP) [14], [15], which also includes specific algorithms for combined multi-robot scheduling and energy optimization. Previous research in energy-optimal sequencing, along with the determination of energy-efficient trajectories in the presence of robots with shared workspaces (*shared zones*), can be found in e.g. [9], [16], [17]. For an excellent survey of existing approaches, see [18]. Following a similar direction, including the new trajectory optimization in Section IV-A, the new algorithms implemented in the AREUS SP focuses on minimizing the acceleration, while assuring practically feasible IR sequences.

To illustrate this multi-robot concept, a real system composed of two robots has been considered, where robot R1 is moving down and R2 is moving up in a shared zone. To avoid collision, both robots cannot be in the shared zone at the same time. The order in which the shared zone should be passed is not defined in the original motion. Thus, two possible sequences are identified:

- *Sequence S1:* R_1 starts a downward motion, followed by R_2 moving up.
- *Sequence S2:* Similar to S1, but R_2 starts first.

The results of this experiment when optimizing the trajectories show that for both sequences, almost 30% of the energy consumption of the two robots was saved by the optimized and coordinated motions. The results also show that the second sequence (S2), where R_2 moves through the shared zone first, consumes less energy. When comparing an original motion, where R_1 moves first, with the solution that the optimizer generates, where it is better to start moving R_2, the final optimized trajectories and coordination saves 45% of the energy.

In this example only two sequences were identified. Generally, many sequences may be included in an optimization loop, where each sequence is tested separately. By including efficient search techniques, involving for instance constraint programming, this exhaustive search can be reduced significantly by integrated optimization methods [19], [20].

To summarize: energy can be saved by 1) optimizing the acceleration in the trajectories, 2) allowing robots to move slower instead of waiting for shared zone access, and 3) changing the sequences of operations, see further details in [13].

V. METHODS FOR IR LIFE CYCLE ASSESSMENT

When in use in industrial robotic factories, the above-described innovative AREUS technologies, as well as technologies in general, are always linked with MEW flows. These MEW flows define the sustainability performance profile of a selected configuration, and in AREUS, this sustainability performance is quantified in terms of environmental and economic impact. In combination with a tailor-made method for the economic appraisal, AREUS employs LCA, the internationally standardized state-of-the-art methodological framework to assess environmental sustainability [21].

In order to effectively support planning and re-/design of robotic factories, a fourth AREUS innovation consists of an integrated method to assess and optimize both environmental and economic consequences of design/technology choices. By means of this method, which will be integrated in a professional software environment, the overall sustainability improvement of a given option can be quantified already in the planning stage. This approach thus addresses an issue which in earlier research has been identified to be a major barrier for implementing environmental strategies in manufacturing companies, e.g. [22]. Main output of the assessment methodology will be one single figure for the environmental performance, represented as a so-called Carbon Footprint (i.e. the sum of contributions to Global Warming) and one single € figure for the economic performance.

Valid sustainability performance assessment is not possible without stating exactly which elements of a production system are included and which not. However, robotic manufacturing systems most typically consist of several interlinked systems and sub-systems, e.g. [23], and system delimitations are often not clearly specified. As part of the integrated assessment method, this AREUS innovation also clearly describes different types of robotic manufacturing systems and maps Key Performance Indicators for them. The three major types of systems distinguished are:

- One robot KR 210 Quantec including control unit;
- One manufacturing cell consisting of 4 robots, welding, gluing and handling technologies and other equipment;
- One production line consisting of 8 (TBC) manufacturing cells and other equipment.

The AREUS system delimitations are defined in view of the different perspectives that the various stakeholders take during the design of robotic production lines, so that stakeholders are enabled to make sustainability-oriented decisions in their individual scope of activity. The decision flow among stakeholders is shown in Fig. 7 with the assessment tool in the center. In order to provide for fair overviews, the same system delimitations are applied for the environmental assessment (LCA) as for the economic appraisal.

As a final crucial element in the AREUS sustainability

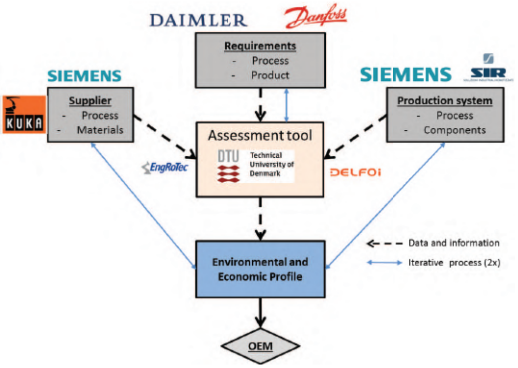

Fig. 7. Information flows among AREUS partners as example for the integration of the AREUS assessment tool in the planning process for sustainable robotic factories.

assessment approach, the entire life cycle of the manufacturing systems is considered. Together with the clear distinction of system levels, this life cycle view ensures that potential sub-optimisations or burden shifts can be avoided when making the assessment. Thus, it becomes visible whether, for instance, a possible material choice that reduces impacts in the use stage of a robot may lead to substantially increased impacts in the disposal stage or whether a certain technology choice on the production cell level may result in increased impacts at a higher level, e.g. at the overall production line level. This total system-wide and total life cycle-wide approach is adopted in AREUS to ensure best-in-class sustainability performance of the developed solutions.

VI. Demonstration Case Studies

The AREUS methodology is experimentally validated in various real production and test environments. The interrelation is shown in Fig. 8, where software optimization is strongly related to novel hardware concepts. For instance, peak power reduction is achieved by both energy storage/exchange technology and methods for energy flow simulation, monitoring and control.

In AREUS, there are seven demonstration facilities being developed in six different countries. Four of them are physical laboratories and three are virtual or cyber-physical demonstration stations. A demonstration laboratory is a physical manufacturing unit, a prototype that is not used for operative production, however, capable to demonstrate real production processes on real equipment. Virtual laboratory is generally software, specific model or a software-tool-chain to demonstrate off-line solutions for manufacturing planning, optimization and evaluation. An overview of the AREUS demonstration facilities is given in Table I. Each demonstration facility has a specific location and a respective project partner, responsible for development and management of this facility.

Virtual Production design demonstration lab (Demo 1) takes place at the Mercedes-Benz production technology center in Sindelfingen, Germany. It demonstrates the AREUS eco-design principles via virtual engineering tools to reduce material use, construction costs and increase energy efficiency simultaneously. All the AREUS optimization approaches are planned to be implemented into production planning software tools that have a large market share so that the AREUS software modules become de facto ingredients for the production planning engineers and system integrators.

A demonstration cell with four robots and tooling (Demo 2) is a copy of a real robot cell from the existing car production. This cell has a capability to produce real car parts, however with a novel hardware design, based on DC energy system, enabling a natural energy exchange between equipment and eased energy storage. This particular demo cell is named Smart Automation Grid. AREUS aims to demonstrate novel technological concepts in maturation

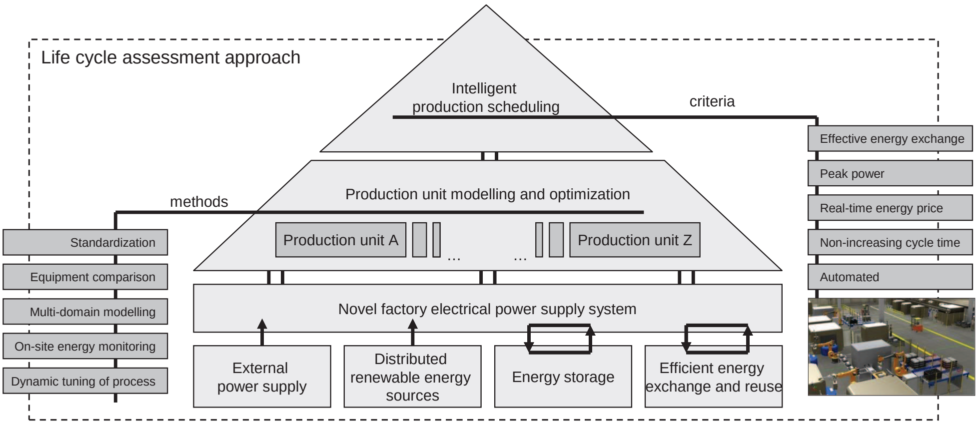

Fig. 8. Interrelation of various AREUS production optimization concepts for highly automated robotic factories.

TABLE I

OVERVIEW OF THE AREUS DEMONSTRATION FACILITIES.

1	Virtual production design demonstration lab	Germany
2	Demonstration cell with 4 robots and tooling based on novel power supply system	Germany
3	Demonstration cell with 5 industrial robots and conveyer system: intelligent production scheduling methods and idle mode control	Sweden
4	Demonstration cell with 3 various payload robots: re-design and re-adaptation of existing plants	Italy
5	Virtual robotic production system optimization demonstration test bench	Finland
6	Industrial robot test bench with prototypes: energy exchange, storage, integration of renewable energy sources	Latvia
7	Virtual lab for LCA/LCC determination for evaluation of the environmental impact & economic appraisal of robotic production plants	Denmark

Laboratory
Virtual lab

level, never experimentally validated before. The cell shows the electrical energy saving potential, higher efficiency integration of renewable power resources and energy storage principles at field level.

A demonstration cell (Demo 3) in Sweden is an existing fully automated assembly station adapted for AREUS, including five industrial robots, conveyor system, and smart automated guided vehicle with a centralized PLC control. This demonstration focuses on sequence control and energy reduction by optimizing the robot movement paths.

In the demonstration cell (Demo 4) in Italy the previous mentioned virtual design tools are experimentally being tested. Principal equipment includes three ABB robots, electrical press, machining tools, screwdriver tools, vibrating feeders, and an energy storage system. The demonstration will focus on AREUS approaches concerning robot system modeling and control method optimization, applicable to existing production configurations.

A 3D virtual factory model (Demo 5) and a scenario were created to demonstrate the integration of enhanced LCA methods into factory planning software for operative use. When processing components, many machines generate waste, the amount of which depends on process parameters that can be modeled. Other important parameters identified to be integrated in the factory model are the transport of components and, in particular, the factory floor area/space that is needed to produce products. This is crucial since e.g. the energy required for heating, cooling, lighting etc. of factories (collectively referred to as overhead energy) typically has a substantial share in the environmental impact of a facility.

An experimental laboratory (Demo 6) is electrically representing a manufacturing work cell built with a purpose to experimentally validate the algorithms for power smoothing and energy consumption reduction technologies. It is a DC power supply system in which energy could be exchanged, harvested, stored and recovered at a factory level.

Primary objective of the virtual lab for LCA (Demo 7) is to assess the environmental and economic sustainability aspects of robotic production plants of any size. In the lab, different design options for robotic production units can be compared in order to find the option that performs best sustainability-wise. In this context, robotic production units are to be understood either as single robots, as production cells or as production lines containing robots.

VII. GENERAL OBSERVATIONS

In this paper, a brief overview of the AREUS framework has been reported. As previously mentioned, AREUS main motivations arise from the need of tools and methods able to leverage the massive adoption of robotic technologies in the manufacturing industries. Several stakeholders may profit, such as:

- **Robot technology providers**, that aim at reducing the energy consumption of their robots, especially when working in multi-robot lines.
- **Engineering software providers**, that are interested in the development of novel tools, able to push forward the state-of-the-art of robot manufacturing systems design and optimization practices, currently focused only on mere production performance;
- **Systems integrators/robotic plants builders**, that are asking for the technologies needed to optimize the sustainability and shorten the payback period of IR plants;
- **Engineering services companies**, that require novel methods for the predictive planning and optimization of operating expenses and eco sustainability, in order to estimate with higher accuracy real business costs and cash flows.
- **Final users**, that would massively adopt robotic manufacturing systems for their superior and unique performances, but they need short payback periods including lower energy cost to afford them.

In order to assess these industrial needs, AREUS is developed with a modular approach to completely exploit its potential in different fields and with various levels of implementation (for example new factories, re-adaptation of existing facilities or different levels of investment affordable by the final user). In fact, each of the four AREUS innovations can be effectively used as standalone technologies or synergically integrated with each of the other modules to gain the best results with a leveraging effect. This strategic approach has been adopted not only to increase the future market exploitation opportunities, but also to foster a step-by-step and scalable approach to guide the market into progressive and easier-to-implement levels of sustainability improvements.

For what concerns potential advantages for future robotic plants, AREUS integrated technological platforms aim at achieving an average robotic plant energy consumption reduction up to 35% (in its full configuration), a peak power reduction of 50% and, at the same time, a reduction of 25% in terms of the total life cycle costs of factories with respect to conventional factories of similar productivity rates.

Naturally, although energy efficiency (and improved use of renewable energy), is the primary aim of the project, the best and more effective results cannot be achieved without a proper integration with the mutually interacting contributions of renewable materials and waste/pollutant management.

VIII. ACKOWLEDGMENTS

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Appendix 12

Apse-Apsitis, P., Šenfelds, A., **Avotins, A.**, Paugurs, A., Priedītis, M. Power Measurement and Data Logger with High-Resolution for Industrial DC-Grid Application. Power Electronics and Applications (EPE'17 ECCE Europe), 2017 19th European Conference on, 2015, Vol. 9, pp. 36–42. ISSN 2255-9140. e-ISSN 2255-9159.

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Power Measurement and Data Logger with High-Resolution for Industrial DC-Grid Application

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Abstract – **Power and energy measurement and monitoring is a key factor for many industries in terms of energy and cost efficiency evaluation. Due to trends of Smart Grid concept application in industrial environment, including decentralized DC-Grid implementation, for precise evaluation – faster and low-cost measurement equipment is needed. Manufacturing industry widely uses industrial robots that have dynamic load characteristics for which faster measurement equipment is needed.**

This paper gives a brief description of the developed power measurement equipment, its structure and interconnection with industrial Profinet network. Further as a testing method steady state and dynamic loads are selected and analyzed. For testing, specially created industrial DC-Grid testing environment and equipment was used. Testing results show that the selected method and idea is working and is able to measure dynamic loads with high resolution. For other industrial load types there is a discussion going on about the issue of how detailed the resolution is needed in industrial SmartGrids, as energy forecast is a new trend in robotic industry and manufacturing planning.

Keywords – **Smart Grids; Industrial power systems; Power measurement.**

I. Introduction

Emerging trends towards intensive enhancement of electrical power supply systems for integration of new types of electrical power generation solutions, extensive power and related operating information flow management and intelligent utilization of electrical infrastructure can be summarized as Smart grid. The existing power distribution system is AC based, but with Smart Grid concept, and DC source integration to the AC grid raises the question of DC-Grid implementation feasibility, where some preliminary research shows advantages of DC-Grid implementation [1]. Some studies show that the powering equipment from AC or DC based equivalent power source in home or office application [2]–[4] the DC-Grid is more efficient due to the fact that less conversion stages are used and the improved network quality.

In Smart Grid context electric car or intelligent battery energy storage system [5] can be consumer or producer generally referred as term - prosumer in several articles [6]–[9], by means that regenerative braking energy can be stored and re-used on demand. Integration of such new power sources in Smart Grid creates not only a problem of safety issues such as fast DC circuit breakers [10] and over current protection [11], but also the need for fast and cheap energy flow control instruments for distributed power metering and monitoring applications [12], [13]. The ability to obtain data on instantaneous power consumption or generation is crucial for operation of any higher level system. Since many power consumer devices today can be referred to as smart or advanced electromechanical devices, regardless of their task or operation principles, it could be said that they are based on one or several electro-technological molecules as presented in Fig. 1.

II. Target System Structure

The same is true also for electric smart grids, regardless of their size, where actuators can be seen as power generating units and sensors provide information about power flow. Various enabling technologies are already available on the market, considering methods of data transmission within power system, including embedded power line communication systems, various telecommunication standards and industrial communication protocols. By increasing the share of power measurement equipment units within power systems, in respect to existing setups of nowadays, such parameters as reliability, self-consumption and investment costs have significant role in decision making of major installation of such devices. New developments along with existing AC distribution system approach considering DC power supply in various applications present the demand for adaptation of existing power measurement equipment. The practical application of power meter unit has been done considering industrial DC microgrid as a case study scenario of intelligent power supply system.

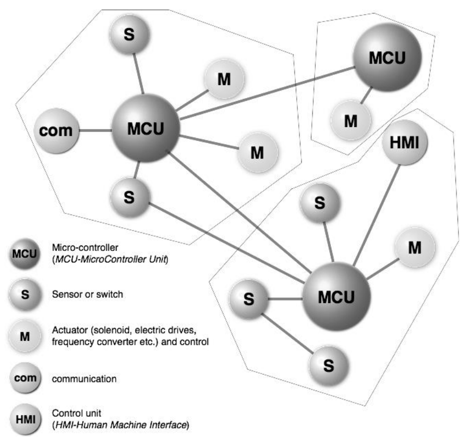

Fig. 1. Visual example of electro-technological molecule structure.

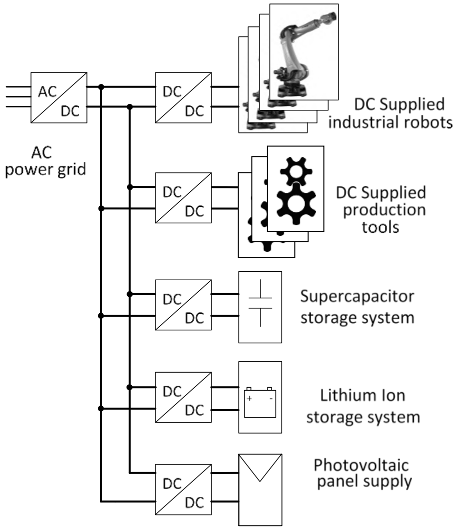

Fig. 2. Example of industrial DC microgrid structure

The concept of such innovative electrical infrastructure has been developed within AREUS project [14] considering 600 V DC voltage based energy distribution, recuperation, storage and exchange operation within manufacturing application. The principal structure of such system is presented in Fig. 2.

A lot of electrical energy consumers or sources operate on DC-Grid. AC/DC or DC/AC converters make it possible to use them also in AC environment. Energy storage devices like super capacitors, batteries, hydrogen cells, etc. allow to store and re-use energy and are designed for DC applications. Such devices are connected to the DC or AC grid via unidirectional or bidirectional energy flow converters. In order to control energy flow this equipment directly points out the necessity to know energy and power values – instantly or in milliseconds, for correct and effective converter and stable power-grid operation. Moreover, simultaneous energy flow monitoring near DC microgrid consumers and energy sources as well as AC grid allow to determine system efficiency and evaluate the weak points of the system from the energy flow point of view. The abovementioned allows making changes in the device workflow in order to increase its efficiency, if possible or necessary. Potential application for intelligent system power flow balancing for manufacturing process is presented in [15].

III. Measurement System Development

Energy measurement device can be seen as a system combined of a set of several subsystems designed for specific tasks. The workflow of energy measurement device can be divided into a sequence of acquisition of electrical quantity, evaluation and information flow within communication infrastructure. In the particular case communication within industrial protocol Profinet was advantageous since application is within automated manufacturing industry case.

A. Suggestions on Electrical Energy Measurement

Typically energy consumption calculations are based on instant power values, especially if consumer generates non-sinusoidal current form. Instant current and voltage value readings (samples) are made and following multiplication is used to calculate instant power, average power or consumed energy [16], [17]. Sampling rate must be at least 4.2 kHz or 42 samples per 1/2T according to standard EN 61000-3-2 [21] and Nyquist frequency.

Active and reactive power measurements and calculations is a continuous dispute between scientists for non linear (or non sinusoidal) waveforms. In general, for power analysis two main approaches exist, where one is Budeanu’s definition based on current and voltage value harmonic parameters (1), or Fryze’s definition (2) based on voltage and current RMS (Root Mean Square) values, calculating power by active and reactive component values.

$$P = U_0 I_0 + \sum_{n=1}^{\infty} U_n I_n \cos\varphi_n; \quad Q = \sum_{n=1}^{\infty} U_n I_n \sin\varphi_n \tag{1}$$

$$\lambda = \frac{P}{S} = \frac{\frac{1}{T}\int_0^T ui\,dt}{\sqrt{\frac{1}{T}\int_0^T u^2 dt}\sqrt{\frac{1}{T}\int_0^T i^2 dt}} \tag{2}$$

Another method is the averaging of voltage and current values via multi-order delta-sigma modulation and the following multiplication [18]. Thus electrical energy measuring and monitoring device installation near every consumer or generator is very expensive. Several methods are proposed to lower the costs, for example [19], [20], in order to achieve widespread installations of electrical energy measuring/monitoring devices. The main disadvantage is the necessity of separate low power source for measuring IC’s power feed and resulting increase in measuring device self-consumption. Moreover, high speed analog-digital converters read grid noise (and generate sampling noise by themselves) and high order filtering must be applied for correct results.

Thus there is a difference between AC and DC energy measurements due to AC and DC environment difference (e.g. power factor existing in AC grid and not existing in DC grid), especially if bi-directional energy flow takes place.

Non-even sampling energy consumption measuring method was proposed to overcome the abovementioned disadvantages. The method allows measuring of bi-directional AC or DC energy flow, design low self power consumption devices and perform measurements down to every 10 ms for DC grids or 20 ms for AC grids or several grids for simultaneous readings.

B. Non-even Sampling Method

According to non-even sampling method [16] the amount of consumed or generated electrical energy during the pre-defined period of time is directly proportional to the sum of current samples over this time multiplied by voltage-frequency transfer coefficient, if current sampling rate is modulated by applied voltage value (Fig. 3).

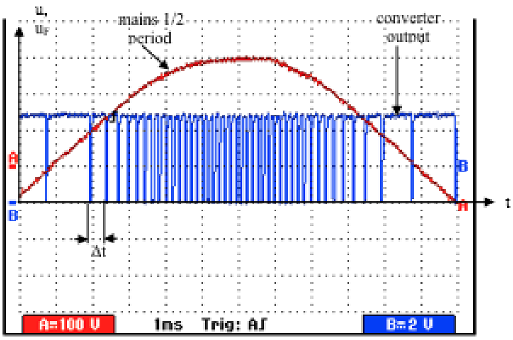

Fig. 3. Example of voltage dependent sampling rate operation.

Converters do not utilize any transformers or voltage dividers and are electrically isolated from micro-controller circuit.

C. Industrial Protocol Selection and Integration

There are various industrial communication protocols and their evaluation [22], [23], but Profinet IO is the leading standard for industrial communication, as it is simple in use and installation, and implementation of PROFIenergy [24] gives benefit in terms of energy monitoring and evaluation. It can be configured to deliver data from one device to another in 1 ms or faster (Isochroous Real Time Profinet IO) [25]. PM (Power Moidule) is connected to Profinet IO via Anybus CompactCom (AnybusCC) module from HMS. This module enables the developer of the embedded system to connect to Profinet IO without advanced knowledge of functionality of Profinet IO.

Data cables in Profinet system are normally made of copper wires. And 100 m cable can be crossed by 1 bit in 0.5 µs. Bridge delay (delay present in switch) depends on conformance type of Profinet IO and its maximum value can be from 3 µs (IRT) to 10 µs (RT). Time of package transmission from the device depends on the length of telegram. If the telegram which consists of 84 bytes is sent (shortest possible Ethernet telegram) then 6.72 µs are necessary. If telegram is 1538 bytes long then the transmission time is 123.04 µs [26]. For example, if data has to cross 4 switch devices and wire connections are 100 m long (Fig. 4) and the shortest Ethernet packet is used then data transmission time can be calculated as shown in (3):

$$4 \cdot (10\ \mu s + 5.0\ \mu s) + 72.6\ \mu s = 132\ \mu s \qquad (3)$$

Time that is needed for data to arrive from AnybusCC to PLC in case of RT Profinet IO configuration, 1 switch, 100 m long connecting wire and telegram size of 1538 bytes should not exceed $0.5 + 10 + 123.04 = 133.54$ µs. Another part of circuit that introduces delay is PM data sending to AnybusCC. The fastest and most complex) is the parallel connection to AnybusCC. That would result in approximately 30 ns long delay time [27]. By summing up all possible delay times it can be estimated that total delay of data is shorter than shortest possible bus-cycle time – 250 µs (IRT Profinet IO), which does not present critical influence on system functionality. In one second data from one PM to PLC can be sent 1 s/250 µs = 4000 times, with largest possible delay of 133.54 µs.

IV. Experimental Setup and Measurement Methods

Verification of the developed active power measurement system has been realized within industrial DC microgrid operation with nominal voltage of 600 V (Fig. 5).

The central element of DC microgrid supply is the common AC/DC interface converter (1) of nominal power 55 kW for bidirectional power flow operation with common current sensing technology available in industry, but keeping in mind that it is also possible to use sensorless topologies as described in [28]. The converter performs the task of stable 600 V voltage supply on DC circuit of microgrid. The AC side power flow is controlled for power factor correction and current harmonic reduction by means of applied passive filter unit.

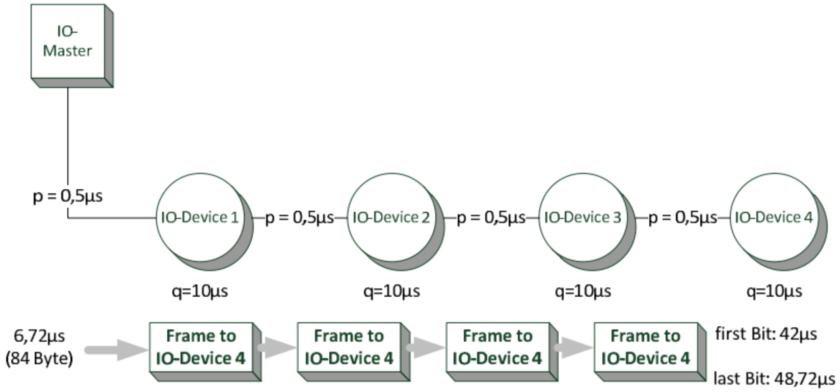

Fig. 4. Calculation of data transmission time.

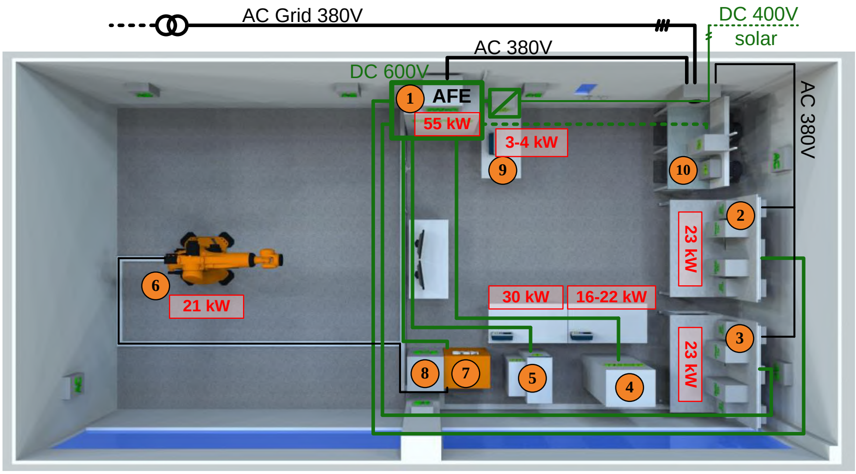

Fig. 5 Experimental verification laboratory hardware testing layout of industrial DC-Grid infrastructure.

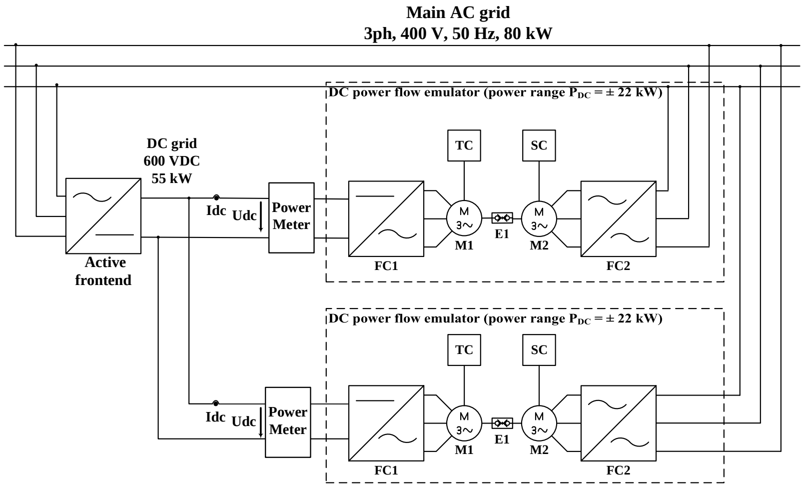

Fig. 6. Structure of DC testing system and measurement points.

The power flow within DC microgrid is enabled by means of drive stand units for power flow emulation (2 and 3). The power range of each of power emulator unit is within 22 kW for both consuming and regenerating energy into common DC microgrid. Such equipment has been designed in order to replicate various power consumption profiles that appear in industrial manufacturing operations taking also possible potential of recuperated energy to be reused within common DC power grid. The operating power profiles applied for dynamic verification of power meter equipment were obtained from industrial robotic manufacturing application. The setup for DC system testing with 2 dynamic power loads is presented in the schematic (Fig. 6).

As shown in Fig. 5, for future testing it is planned also to use other load types, such as solar panel DC/DC converters (9), Lithium-ion battery energy storage system (4), supercapacitor energy storage system (5), and also a 600 V DC powered industrial robot prototype (6) controlled by robot controller (7) and industrial cell Master PLC controller (8), as well as wind generator (PMSG) (10) driven by AC motor can be used as testing object.

For laboratory measurements three tests were created and measured under steady state load, dynamic load (real robot consumption profile), and the comparison with data was obtained through Profinet network.

The developed power measurement hardware testing prototype is shown in Fig. 7 where it has measurement module [12], [13] with two communication outputs, where AnyBus module is devoted to Profinet communication with Programmable Logic Controller and additional optical circuit is for communication and data transfer to personal computer. The device is powered from 24 V_{DC} voltage, voltage measurements can be done in the range of 200 – 700 V_{DC} and nominal is 600 V_{DC}, current measurements in the range +/−70 A, max measurement resolution is 1ms, but nominal resolution is 20 ms.

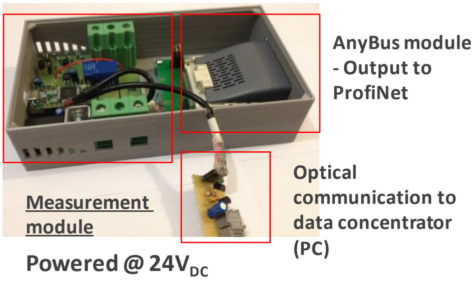

Fig. 7. Developed power measurement hardware testing prototype.

The novel power measurement equipment was compared to the existing laboratory grade Newtons N4L power analyzer with power measurement functionality. In order to verify any existing deviation of the obtained data extracted by means of power measurement prototype with respect to existing and calibrated equipment by manufacturer N4L, model PPA3340 data was collected at steady state operation within power range of 18 kW recuperating to 20 kW consumption, by means of parallel measurements.

In order to evaluate dynamic response of power meter prototype the electrical quantities of voltage and current was obtained by means of oscilloscope along with direct power measurement of measurement device. In this case a motor drive based system (see Fig. 6) was used to test the AREUS DC power meter. The system can dynamically control the DC power flow in both consumption and generation modes within its respected power boundaries of −22 kW to +22 kW.

The power flow control is realized by dynamically changing the torque of an asynchronous machine, whilst keeping its rotational speed constant (4).

$$P_{DC} \approx T \cdot \omega \tag{4}$$

where

P_{DC} power measured at the DC bus of the frequency converter driving the asynchronous machine;

T mechanical torque;

ω rotor angular velocity.

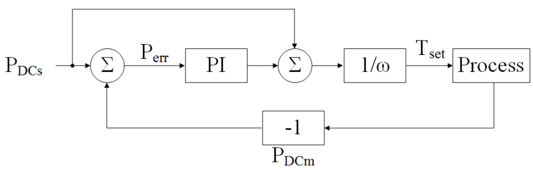

Fig. 8. Block schematic of the motor drive system's power flow control loop.

$$T_{set} = \left(P_{err} \cdot W_{PI} + P_{DCs}\right) \cdot \frac{1}{\omega} \tag{5}$$

where

T_{set} the set torque value;

P_{err} the difference between the set and the measured DC power;

W_{PI} the transfer function of a parallel PI regulator;

P_{DCs} the set power value.

AREUS DC power meter is implemented in the feedback loop of the system's power flow controller (Fig. 8), which enables the inclusion of various regulation methods, thus optimizing the system's performance. The control method used in equation (5) enables 100 % precise recreation of a real industrial robot electrical load (consumption profile), thus giving real-life dynamic testing environment for power measurement device.

PROFINET Data acquisition network structure and functionality of CMs (communications module) has been tested in the line structure of Profinet IO network (Fig. 9).

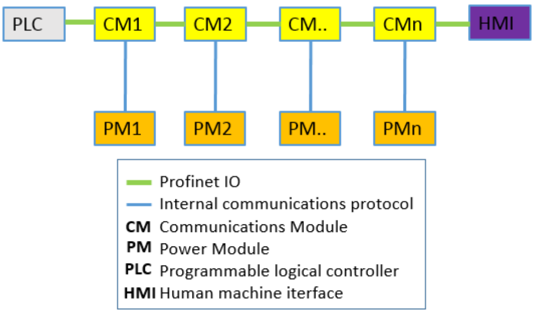

Fig. 9. Line structure of Profinet IO network.

The structure is possible because the Profinet IO 2-Port Plug-In Module (AnybusCC) has a built in switch. For tests, CM in conjunction with PM has been used, which is dedicated to measure power at the nodes of DC busses of industrial robots. As a PLC has been used CPU 1212C from Siemens, IR Profinet IO standard and for visualization of system functionality Siemens TIA portal integrated plotting tool has been used and afterwards data has been extracted and formatted with MS Excel (Fig. 12).

V. Experimental Results and Analysis

The novel DC power meter was connected in series between the AFE 600 VDC output and the motor drive system's DC input and measured the momentary DC power values. Two types of verification experiments were performed. In the first case the dynamic power flow of an industrial robot was emulated with the motor drive system. The DC power meter's averaging time was set to 15 ms. As a comparison, the DC power was measured with Rigol DS1104Z oscilloscope, using PROSySCP 35 current probe and Tektronix P5200 differential voltage probe. The logged data from both measuring devices are summarized in Fig. 10.

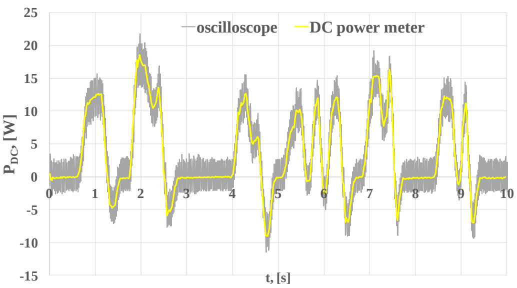

Fig. 10. The first case: dynamic power flow measurements from the novel DC power meter and the Rigol DS1104Z oscilloscope.

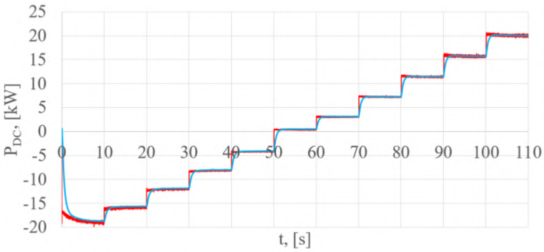

Fig. 11. The second case: constant power steps throughout the motor drive system's power range. Measurements from the novel DC power meter (red line) and the N4L PPA5530 power analyzer (blue line).

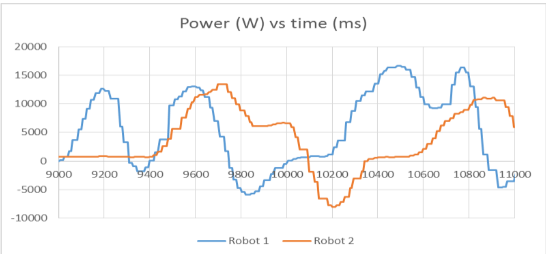

Fig. 12. Instant power consumption of two simultaneously working robots acquired through Profinet.

TABLE I

RELATIVE DEVIATION OF THE NOVEL DC POWER METER IN COMPARISON WITH THE N4L PPA5530 POWER ANALYZER

P_{DC} (DC power meter), [W]	**Deviation, [%]**
−18974.84	1.44 %
−15920.19	1.32 %
−12037.49	1.32 %
−8169.73	1.97 %
−4203.16	3.06 %
415.60	21.16 %
3061.77	3.22 %
7261.49	0.99 %
11491.05	0.69 %
15798.17	0.86 %
20131.46	0.84 %

In the second case verification tests were performed by applying constant power values throughout the motor drive system's power range (Fig. 11). In this case, the novel DC power meter measurements were compared with data from N4L PPA5530 power analyzer (voltage measurement – internal, current measurement with HF100 current shunt). The PPA5530 was set to DC coupling, 5 Hz filtering. Acquisition window was set to 15 ms.

VI. CONCLUSION

In both steady and dynamic testing cases the developed power measurement equipment shows very fast, precise and stable measurements that are even faster than N4L PPA5530 power analyzer. The measurement deviation in work range is within acceptable range.

Implementation of optical communication interface allows stable real-time measurement data transmission to the personal (PC) computer database, thus eliminating connection problems to PC due to various electromagnetic interference (EMI) radiations, caused by typical industrial equipment.

CM working speed is fast enough to replicate power curves of industrial robots, although PM is not connected directly to AnybusCC by parallel connection, but through one intermediate node and serial connections.

Next measurements should be done in other non-linear load situations and compared against the measurements done with faster and more precisely calibrated equipment. In case Profinet and PLCs are used, there is a discussion about the time resolution for dynamic loads and PLC ability to send the necessary data. At these testing loads, the 20 ms resolution is enough for energy calculation, but more load types should be tested to validate this approach of energy forecast.

Equipment testing within industrial application case is foreseen for determination of optimal functionality followed by price estimation for the prototype modified for typical electronic equipment production process.

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Appendix 13

Avotins, A., Bicans, J. Context Application to Improve LED Lighting Control Systems. No: 2015 56th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON): Proceedings, Latvia, Riga, 14–14 October 2015. Riga: Riga Technical University, pp. 135–138. e-ISBN 978-1-4673-9752-0.

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Context Application to Improve LED Lighting Control Systems

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***Abstract* – Paper deals with existing and future LED lighting control system architectures for Smart Grids and introduces to context aware intelligent LED lighting control system. Scope of this paper is limited to context awareness integration into management components, using networked control systems to identify particular context awareness applications in order to improve utilization efficiency, and minimise energy consumption. To prove the concept an analysis with empirical case study for street lighting and public building context aware lighting scenarios is presented.**

***Keywords* – Smart Grids, lighting control, networked control systems, context awareness.**

I. Introduction

Isamu Akasaki, Hiroshi Amano and Shuji Nakamura research [1] was a trigger for further development of white LED technology, and with various small white LED dye combinations in series, parallel and matrix configurations in one chip, later also called as "power LED" which is nowadays typically used in LED luminaries for lighting applications.

There are three main lighting system application types – indoor, outdoor and decorative lighting, but in all of these sectors lighting system developers and maintainers are installing energy efficient LED luminaries increasingly more often. Retrofitting of existing incandescent, halogen, fluorescent, mercury and high pressure sodium vapour lamps gives economical benefit in terms of electrical energy savings. In latest years a new tendency emerges – "dimming", by controlling LED current and changing LED light source output in a range 0-100%, thus also LED luminaries' consumption, which was not possible with gas discharge light sources. Lighting system networks become more and more complex, as they start to integrate lighting control systems based on power-line or wireless (radio, ZigBee, WiFi, GSM/GPRS, etc.) communication systems, obtain telemetric data about each luminary and at the same time enable control of the system. In street lighting application energy savings of 30-50% can be obtained, if compared to High Pressure Sodium vapour (HPS) luminaries.

In any type of LED lighting system there are two system control levels, where the first level is hardware level with appropriate power supplies, LED dimmers, control and communication nodes, which can enable bidirectional data transfer with the second (high level software level) control level, which contains lightweight management software to perform low level telemetric and/or sensor data analysis and controlling/management operations. Integrated software based controllers in the future will play significant role in creating more advanced smart lighting control systems.

If we talk about hardware level, one of the important parameter is LED luminary ON/OFF switching times and also to have possibility to pre-program and re-program time periods for the several periods, for example in street lighting application "night time" (see Fig.1.), thus having several regimes with pre-specified MIN and MAX values of the luminary light output for each time period. This feature already enables improved energy saving even in stand-alone regime of the luminary. In this case the data network is not overloaded with additional information transmission. Each time slot length can be very different in each room or building section for indoor application or on each street/ street segment (outdoor application). When setting up the luminary, the more precise condition and operational data is available and more precise time slot length is defined and used, the better the energy saving results are during luminary operations.

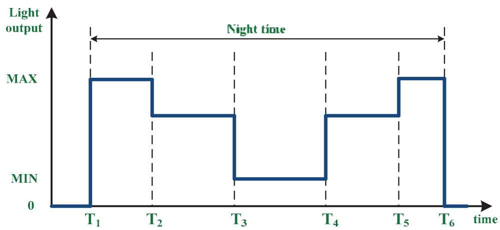

Fig. 1. Example of time zone and light output level distribution.

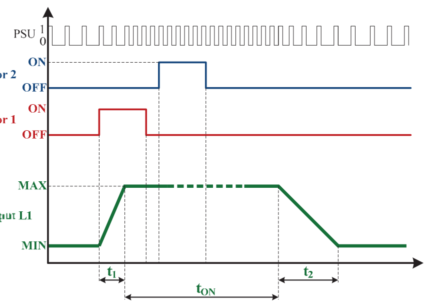

Fig. 2. Example luminary dimming profile in case of sensor triggered lighting control system.

An individual dimming profile should be defined for each luminaire. This will allow a gradual change of brightness level, as LED light output directly depends on LED current, it can turn ON almost instantly, thus we get possibility to have glare issues. Therefore, diming profile should have gradual dimming (see Fig.2.). Times t_1, T_{on} and t_2 must be

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programmable/adjustable, and luminous output levels for high (MAX) and low (MIN) can be programmed.

The aim of this study is to analyse context application for lighting systems, and to compare it with some existing solutions analytically, to improve energy consumption reduction.

II. Control System Architectures

In perspective LED technology will advance and obtain better light output efficacy (Lumen/Watt) ratios, as Cree has announced it reached 303Lm/W in the laboratory environment [2], but it will take time till this LED reaches market as a product. In parallel new ICT and software systems are being developed, getting closer to future "Smart Grid" architecture concept, by means of getting more decentralized and by development of new control algorithms. Additionally, advanced software applications will make more influence in energy savings.

A. LED Based Lighting System Classification

Existing lighting classification is based more on application type, like indoor, outdoor, decorative, itself, and only then the appropriate type of light source is selected. Nowadays LED can replace most of the existing light sources, therefore as only one light source type is used, the technology, especially control systems and their elements, plays a very significant role. In our classification we say that in general there are three systems possible, as shown in Fig.3. Detailed hardware architecture for these systems is explained very good in research [3], which says that with movement detection sensors, lighting system can save up to 70% of electrical energy compared to HPS.

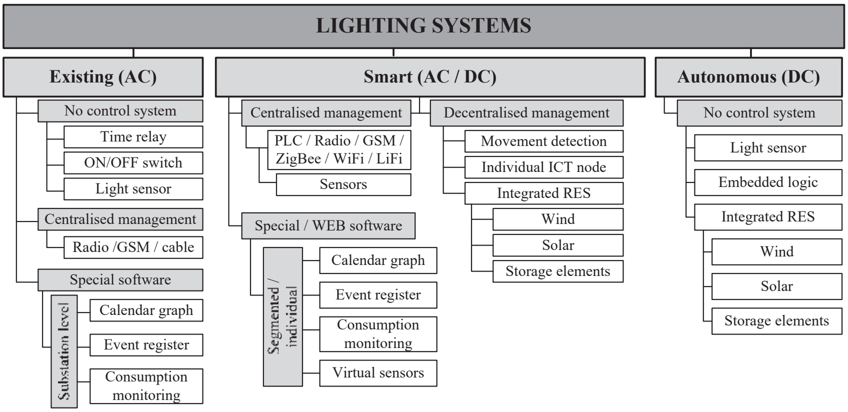

Fig.3. Classification of LED based lighting system architectures.

B. Existing control systems

If we look at existing control systems, they are alternate current (AC) powered, and can have no central management system (CMS) at all, as they work under time relay, central switch, light sensor or their combination. In lighting management system companies or municipalities there can still be CMS based on radio, GSM/GPRS or cable communications, with special software, limited capability to measure energy in electrical substation only [4], thus the main functionality is only to switch ON/OFF the system.

C. Smart control systems

Existing smart control systems [5]-[8] are currently AC powered, but integration of Renewable Energy Sources (RES) into the lighting system makes a part of the grid to become direct current (DC) powered. Smart systems can be applied in both indoor and outdoor applications, and the only thing that is changing is the constructive parameters (luminary power, dimensions, LED driver, temperature management, etc.) of an LED light source, but the rest of the technology (ICT, software, sensors) will stay the same. The main difference from existing systems is sensor usage for each lighting pole and that software makes it possible to apply more functionality and smarter control algorithms using data from other databases.

D. Autonomous control systems

Autonomous lighting systems are relatively small, mostly one or up-to several pole size, therefore, they are decentralized (no control system), use integrated RES, have some embedded logic and electrical circuit with storage element.

E. Context Awareness Usage in Control Systems

Each and every lighting system, either it is street light, industrial or public building light, operates in certain environmental, economic and physical conditions. One way to describe these conditions in a formalized way is to use context approach. Context can be described as a set of circumstances or facts that surround a particular event, situation, object, etc. In smart lighting solution domain contextual awareness can improve operational decision making process, improve utilization efficiency, minimize setup costs and provide many more benefits. In this paper context application possibilities are analysed in order to minimise total cost of ownership expenses, in particular setup, operational and maintenance costs. It is identified that contextual information application in LED lighting control systems is subject of research in recent years. Researchers focus mostly on smart/adaptive/intelligent LED system management systems for office and household buildings [6]-[7]. This approach could be used in larger scale applications like, public service buildings (bus terminals, airports, railway stations) where some of the physical sensors could be replaced by logical and software based sensors. It is identified, that this approach is used for energy distribution and load forecasting purposes [5] and street lighting applications could serve as a tool to compensate some "force-majeure" situations where some grid units are not able to handle the workload.

III. Context Awareness Integration Into LED Street Lighting Control Systems

A. *Design of Context Aware Lighting System*

Context can be acquired by means of using physical, logical and virtual sensors. Physical sensors read environment characteristics like, light, noise, humidity, heat, motion levels. Logical sensors are using various information sources like databases, physical sensors and by means of processing, provide logical decisions in the output. These sensors provide fused/combined and verified output from various sensors. Virtual sensors on the other hand are purely software based and provide contextual information from various data sources, like, databases, web services, knowledge bases, etc. In real life situations, context is gathered from all listed sensor kinds as single input might contain corrupted or noisy information. Various similar information sources could avoid wrong decisions and facilitate sensor input conflict handling. In particular, PIR, piezoelectric, infrared, heat, optical, and power sensors can recognize object (human, animals, vehicles, etc.) presence in monitored area and their behaviour. In this case we would like to mention that there might be situations where physical person monitoring sensors cannot be installed due to privacy legislation constraints. Logical sensors can use physical sensor input to provide new data, like, moving intensity, object count and many other parameters. Additionally, virtual or software sensors can provide information like weather forecast, planned resource utilization (number of cars that will pass road/street segment (based on historical information), number of visitors and many other). Moreover, the number of physical sensors can be decreased by replacing them with input from other kinds of sensors eventually decreasing setup and maintenance costs by keeping the same service quality level, as some environmental parameter values can be calculated.

In typical smart lighting systems it is identified that most common contextual information application is calendar/schedule base, where system owner defines LED operation time and light intensity taking into account the length of the day. Some more advanced systems use light sensors to adjust LED lighting levels according to actual environmental conditions. Taking a look on lighting system management we see that lighting system is a part of a large grid and final price of the generated light is subject of rapid change - electricity on open market/pool is changing based on demand and electricity availability. There might be options to increase savings by adjusting energy consumption not only by following environmental situation but additionally by following grid conditions and pool price. In order to design context aware lighting system, system's architects should identify and list all technological, legal, environmental aspects of lighting system operation environment and identify relationships between all these components.

B. *Context Integration Into Existing Architectures*

For existing architectures contextual information could be applied for smart and autonomous systems. As example information about malfunctioning individual luminaire unit could be used to increase light level of the side units to compensate a lack of light on given section. This information can be gathered directly from controller unit, or acquired by analysing segment energy consumption. For bus terminal or airport scenario individual area utilisation schedule or time table could serve as a basis to provide more light for planned utilization date and time and during idle periods keep light level at minimum, without any physical sensor setup. Additionally 3rd party vendors can provide contextual information, like energy companies, service providers. These are only few possible application examples.

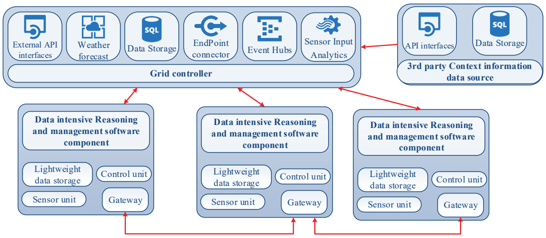

Fig.4. Basic software architecture for context integration.

To facilitate above discussed scenario the following architecture concept is introduced. System setup consists of sensors, control nodes/controllers, autonomous and grid power sources and more advanced software based components with deeper integration with sensor and controllers infrastructure. System gathers contextual information from its own and 3rd party data sources. Proposed system architecture is scalable in both ways; vertically (add more resources) and horizontally (add more nodes). It consists of sensing, control and reasoning components implemented on various levels, that can operate completely autonomously or as a part of existing system. Each component encapsulates broader functionality by having several subcomponents, like raw sensor data collection, data pre-processing, analysis and interpretation, sensor data fusion, reasoning and control component management subcomponents. The set of implemented functionality depends on available sensing, communication and computing resources. The most beneficial context application is in centralized and semi-autonomous systems at cluster or grid section level.

IV. Analytical comparison of control systems

Existing traffic management systems are based on Programmable Logic Controller control systems, and traffic lights are regulated according to hourly traffic speed and intensity database data that can be used also for street lighting CMS to predict traffic and use appropriate light output in certain night time zones (see Fig.1.). By implementing motion detection sensors [9], real time data of traffic intensity and speed could be provided to traffic management systems. The interface for sending software control data to hardware level is described in TALQ Bridge specifications [10].

Proposed context aware application is empirically analysed for illuminated highway segment. Traffic intensity during the daytime can be different on each road as it is shown in Fig.5., and such info could be called 3rd party data source.

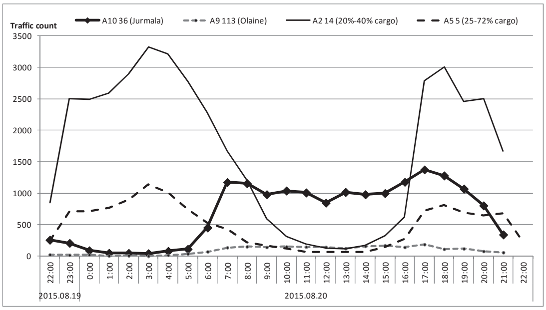

Fig.5. Traffic intensity measurement data obtained from internet databases.

To estimate analytically power consumption, we can define 4 LED lighting system situations, where 1st – system has twilight-sensor, 2nd - calendar graph based, 3rd – system with motion detection sensors and 4th – context based (virtual sensor) control inputs.

As a Case Study we use street with 50 dimmable LED luminaries with power of 150W, assuming that traffic is as for highway "A10 25 (Jurmala)" (see Fig.5.). For this day sun rises at 6:04 and goes down at 20:50. City starts the lights at 21:18 and switches OFF at 5:32. According to [11] street can have 4 time zones for 2nd, 3rd and 4th situations, for traffic intensity "<100" - ME4 class (40% of P_{nom}), for "100-500" – ME3 (50%), for "500-1000" – ME2 (75%) was used. In case of 1st situation light is lit at 100%. To calculate single LED luminary energy consumption (E_{12}, Ws) for the period t_1 till t_2 (see Fig.2.) we use formula:

$$E_{12} = P_{\min} \times (t_1 + t_2) + \frac{(P_{\max} - P_{\min}) \times (t_1 + t_2)}{2} + P_{\max} \times t_{ON} \quad (1)$$

Where t_1 and t_2=1sec., t_{ON}=10sec., P_{min}=20%, Pmax=50% and 75% during time of 21:00-23:00 (same as calendar graph).

TABLE I

Energy Consumption Comparison of Control System Situations

Situation (24 hour analysis)	Energy, kWh	%
1st - twilight sensor	69,25	100%
2nd - calendar graph	34,06	49%
3rd - motion detection sensors	16,50	24%
4th - context based (virtual sensor)	27,13	39%

V. Discussions and Results

Case Study energy consumption comparison of control system situations results are shown in Table I, where most energy saving situation is by using motion detection sensors, but to add such sensors to each pole an investment of ~65EUR/pcs is needed, a solution is to combine with context based data inputs, thus obtaining energy consumption between 2nd and 3rd situation. Light quality is taken into account. The calculations are not 100% precise, as some assumptions have been used. Analytical calculations show promising results for deeper research, using more precise data from city traffic intensity, develop case study with larger area and longer time period, with period of one year. Next step then would be development of hardware and system for obtaining results from real lighting system installation.

Acknowledgement

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Appendix 14

Apse-Apsitis, P., **Avotins, A.**, Ribickis, L. Bidirectional DC/AC Energy Flow Measurement. No: 2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG): Proceedings, Latvija, Riga, 11–13 May 2015. Riga: Riga Technical University, pp. 465–468. e-ISBN 978-1-4799-9978-1.

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Bidirectional DC/AC energy flow measurement

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***Abstract*—Bidirectional energy flow monitoring near 230 V AC or 600 V DC micro-grid consumers - industrial devices or household consumers - rise questions regarding measurement methods and devices self power consumption, price and precision. Article deals with overall 3x230V+N AC and 600V DC micro-grid bidirectional monitoring system design as well as measurement modules communication and data logging.**

Keywords—power conversion, AC/DC micro-grids, bidirectional power flow, energy measurement,

I. INTRODUCTION

A lot of electrical energy consumers or sources operate on DC and contain AC/DC or DC/AC converters thus making them possible to use them in AC environment.

DC energy storage devices like super capacitors, batteries, hydrogen cells etc. allow to store and re-use energy, thus making overall system more effective from energy utilisation point of view. Such devices are connected to the DC micro-grid via bidirectional converters.

Active front-end AC-DC-AC convertor module is used to feed DC micro-grid and return excess of energy in to AC grid in case if isn't possible to store energy in to storage devices.

Simultaneous energy flow monitoring near DC micro-grid consumers/sources and AC grid allow to determine system efficiency, as well as weak system points from energy flow point of view. Mentioned above allow to make changes in to devices workflow in order to increase efficiency, if possible and necessary.

Article deals with overall monitoring system design as well as measurement modules communication and data logging. Several details cannot be represented here due to current Project restrictions.

II. SUGGESTIONS ON ELECTRICAL ENERGY MEASUREMENT

Typically energy consumption calculations are based on instant power values, especially if consumer generate non-sinusoidal current form. Instant current and voltage value readings (samples) are made and following multiplication are used to calculate instant power, average power or consumed energy [1], [2]. Sampling rate must be at least 4,2 KHz or 42 samples per 1/2T according to EN 61000-3-2 [7], and Nyquist frequency.

Other method are voltage and current values averaging via multi-order delta-sigma modulation and the following multiplication [3].

Thus electrical energy measuring/monitoring device installation near every consumer or generator are expensive. Several methods are proposed to lower costs, for example [4], [5], in order to achieve widespread electrical energy measuring/ monitoring devices installations. The main disadvantage is necessity of separate low power source for measuring IC's power feed and resulting increase in to measuring device self-consumption.

Between AC and DC energy measurements are a difference due to AC and DC environment difference, especially if bi-directional energy flow take place.

Non-even sampling energy consumption measuring method was proposed to overcome mentioned above disadvantages [6]. Method allow to measure bi-directional AC or DC energy flow, design low self power consumption devices and perform measurements down to every 0.1 s.

III. NON-EVEN SAMPLING METHOD

Non- even sampling method [6] propose that mains voltage

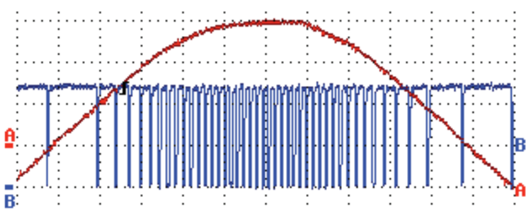

Fig.1.Voltage-frequency converter output signal **B** v.s. input voltage **A**.

are converted to frequency by voltage-to-frequency (U ➔ f) converter and output frequency are proportional to input voltage (Fig.1.), instead of voltage reading via transformer, voltage divider etc.

Voltage-frequency converter output signal (pulses) are transferred through isolating optocoupler and used as micro-controller's ADC strobe signal. Strobe signal frequency (period) determine current sampling intervals Δt.

According to non-even sampling method, amount of consumed or generated electrical energy during the pre-defined period of time, is directly proportional to the sum of current samples over this time, multiplied by voltage-frequency transfer coefficient, if current sampling rate are modulated by applied voltage value.

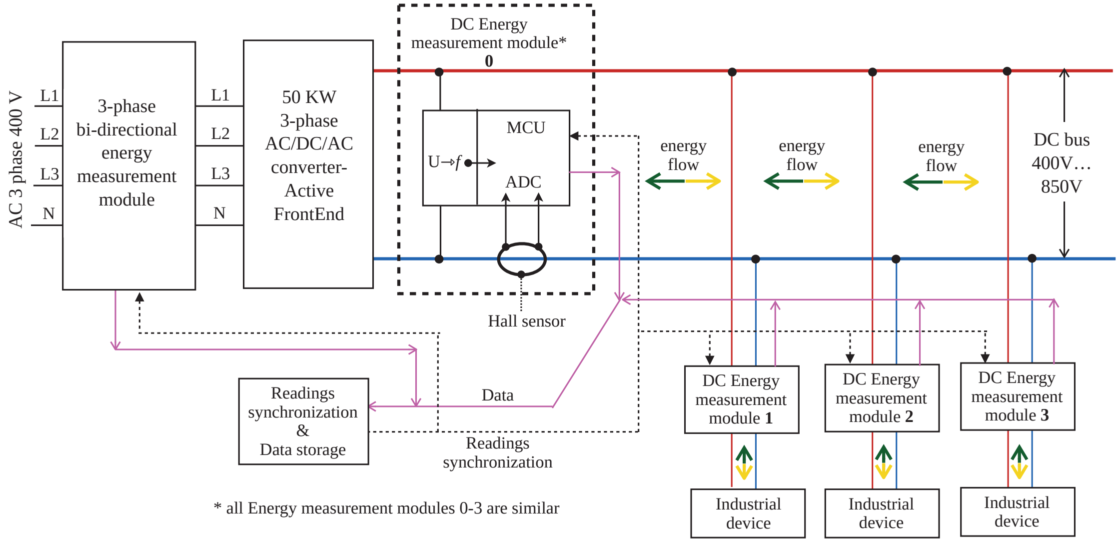

Fig.2. Energy measurement modules installation on AC side and DC micro-grid.

IV. SYNCHRONOUS MEASUREMENT DEVICES INSTALLATION AND DESCRIPTION

A. *Description*

Measurement devices installation diagram on DC micro-grid are shown on Fig.2. DC micro-grid is connected to AC mains by active front-and converter.

All DC energy bi-directional flow measurement modules are designed to measure electrical parameter values taking in to account bi-directional energy flow due to recuperation. Overall installed DC micro-grid power is up to 50 KW.

AC energy bi-directional flow module practically represent three, similar DC energy flow measurement modules. In this case only one MCU are used for all readings, calculations data storage and communication. Due to bidirectional energy flow, AC modules utilise two voltage to frequency converters - one for each AC half-period (Fig.3.)

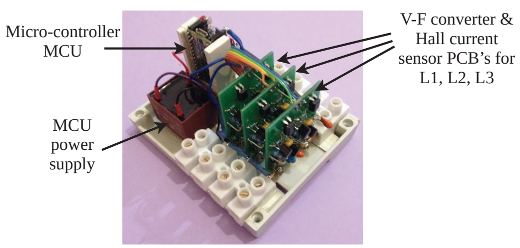

Fig.3. AC 3-phase bidirectional energy consumption measurement module

Module micro-controller unit (MCU) include 32-bit Cortex M4, micro-controller(72 MHz, 12-bit ADC). Popular and very low priced 8-bit, 16 MHz micro controllers with 10-bit ADC can be applied in cases when reduced precision is acceptable - mainly form energy flow monitoring and overall estimation.

Data communication are based on UART or USB (preferable) protocols and devices. Industrial systems typically use EtherNet or Profinet protocols. Additional modules or protocol converters must be added in order to realise these protocols.

Energy flow readings from modules can be synchronised via special synchronisation circuit. Such option is necessary if energy values are taken over short time periods - 10 ms to 500 ms. Short period energy measurement generate important data flow and large data log files.

B. *Voltage-frequency convertor*

Designed patent pending voltage - frequency converter is self-powering, electrically isolated from MCU and consume less than 2 mA if input voltage is 850 V or less than 1.9 W. Energy self consumption become important is significant number of modules are installed.

Converter input -output curve are shown on Fig.4. Overall tested voltage range (linear frequency change) is 120V…950V.

Basically voltage - frequency converter act as native low-pass filter thus eliminating errors caused by noise.

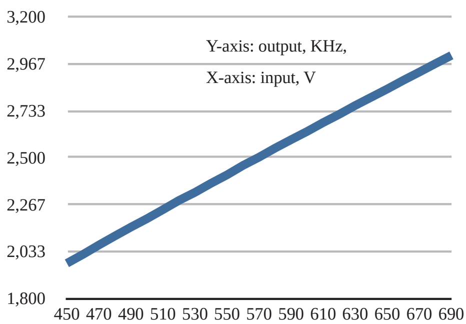

Fig.4. Voltage to frequency conversion curve

X-axis: input voltage, V; Y-axis: output frequency, KHz

C. Current sensing

Today, DC component can be generated and injected in to AC grids from power electronics devices - solar power, wind power and energy storage converters, smart houses and buildings, etc. Low DC current values in AC current are difficult to measure [8].

Described simultaneous energy flow measurement in all 3 phases + current in to neutral allow to detect even small DC injection in to AC grid, possibly take place due to Active FrontEnd converter.

Current measurement are provided by contactless radiometric Hall sensors in all modules.

Sensors patent pending design - absence of ferromagnetic materials in to sensor magnetic circuit but still good resistance to stray magnetics fields - allow to avoid any influence of remanent induction B_r on magnetisation curve when H is zero - no current flow (Fig.5.).

Exception is initial design where ferrite core was applied (Fig.6., upper left).

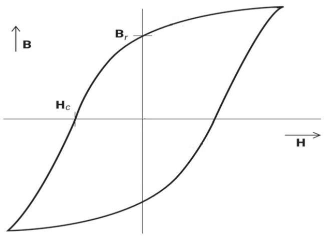

Fig.5. Typical ferromagnetic magnetisation B-H curve

Hall current sensors are able to sense AC and DC current. Current transformers, even with compensation winding, mainly perform the best in to AC environment. Current transformers typically are larger in size too.

Known magneto-resistive magnetic field sensors have some small advantages against Hall sensors but are more expensive and a bit specific implementation.

Ratiometric Hall sensor output voltage V_0 typically is a half of sensor supply voltage V_{CC} when magnetic field *B* is zero -no current flows - (1):

$$V_0 = \frac{1}{2} V_{CC}, \quad (1)$$

To know real current value, from corresponding to this value output voltage V_0 must be subtracted (2):

$$I \approx V_R - V_0, \quad (2)$$

Obviously, precise value of V_0 is important in order to calculate real current value so periodically V_{CC} must be measured to calculate real V_0 value. Temperature changes also have influence on V_0 value.

Available on the market Hall sensors error under different conditions are in range 0,25%…2.5%. for temperatures around 25 ^{0}C. Precision is comparable to current transformer precision on AC measurements.

V_0 value or more precisely, “zero current” V_R value can be calculated average value from read samples if only AC component must be measured (DC component not exist or isn’t important). Well known current transformers also measure only AC component.

In order to calculate V_0 AC voltage symmetry in positive and negative half periods is important due to non-even sampling. Without symmetry there are different number of samples in each half period and V_0 can be calculated as (3):

$$V_0 = \frac{1}{2}\left(\frac{\sum_1^{N1} i_+}{N1} + \frac{\sum_1^{N2} i_-}{N2}\right), \quad (3)$$

where

N1-number of samples in positive half period,

N2-number of samples in positive negative period,

i_+ particular sample in positive half period,

i_- particular sample in positive negative period.

Programmable gain amplifier is applied in front of the ADC in order to perform automatic and MCU controlled measurement range change. Gain can be set as 1, 2, 4 and 8. Range change doesn’t relay on readings average value over time period but on instant sample value and amplifier gain is instantly adjusted for the next sample reading.

Sampling noise reduction are achieved through ADC readings averaging - standard feature for many Cortex M4 micro-controllers. Described designs utilise averaging of 4 readings and ADC sampling time (“ADC ready”) is less than 4 microseconds.

D. Modules design

Initial design of AC and DC energy flow measurement (sensor) modules are shown on Fig.5 Designs take in to account DC micro-grid voltage value, possible DC arcs and average micro-grid power 25-30 KW.

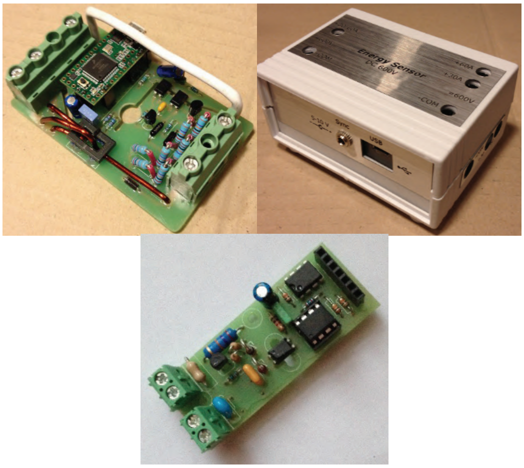

Fig.6. AC (bottom) and DC (top right and left) energy sensor modules

AC modules (Fig.3.,Fig.6. below and Fig.7.) include resettable fuse and varistor protection, DC module include protection against possible reverse DC polarity connection to voltage-frequency converter.

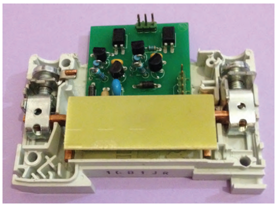

Fig.7. One part of 3-phase 50kW AC energy sensor module

Several developments (based on different MCU) of devices was tested: converters, software and communication.

UART (speed up to 115,2 Kbaud) and USB (speed 12 Mbit/s) communication allow to store readings in to log file or FileMaker Pro database. Communication allow to store measurements starting from 100 ms intervals.

More fast USB communication cable also provide DC module power supply.

USB communication was choose to lower overall costs, in case if several consumers/generators are in to close distance (up to 5m between consumer/generator and USB hub or computer).

UART communication allow more effective implement industrial EtherNet or ProfiNet communication.

IV. Conclusions and Future Work

Synchronised multipoint installation energy flow sensors allow to analyse DC micro-grid parameters, create data log files and store information.

Energy flow sensors also can act as possible electrical equipment fault detectors due to wear-out and ageing - constant increasing of consumed energy turn attention to the possible problems in to future.

Several improvements must be made in to sensors design - possibility to install as standard devices in electrical cabinets, for example.

Acknowledgment

The research leading to these results has received funding from the European Community‘s seventh framework program under grant agreement No. 609391 (AREUS- Automation and Robotics for European Sustainable manufacturing).

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Appendix 15

Avotins, A., Apse-Apsitis, P., Kunickis, M., Ribickis, L. Intelligent LED Street Lighting System – LITES Project at Riga Technical University. In: Riga Technical University Research. Riga: RTU Press, 2015, pp. 31–33.

Available at: https://issuu.com/rigastehniskauniversitate/docs/mpt_journal/32.

INTELLIGENT LED STREET LIGHTING SYSTEM – LITES PROJECT AT RIGA TECHNICAL UNIVERSITY

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ABSTRACT

Energy saving plays a significant role in nowadays European political and economical decisions. Street lighting system is a vital necessity for each city, but it consumes a lot of electrical energy to produce light, therefore energy saving is a topical problem in this case. Article gives an overview of European Framework project called LITES [1, 2] main results, describing the intelligent street LED lighting system technology architecture developed and focusing on energy saving real life experimental results at Riga Pilot Site.

***Keywords**: lighting, lighting control, Smart Grids, LED lamps.*

INTRODUCTION

The street lighting system is a necessity in order to have a safe city traffic and increase the comfort level for citizens, and in most cases the lighting systems tend to be as wide as the city street layout itself, therefore it has a lot of luminaries, consuming a significant amount of electrical energy.

The current lighting networks and systems that are designed for High Pressure Sodium (HPS) vapour source luminaries typically have centralized control systems [3], mainly used only for powering ON or OFF the electrical cabinets (or substations) where several sub-cabinets and streets with luminaries are connected. In this case, the lighting network control signal is transferred by means of radio or GPRS communication method. The system has a calendar graphic/table, where ON/OFF time is specified for each day, throughout the year, then the control command can be sent automatically or by system operator (personnel). For smaller cities and areas, in order to obtain more savings, it is common to use also delay timers, especially for low traffic streets, in this case the light comes ON later than in the rest of city, at the same time it also smoothes out the load pikes on the electrical grid.

Next step in such system evolvement is to develop new LED drivers [5], regulation techniques [4] and add communication (radio or power line) facilities [3], in order to obtain hourly consumption of each lighting pole and by adding movement detection sensors on each pole, to obtain maximum energy savings as light won't be lit if there is no traffic participant on the street. Therefore several international partners from universities and industry launched a European Framework project called LITES, and this article shows some overview on the results.

LITES PROJECT DESCRIPTION

LITES project started at the end of 2009, with main objective to demonstrate in real life experimentation that intelligent street lighting using solid-state lights LED drastically reduces energy consumption, while the lighting service delivered is compliant with road classes CE2–CE5, *S*- and *A*- according to the standard of EN13201. Fulfilling it means that LITES technology can be installed on a secondary street, commercial access, allotment, pedestrian way, cycle track, and it is compliant with all electric standards for luminaries general requirements and tests as well. The project was ambitious even at that time, therefore the project team faced many difficulties, but after five years it was eventually successful. The LITES technology is being tested at 3 different pilot sites in Riga RTU Campus (Latvia), Bordeaux (France) and Aveiro (Portugal), more info available at LITES project web-page.

DEVELOPED SYSTEM

The LITES project has developed a street lighting solution that provides a significant energy saving potential up to 70 %. The LITES technology is an intelligent public street lighting service using solid-state LED luminaries with embedded intelligence. The core element of the solution is the dimming of the lamp depending on the environment parameters; a set of embedded sensors measures the ambient light, temperature, current, and detects motion. Output data of sensors is then processed by the embedded intelligence allowing optimum regulation of light (intensity) levels.

The embedded intelligent control of the light dimming ensures a significant drop of energy consumption while fully respecting the European standards of security ruling the target category of public places.

To make lighting system more robust and thus more attractive to the lighting market, it is wise to make the LED luminary power supply with integrated control node, as shown in system architecture (Fig. 1).

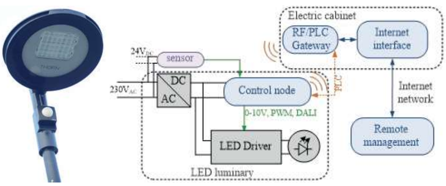

Fig. 1. *Developed LITES luminary (right) and LITES system architecture (left)*

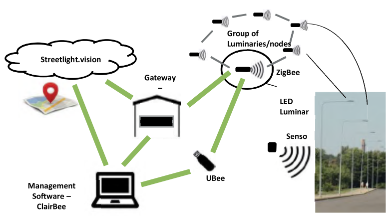

Fig. 2. *LITES technology communication architecture*

The LITES technology (see Fig. 2) consists of three main blocks: 1 — Luminary, sensor and communication node; 2 — Gateway and Network infrastructure, 3 — Local management tool and online management tool Streetlight vision. UBee is a ZigBee network communicator to enable configuration of stand-alone parameters of each LITES luminary, dedicated for maintenance engineers. The gateway enables the network management and data transfer to WEB server, where both energy and sensor data can be analyzed.

RTU PILOT SITE AND ITS ENERGY SAVING RESULTS

The RTU campus is a pilot site situated furthest to the north, therefore weather conditions and daylight hours differ from other LITES project Pilot Sites. The maximum temperature variations between winter and summer can reach up to 60 degrees Celsius (from –30 °C in winter to +30 °C in summer). The climate of Riga is humid continental and proximity of the sea causes frequent autumn rains and fogs. In Riga Pilot Site, 29 LITES LED luminaries are installed, of which 10 are located on Zunda Krastmala Street (mainly car traffic, see Fig. 3), 15 are located inside RTU Campus with mainly pedestrian traffic, 4 are located at Azenes Street for different movement detection sensor testing.

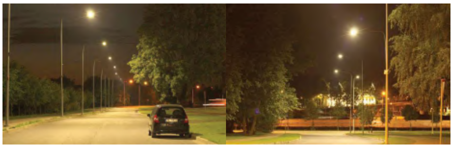

Fig. 3. *LITES luminaries on Zunda Krastmala in Riga (R2)*

All 10 pcs of R2 street profile poles (95 W luminaries) are equipped with ABB energy counter to compare the energy readings between standard counters and the LITES system. Additional 5 pcs of ABB counters are installed in existing poles with HPS lamps to obtain data and be able to compare the average efficiency in this case. The total installed power for Riga Pilot Site is 2,215 W.

Also knowing the exact times when Riga City is turning ON/OFF the lighting system, it is possible to analytically calculate energy savings that are achieved only by retrofitting, replace old High Pressure Sodium (HPS) luminary with LITES LED luminary without sensors and communication system. In this case energy savings reach up to 42%.

Also for further calculations and LITES reading justification and comparison, we should calculate the Riga Pilot Site lighting system “minimum”, where luminaries are at 15 % power level, and “maximum”, where luminaries are at 100 % power level, consumption values, as we do not know the traffic intensity, and thus how many times the sensor will trigger the luminary to max light (power) output. Fig. 4. represents overall Riga Pilot Site energy consumption for last months, the values are obtained via gateway and management software. In order to compare the total LITES technology (incl. sensors and communication) consumption against total HPS luminaries, 10 pcs of 157 W and 15 pcs of 117 W HPS luminaries (real measured wattage for HPS) are used for such comparison, which are multiplied by lighting hours — same as for LED luminaries. In this way we obtain results shown in Fig. 4, with LITES technology energy savings up to 72–73 %.

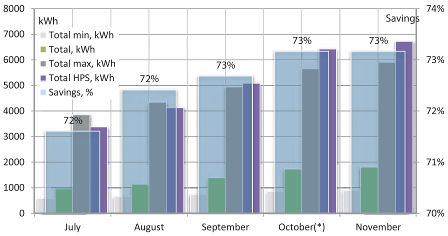

Fig. 4. *Energy consumption at Riga Pilot Site*

CONCLUSIONS

The measurements show that using LITES technology it is possible to get additional 30 % of energy savings, thus reaching 73 % in total. The research also shows that more energy savings are obtained in pedestrian zones, and little less in street areas. More energy savings are possible if system initial (stand-alone) parameter (like min and max values) configuration is fine-tuned for specific street and its traffic intensity.

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KOPSAVILKUMS

Mūsdienās Eiropas politikā un ekonomikā aktuāla tēma ir enerģijas taupīšana, kas atspoguļojas Eiropas finanšu instrumentu programmās. Katras pilsētas neatņemama sastāvdaļa ir ielu apgaismojuma sistēma, kas patērē ļoti daudz elektroenerģijas, tādēļ enerģijas taupīšana šajā gadījumā ir svarīgs uzdevums. Raksts sniedz ieskatu Eiropas Ietvarprogrammas projekta LITES galvenajos rezultātos, aprakstot izstrādātās inteliģentās ielu LED apgaismojuma sistēmas tehnoloģijas arhitektūru, kā arī parādot enerģijas ietaupījuma rezultātus, kas iegūti reālos praktiskos mērījumos, kuri veikti testēšanas poligonā Rīgā.

Appendix 16

Avotins, A.; Apse-Apsitis, P.; Kunickis, M.; Ribickis, L., "Towards smart street LED lighting systems and preliminary energy saving results", 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2014), pp.130–135, 14–14 Oct. 2014

DOI: 10.1109/RTUCON.2014.6998219

Towards Smart Street LED Lighting Systems and Preliminary Energy Saving Results

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Maris Kunickis (*PhD student, Riga Technical University*),
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***Abstract* – The article gives an overview of various researches dealing with smart or intelligent street lighting systems, and what is meant with this term in different countries. Several available architectures of smart street lighting systems as well as those for future are described and discussed. Further some researches and developments of such systems in Riga Technical University are explained with the examples, also showing preliminary practical energy saving results of tests in real conditions of Riga city infrastructure. This is the first part of articles series about this research.**

***Keywords* – LED lamps, lighting, lighting control, smart grids.**

I. Introduction

The street lighting system is a necessity in order to have safe city traffic and increase comfort level for citizens, and in most cases the lighting systems tend to be as wide as the city street layout itself, therefore it has a lot of luminaries, consuming a significant amount of electrical energy.

During the past several years, a new lighting street technology, basing on Light Emitting Diodes (LED), has come into the market. First LED street luminaries were quite simple, and were mainly supposed to replace High Pressure Mercury vapour light source based luminaries. At the beginning luminary price was high, for example, in Riga (Latvia) at year 2009 165W JOLIET 6 High power LED streetlight luminary costs were around 1200EUR, with efficacy only 64Lm/W [1]. Nowadays the efficacy of LED luminaries (for example Philips, Thorn, Schreder, Cree) has been about twice increased, at the same time decreasing the price of it for almost 50%, thus enabling compete with High Pressure Sodium vapour source based luminaries, in terms of energy efficiency. These technological achievements also allow a continuous increasing LED indoor and street luminary market share in the global lighting market, which is also reflected in various high-brightness LED market forecasts.

The current lighting networks and systems, that are designed for High Pressure Sodium (HPS) vapour source luminaries, typically have centralized control systems, mainly used only for powering ON or OFF the electrical cabinets (or substations) where several sub-cabinets and streets with luminaries are connected. In this case the lighting network control signal is transferred by means of Radio or GPRS communication method. The system has a calendar graphic/table, where ON/OFF time is specified for each day, during the whole year, then the control command can be sent automatically or by system operator (personnel). For smaller cities and areas, in order to obtain more savings, it is common to use also delay timers, especially for low traffic streets, in this case light comes ON later, than in the rest of city, at the same time also that smoothes out the load pikes on the electrical grid. In some countries [2] a popular solution for automation is to install twilight switches (Integral photoelectric sensor like "Finder 10.51") in electric cabinet, or even use embedded brightness sensors for each luminary, especially common in autonomous LED based luminaries [3-5], powered from accumulators charged by solar panels, or in combination with wind turbines or AC grid [6]. Of course some city HPS based lighting systems (or electric cabinets) are controlled by systems like Reverberi Enetec [19], by means of stabilizing AC line voltage and for HPS dimming – decreasing the voltage level, thus decreasing the lamp power and light output. The communication can be made via Power-line Carrier, full management GPRS modem, as well as GSM and Ethernet interface, thus enabling power metering for whole line. It can be said that such systems are first smart (smarter) systems compared to described previously, enabling energy savings already for HPS systems in a range from 25%-40%. The disadvantage is that HPS lamps could be regulated just from 50% to 100% and can cause color shift and color rendering index (CRI), as well as significant drop of luminous efficacy (lm/W), also it takes a time for lamp to heat up, in order to get max luminous output.

When the time passes all control systems become more and more advanced (smarter), thus it happened in street lighting control systems. If the first LED luminary ballasts were without LED driver – a special circuit for constant current regulation, then few years later most of the LED luminary manufacturers equipped ballasts with the constant current drivers, power factor correction (PFC) circuits, and lately also with dimming inputs, thus enabling to utilize LED main advantage – to instantly regulate light output in full range - from ~0% to 100% with no photometric parameter changes. This is also main feature that is important driving force for the research and development of more advanced lighting control systems in past few years, both for universities and industry. Lots of new LED luminaries and lighting control system examples can be seen in exhibitions like Light&Building.

Further article describes research and practical results obtained at Riga Technical University projects related to street lighting system development and such system testing in real life conditions.

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II. SMART STREET LIGHTING SYSTEMS

A. Definition

There are numbers of research articles available that are mentioning term "smart street lighting system" or "intelligent street lighting system". And here the question arises, what exactly smart street lighting system is, and where it came from. Also within these numbers of articles like [10-14], who have in titles these terms like "smart" or "intelligent" lighting system, in the text actually does not reflect the meaning or explanation – why it is "smart" or "intelligent", only few of them [2,6] give or use reference that explains what the authors meant with this terminology. At first it seems, that most people just grabbed fancy word and added to the article title, just to make it sound more important.

Thus another question arises again when and what we can call "smart" or "intelligent" street lighting system. When looking for definitions for these terms in IEEE standards and definitions, there is no explanation yet, but you can find only separate or similar words, like "Smart Grids", "intelligent electronic device (IED)"[7], that says it is "any device incorporating one or more processors with the capability to receive or send data/control from or to an external source", and "smart transducer", that "provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity, simplifying the integration of the transducer into applications in a networked environment". Thus it could be agreed that "smart" means ability to be a part of network – send/receive data, and have parameters above common system with an added value or special functions.

Also "street lighting system" is a part of electrical "grid" and also "city", therefore when term "Smart Grid" was introduced, "smart lighting systems" and "Smart City" became more and more common in literature. It could be said, that in future smart street lighting network will be a part of smart city, like city of Quebec added a bus lane control system to Echelon's Street Lighting Solution and eliminated the cost of a second infrastructure [8]. Also the smart lighting grid can be used for harvesting energy from micro-generators, like wind turbines, solar panels, etc.

B. System Architectures

Some cities (for example Riga city) still use lighting system with control method as described in [9], where Main Control System (MCS) is controlling one electric cabinet equipped with Automated Control System (ACS) and current measurement devices, which then can give feedback signal, back to MCS through radio frequency communication signal (other cases use GSM or GPRS signal).

Also during the last couple of years, Riga city, like many other cities across the world, started to install first LED luminaries, at the same time not changing the existing network or control system layout. In this case Fig.1 shows the LED luminary layout and connection to existing AC lighting network. These LED luminary drivers did not have inputs for dimming signals, in order to increase or decrease the power and thus light output.

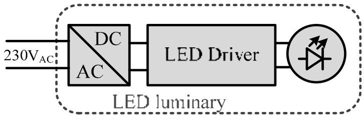

Fig. 1. LED luminary layout and connection to existing lighting network.

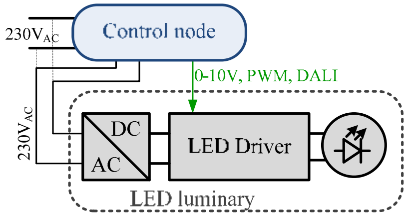

Fig. 2. Architecture with control node.

As the energy savings for LED system that only replaces the mercury or sodium (HPS) vapour lamps were not high enough in terms of investment payback time (also return of investment (ROI)), new LED luminaries as shown in Fig.2 were developed and proposed to market. In this case system replaced the ballast that now has dimming inputs (typically 0-10Vdc, PWM, DALI- digitally addressable lighting interface), in order to change the LED PCB plate driving current, thus it's possible to regulate the consumed power. Also such system needed a control node, for example "Philips DynaDim", "Vossloh Schwabe iMCU", "Schreder LuCo-AD", etc.), that controlled LED driver, according to preprogrammed power levels for each day, according to calendar graph. Such system is good for smaller cities with smaller budget, as it is saving energy during the night time, but the problem is that programming is done in the factory, and typically it is quite hard to reprogram it if necessary, also the LED luminaries were not connected to central management system, thus it is not possible to see the power status or failures.

Therefore new control nodes, as shown in Fig.3, were developed, that have communication circuits and thus ability to send/receive data from central management system through a gateway. Such architecture can be called as smart street lighting system, as it is described in various researches like [9-14].

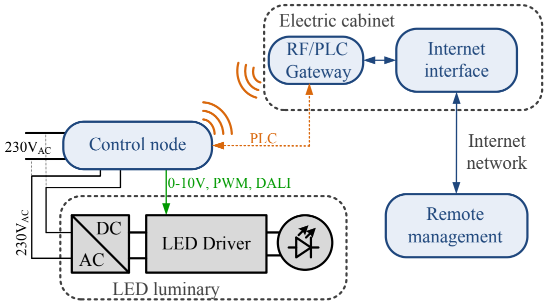

Fig. 3. Architecture with control node with communication circuit.

As it can be seen from Fig.3 control node communication can be realized via Power Line Communication (PLC) or wireless/radio communication, like ZigBee. In this case control node is a separate device that can be installed in the luminary, or in the lighting pole. Further the gateway sends/receives data from control nodes and transfers them to the internet. The luminary power levels are predefined for the each hour of the night-time, thus there are some minimum or maximum light output levels, and energy savings are based on those settings.

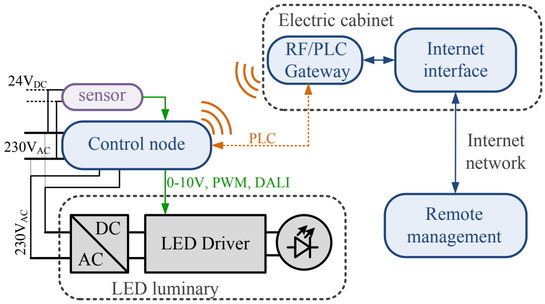

Fig. 4. Architecture with control node and movement detection sensor.

To make the system smarter or give it ability to work in decentralized way, a movement detection sensor must be added to the system, as shown in Fig.4. The sensor can be powered from AC mains (230V), or with separate power supply – 24V DC (typically). In this case the command to increase or decrease light output level (also power) can be given by this sensor, where the triggered luminary via control node can send “ON” signal to the closest luminaries, thus lighting up the lamps in advance of traffic participant.

In case of system shown in Fig.3, the minimum light output level must reach at least the lowest road lighting class values described in EN 13201 standard, for example ME6, thus there are limits regarding the minimum light output level (typically 30-50% of nominal power) and possible energy savings. In case of the system shown in Fig.4, the sensor brings luminary at full or maximum preprogrammed power only when it is needed, respectively – when presence of car or pedestrian is detected. Thus it is possible to maintain even more lower level of the luminary light output, for example 10-15%, in this way getting even more energy savings.

To make system more robust and thus more attractive to lighting market, it is wise to make the LED power supply with integrated control node, as shown in Fig.5.

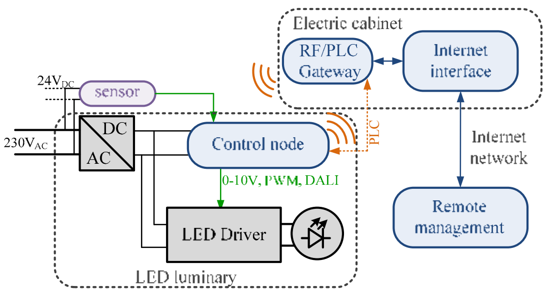

Fig. 5. Architecture with embedded control node and movement detection sensor.

Typically lighting grid network is switched OFF during the daytime, in order to avoid conductive losses in the power lines, thus the luminaries also are offline. The city lighting grid is large, and it is possible to apply Smart-Grid or Smart-City concept, if we would add the wind generators or solar panel arrays to the existing AC powered system, like it is shown in Fig.6. The mentioned alternative energy sources can be also microgenerators, placed on the top of the lighting poles, for example research done in [6]. Anyway special power converters, will be needed for this system, and various new topologies, like [15,18] are available.

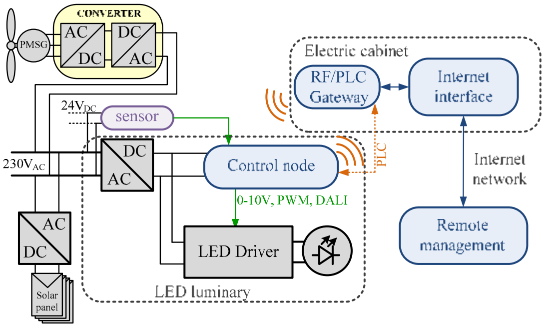

Fig. 6. Architecture with AC grid connected renewables.

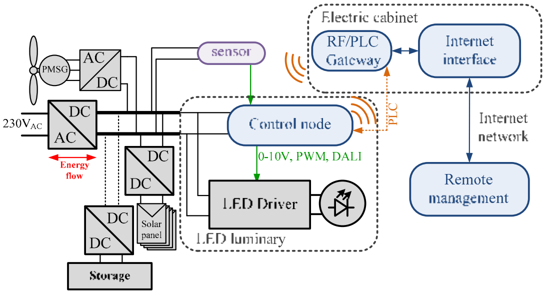

Fig. 7. Architecture with DC grid connected renewables.

The next step could be implementation of DC-Link in the lighting system power grid, this approach would decrease losses in AC-DC converters used to power LED luminaries and also for solar/wind energy injection in the Grid. In this way only DC-DC converters are needed, which have efficiency above 92%, typically close to 98%, and there are no Electromagnetic Compatibility issues or problems related to cos(f) or THD. Also different modulation techniques [16] can influence the total efficiency of the LED driver, as well as the power supply methods for intelligent LED luminary [17] If we add energy storage element (capacitor, Lithium-Ion, etc.), it can even shave the power peaks, which happen when all luminaries are switched ON at first time of the evening. This approach should be investigated more deeply, focusing on conductivity losses in the power lines and create a power supply that is able to switch off output, while input could be powered by renewable energy sources.

III. Analytical Architecture Comparison

Municipality (or other end-user), could use one of architecture described in Fig.1-Fig7 for the street lighting system, but it is not obvious what is best solution in terms of energy savings and ROI (Return Of Investment). Further we will analyze architectures shown in Fig.1-Fig.5, where analysis is based on research data obtained within EU project LITES [22] and various street lighting retrofit projects in Latvian municipalities, mainly dealing with retrofitting high pressure mercury vapour and sodium vapour based luminaries to LED based luminaries.

A. Common Evaluation Parameters

In order to compare different architectures, we need to set-up common basic starting conditions. As High Pressure Sodium (HPS) luminaries are quite common in European street lighting systems, as first condition for calculations we assume that existing street consists of 30 pcs of HPS luminaries, in this case we select Philips Malaga SGS102 150W (12425Lm) with HPS lamp SON-TPP150W (total cost 150 EUR/pc). As equivalent to HPS we select LED luminary manufactured by Philips Indal BGP623 with 8300 Lm and power 71W (approx. 430EUR). The selection is based on Dialux calculations for real ME4-ME6 class street profiles and complies with according normative parameters, but in other situations there can be differences. Thus the total installed power of HPS lighting system is 5,07kW and for LED system – 2,667kW.

Further it is necessary to determine common lighting system ON/OFF timing, thus Fig.8 shows sunrise and sunset timing for each month of the year, in order to get maximum possible working hours of the system we exclude twilight times. In this case we get 4352 lighting system working hours per year, which is used in further calculations.

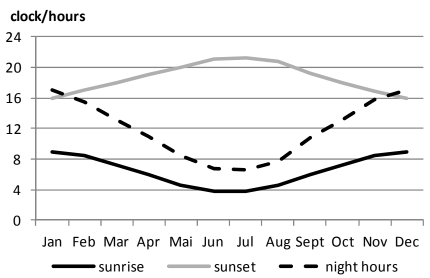

Fig. 8. Monthly time of sunrise/sunset hours per year.

As the architectures shown in Fig.2-Fig.5 are exploiting dimming (light output regulation) capabilities, it is necessary to set-up also common dimming profiles, defining the number and length of the time on the zones during the night, as it is shown in Fig.9 and Fig.10 is based example available in [21].

Further selection of dimmable LED luminary light output values is partly based on [21,22] as well as materials from Latvian municipality most common choices in retrofit projects. For calculations minimal light output values for dimming profiles shown in Fig.10 are used.

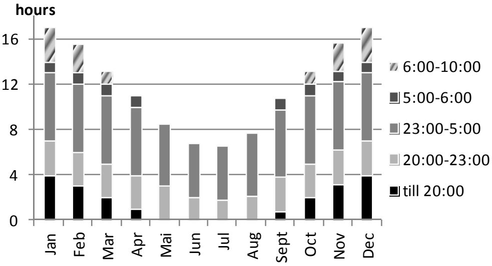

Fig. 9. Monthly night-hours for dimming profiles.

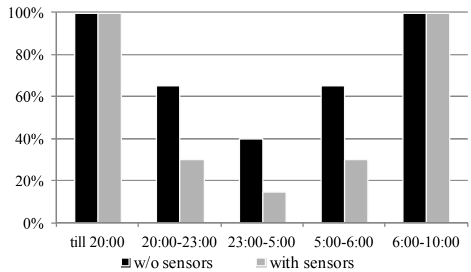

Fig. 10. Minimal light output values for dimming profiles.

From parameters shown in Fig.9 and Fig.10 we can calculate average light output values per year, where for lighting systems without sensors (Fig.2 and Fig.3 architecture) it is 61%, but for systems (Fig.4 and Fig.5) with movement detection sensors it is 39%, as we can use lower minimal light output values.

Further we need to take into account also consumption from peripheral devices, like control nodes (controller and communication device), sensors and gateway devices (Fig.2-Fig.5). For the system shown in Fig.2 we can use Philips Dynadimmer controller (without communication function), and in this case we need 30 such devices, where each has 0.5W consumed power [21], device costs approx. 30EUR/pc.

For control nodes with ZigBee, like [23] with average cost of 50EUR, or Power Line Carrier (PLC), like [24] with average cost also 50EUR, communications we assume that in average stand-by plus transceiving regimes these devices has maximum 3W consumed power. In case of communication ZigBee or PLC gateways, for example Teliko C-Box [24] with price 460EUR, that enable data transfer to the internet (Web server), stand-by consumption is 15VA, but transceiving regime it is 20VA, so we can assume that average consumption is 17,5W.

For systems shown in Fig.4 and Fig.5 we use movement detection sensors, like Steinel IS3180 [25], with 0,9W consumption power and price of 80EUR. Such sensors must be placed on each lighting pole, as their range is only 20m at 2m height. For electricity cost calculations a fixed average price - 0,125442 EUR/kWh is used, as in Latvia, for lighting systems special rate “T-9” is used, with different price ratio for night (and weekend) hours and day-time hours.

B. Analytical Results

From calculations, the yearly consumption for LED luminaries (excluding peripheral devices) is 11654 kWh/year (installed power is 2,677kW).

Typically it is considered that peripherals, like controllers, communication nodes, sensors, etc, are consumers below 1W, and typically are negligible, but in reality they can consume up-to 5%, as shown in Table 1. In case of Fig.4 and Fig.5 the difference is because the control node is embedded in power supply, therefore less losses in converters.

TABLE I

PERIPHERAL CONSUMPTION INFLUENCE ON TOTAL CONSUMPTION

Architecture	Peripherals		% from total consumption	Total investment
	P, (W)	E, kWh/year	%	EUR
Fig.1	0	0	0,0%	12900
Fig.2	15	65,29	0,6%	13800
Fig.3	107,5	467,88	4,0%	14860
Fig.4	134,5	585,40	5,0%	16360
Fig.5	74,5	324,25	2,8%	16360

Further Fig.11 shows potential (as obtained analytically) energy savings for architectures (Fig.1-Fig5.), compared to existing HPS based lighting system. As it can be seen, with simple retrofitting (Fig.1.) it is possible to get energy savings up to 47%, but adding more controls and functionality ("smartening the system"), it is possible to get additional 20-30% energy savings.

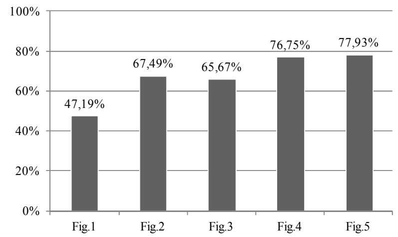

Fig. 11. Potential energy savings compared to HPS system.

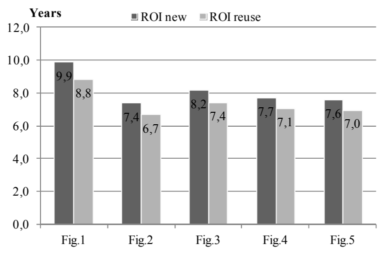

Fig. 12. Return of investment values.

If looking from return of investment (ROI) point of view, the system payback time is shown in Fig.12, where only profit from energy savings are taken into account (no costs of HPS lamp replacement during maintenance period added). Fig.12. also shows two ROI values, where darker one is for new and retrofitted systems, and the other is when the old HPS systems are reused for spare parts.

IV. PILOT SITES AND PRELIMINARY RESULTS

During research and development projects Riga Technical University has created three pilot sites in Riga city to test smart street lighting systems with LED luminaries.

Pilot Site at Mezha street is using architecture shown in Fig.2, system replaced 18pcs of 85-120W HPS luminaries to 60W LED luminaries, where communication and control is done only via ZigBee network, implementing calendar graph ON/OFF timings, this gave 40% energy savings, using "dimming" function was added during night – savings were 51-72% (average per year was around 60%). Larger savings are due to existing luminaries were oversized in terms of light output.

PilotSite in Rietumu street is based on Fig.3 architecture, replacing 22pcs 114-120W HPS luminaries with 22pcs 74W LED luminaries, where ZigBee is initial communication network, but GPRS is used to transfer data to database. This gave 37% energy savings from retrofit only, but using dimming function – it increased to 49%-83% (average per year – 59%). Large savings were obtained due to fact that luminaries were oversized, thus also large light pollution was in that area. With special secondary optics (lenses) it was possible to obtain even better light uniformity, thus less power was needed.

Further experience from LITES project [22] will be discussed, where smart LED lighting system (Fig.4.) is tested in real life conditions in three European climate zones, where first PilotSite is in Bordeaux, second is in Aveiro and the third is in Riga. Riga PilotSite is located in Zunda krastmala, system consists of 29 luminaries, where 12 are 95W and 17 are 65W luminaries. Preliminary results show that from installation date (February 2014), energy savings are 70.8%, and it increases, as the nights become longer. The movement detection sensors installed on the poles, allowed decreasing the minimum light output level to 15%.

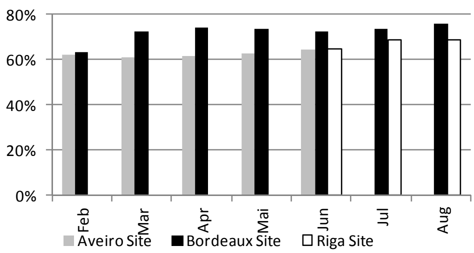

Fig. 13. Energy savings in LITES project Pilot Sites.

Fig.13 shows the energy savings for all LITES project pilot sites, and it can be seen that the values are less, but still close to the potential energy saving calculations shown in Fig.11. Furthermore, in Riga PilotSite a special energy counter is installed into the lighting poles, to compare the readings from nodes. Initial measurements show that difference is 1,4% in average (nodes show more consumption). Therfore actual savings in Riga PilotSite for June is 66%, for July is 70,80% and for August - 71%.

V. Conclusions

From architecture analysis, it can be seen that smart street LED lighting systems (Fig.4, Fig.5), even with higher investment costs (See Table 1.), have the highest energy savings and fastest ROI time.

The numbers in terms of energy savings using smart street lighting systems are similar for various researches [2]-[6], and the Pilot Sites in Riga justifies that with practical measurements.

The next task is to analyze for obtaining comparable energy saving and ROI values for architectures shown in Fig.6-Fig.7. Further it is planned to continue monitoring LITES system and test smart street lighting system based on Zigbee-WiFi communication [9], installing 8 luminaries in campus location.

Acknowledgements

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Appendix 17

Apse-Apsitis, P., **Avotins, A.,** Ribickis, L. A Different Approach to Electrical Energy Consumption Monitoring. No: Proceedings of the 16th European Conference on Power Electronics and Applications, Finland, Lappeenranta, 26–28 August 2014.

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A different approach to electrical energy consumption monitoring

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Keywords

Sensor, Measurement, Energy system management, Diagnostics, Current sensor

Abstract

A different approach to electrical energy/power calculation by means of summing of non-even time current samples over short time periods are described in to the article.

Introduction

It’s overall accepted that energy consumption calculations are based on instant power values, especially if consumer generate non-sinusoidal current form. Usually instant current and voltage readings - ADC (Analog to Digital Converter) readings - and following multiplication are used to calculate instant power and average consumed power or energy [1], [2]. Non-sinusoidal current forms are generated by consumers equipped with simple rectifier-capacitor input. Moreover, power factor is remarkably lower than 1, because power factor correction must be applied for devices with installed power more then 75W.

Other method are voltage and current values averaging via multi-order delta-sigma modulation and the following multiplication [3].

Electrical energy measuring/monitoring device installation near every consumer are expensive. Several methods are proposed to lower costs, for example [4], [5], in order to achieve widespread electrical energy measuring/monitoring devices installations.

Electrical safety during metering is very important. Here the main problematic question is voltage sensor isolation from power line. Isolation transformers, for example [6] are more heavy and bigger sized compared to Hall current sensors, even current transformers available today [7], [8]. Due to mentioned, many energy metering solutions implement non-isolated voltage measuring by simple resistive voltage dividers and calculation (micro-controller) circuits.

Below are described a different approach to electrical energy metering in order to simplify measurement device as well as achieve necessary safety conditions.

Non-even sampling energy consumption measuring method

As known, AC active energy usually are defined as integral value of instant value p over 1/2T or area W1/2T (Fig.1a). Simultaneous readings of instant voltage and current values u, i allow to calculate instant power value p with the sampling rate of $1/\Delta t$ and energy w over time period Δt (Fig.1b). Sampling rate must be at least 4,2 KHz or 42 samples per 1/2T (EN 61000-3-2 [9], Nyquist frequency).

Sampling allow to substitute area W1/2T, representing energy during 1/2T, with sum of smaller areas (Fig.1c) (1), assuming that i, u are constant during Δt:

$$W_{1/2T} \approx \sum_{0}^{T/2} p\Delta t = \sum_{0}^{T/2} ui\Delta t, \qquad (1)$$

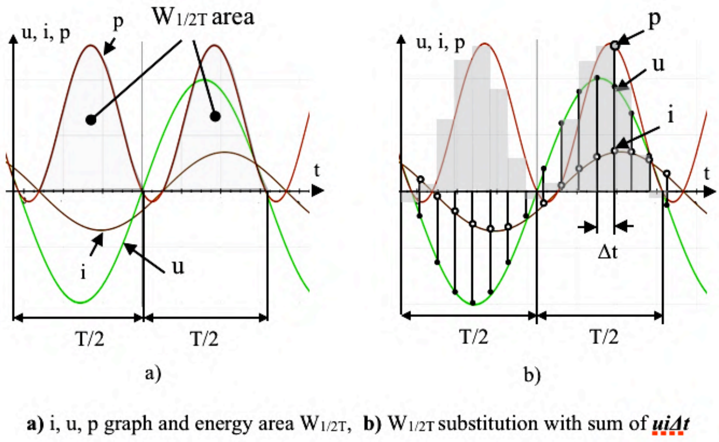

Fig.1. AC instant voltage **u**, current **i** and power **p** graphs and half-period active energy area $W_{1/2T}$

Described rectangle approximation are widely used today in electrical power/energy metering devices. The main design problem for known devices are electrical isolation to achieve necessary safety and input signal noise reduction.
Micro-controller ADC's work only with positive input voltage in range 0...+3,3V or 0...+5V, depending from micro-controller. So, DC component - a half of ADC reference voltage - must be added to the sensing signal. Typically this is done by adding resistor divider.
In oder to simplify electrical power/energy, different approach are proposed.
Here, instead of voltage readings via transformer, voltage divider etc., mains voltage are converted to frequency by voltage-to-frequency (U ➔ f) converter and output frequency are proportional to input voltage.
Voltage-frequency converter output signal (pulses) are transferred through isolating optocoupler and used as micro-controller's ADC strobe signal. Strobe signal frequency determine current sampling intervals Δt (Fig.2).

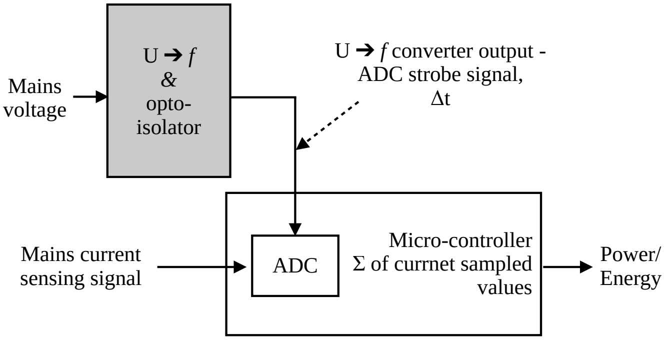

Fig.2. Power/Energy measurement block diagram, containing voltage - frequency converter

For sinusoidal voltage (mains) Δt changes also are sinusoidal as are shown on Fig. 3.

Voltage-frequency transfer ***K*** function (2) must be linear:

$$f_{osc} = K \times u, \quad \text{or} \quad \frac{1}{T_{osc}} = K \times u, \qquad (2)$$

In this case, as mentioned above, $T_{osc} = \Delta t$ thus expression (1) can be re-written, including (2):

$$W_{1/2T} \simeq \sum_{0}^{T/2} p\Delta t = \sum_{0}^{T/2} ui\Delta t = \sum_{0}^{T/2} \frac{1}{KT_{osc}} i\Delta t = \sum_{0}^{T} \frac{1}{K} i = \frac{1}{K} \sum_{0}^{T/2} i, \qquad (3)$$

According to expression (3), electrical energy during 1/2T or T are proportional to the sum of current samples over 1/2T or T accordingly, if sampling rate are modulated by applied voltage.

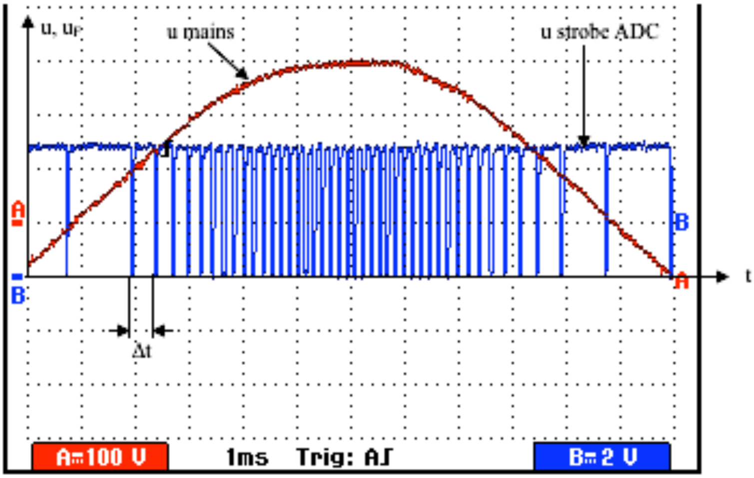

Fig.3. Voltage-frequency converter output signal **B** v.s. input voltage **A**.

Experimental devices and results

Several versions of the energy metering devices, based on described above method, was tested (Fig.4).

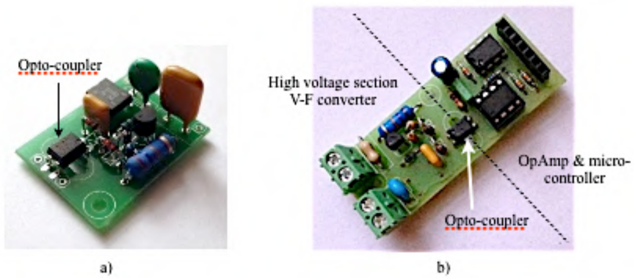

Fig.4. Energy metering devices prototypes: a) simple voltage-frequency converter module, b) with integrated voltage-frequency converter, current transformer operational amplifier and ATtiny85 micr-controller

The main difference between tested devices was applied micro-controller: 8-bit AVR micro-controllers, 16MHz clock ATmega328 or 8MHz clock ATtiny85 [10], or 32-bit 72 MHz clock STM32 ARM Cortex micro-controller [11]. Clock frequency determine ADC conversion speed, thus determine highest applicable output frequency for voltage-frequency converter. Mentioned is important only for ARM micro-controllers.

Triac based voltage regulator was applied as variable load. Typical load voltage and current waveforms are shown on Fig.5. Such triac phase regulation allow to regulate voltage on the resistive load, generate current harmonics as well as change power factor. In the same time, resulting current form cause errors when triac are OFF in case of low-cost current transformer [12].

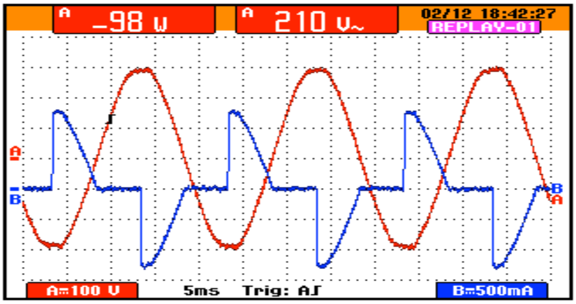

Fig.5. Mains voltage **A** and regulated resistive load current **B**

Metering module (for example - shown on Fig.4b.) direct output (sum of ADC readings) are shown on Fig.6. Each bar represent sum of current ADC readings, non-even sampled according to mains voltage value, over 1 sec.

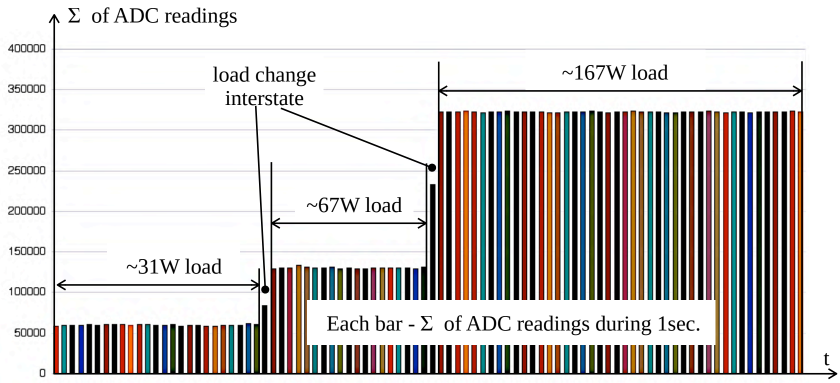

Fig.6. Metering module raw data (coefficient K aren't applied) output graph by 1sec.

Conclusion

Described method allow to create simple, effective and inexpensive electrical energy metering, monitoring and flow controlling / measuring devices for AC and DC consumers, energy sources and grids. Embedded in to micro-controller at least UART communication ports are ideal possibility for remote energy data readings. Communication with external data storage device (flash memory) or database software allow to create data logging system for one consumer / generator or synchronous data logging for several consumers / generators.

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Appendix 18

Avotins, A., Ribickis, L. Toward Intelligent Lighting Systems with Power LED. The 51st Annual International Scientific Conference of Riga Technical University RTUCON2010, Latvija, Riga, 13–14 October 2010.

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Section of
Power and Electrical Engineering

ABSTRACT BOOK
AND
ELECTRONIC PROCEEDINGS

RIGA, 2010

Rīgas Tehniskās universitātes
51. ikgadējā starptautiskā zinātniskā konference

Sekcija
Enerģētika un Elektrotehnika

KOPSAVILKUMU KRĀJUMS
UN
ELEKTRONISKIE MATERIĀLI

RĪGA, 2010

Ansis Avotins, Leonids Ribickis, Toward intelligent lighting systems with power LED

The European Union has approved the Action Plan in 2008, which anticipates to reduce the GHG emissions by 20%, reduce energy consumption (or improve energy efficiency) by 20% and obtain 20% of energy from renewable sources by year 2020, therefore in several documents of the European Union a special emphasis has been applied on energy efficiency and alternative energy sources, like it is offered in SmartGrid concept. The paper describes the existing lighting system and situation in Latvia and Riga, the possibilities of implementation EU energy policy in SmartGrid context, potential problems in the existing street lighting systems, existing standards, requirements and challenges for future development of new intelligent lighting systems with power LED luminaries. The paper gives an introduction to a number of challenges associated with intelligent lighting systems. Powerful LED has its own specific characteristics that differ from the existing high pressure sodium lamps, therefore a special power supply must be developed to get the maximum LED light output performance and efficiency, while ensuring the protection and proper management of lighting. The paper gives a brief description of intelligent luminary and control functions, and illustrates a number of power supply topology suitable for LED luminary. Since the intelligent lighting system consists of several sensors and local control units, the development of communication hardware between the control units, could be very problematic, due to various interference and noise reasons, so in future researches a special attention should be paid to the EMI performance, to reduce noise and evaluate impact on luminary IT hardware part.

Ansis Avotiņš, Leonīds Ribickis, Soli tuvāk inteliģentā apgaismojuma sistēmām ar jaudīgām LED

Kopš 2008. gada Eiropas Savienība ir akceptējusi Rīcības Plānu, kas paredz līdz 2020. gadam samazināt SEG emisijas par 20%, samazināt enerģijas patēriņu (vai uzlabot energoefektivitāti) par 20%, kā arī 20% enerģijas iegūt no atjaunojamiem energoresursiem, tādēļ vairākos Eiropas Savienības dokumentos īpašs uzsvars tiek likts uz energoefektivitāti un alternatīvo enerģijas avotu izmantošanu, līdzīgi, kā tas tiek piedāvāts SmartGrid (Viedais tīkls) koncepcijā.

Rakstā tiek aplūkota esošā apgaismojuma sistēmu situācija Latvijā un Rīgā, iespējas ES energoefektivitātes politikas īstenošanā, SmartGrid kontekstā, iespējamās problēmas esošajās ielu apgaismojuma sistēmās, esošās reglamentējošās normas, prasības un uzdevumi turpmākiem pētījumiem, lai izstrādātu jaunu inteliģentu apgaismojuma sistēmu ar gaismekļiem uz jaudīgo gaismas diožu (LED) bāzes.

Rakstā tiek izšķirtas vairākas problēmas, kas saistītas ar inteliģenta apgaismojuma sistēmu izstrādi. Jaudīgajām LED diodēm ir savi raksturīgie parametri, kas ir atšķirīgi no esošajām nātrija augstspiediena spuldzēm, līdz ar to ir jāizstrādā speciāls barošanas bloks, lai iegūtu maksimālo LED gaismas atdeves veiktspēju un efektivitāti, vienlaicīgi nodrošinot aizsardzību un pareizu apgaismojuma vadību. Rakstā tiek dots īss gudrā/inteliģentā gaismekļa un vadības funkciju apraksts, kā arī tiek aplūkotas vairākas LED gaismeklim derīgas barošanas bloka topoloģijas. Tā kā inteliģentā apgaismojuma sistēma sastāv no vairākiem sensoriem un lokāliem vadības blokiem, tad komunikācijas aparatūras izstrāde starp šiem vadības blokiem, var būt sarežģīta dažādu traucējumu un trokšņu dēļ, tādēļ turpmākajos pētījumos īpaša vērība ir jāpievērš EMI rādītājiem, lai tos samazinātu un jānovērtē to ietekme uz gaismekļa IT aparatūras daļu.

Ансис Авотиньш, Леонид Рыбицкий, Системы интеллектуального освещения будущего на основе мощных светодиодов

В 2008 году Европейский союз утвердил план действий, который к 2020 году предусматривает сокращение выбросов парниковых газов на 20%, сокращение потребления энергии (и повышение эффективность передачи) на 20%, а также выработку 20% энергии возобновляемыми источниками. По этой причине в ряде программ Европейского союза, особое внимание было уделено вопросам энергоэффективности и альтернативным источникам энергии так, как это предусмотрено концепцией «умных сетей» (SmartGrid). Статья описывает: существующие системы освещения и ситуацию с освещением в Латвии и Риге, возможности реализации стратегий ЕС в контексте «SmartGrid», потенциальные проблемы существующих систем уличного освещения, существующие нормы, требования и проблемы (задачи) дальнейшего развития новых интеллектуальных систем освещения с мощными светодиодными светильниками. В статье рассматриваются проблемы, связанные с интеллектуальными системами освещения. Физические основы мощных светодиодов отличаются от натриевых ламп высокого давления, поэтому для светодиодных светильников должны быть разработаны специальные блоки питания, чтобы добиться максимальной отдачи света светодиодов их КПД при одновременном обеспечении защиты и управления освещением. В статье описываются также интеллектуальные светильники и функции управления, а также даются топологии блоков питания подходящих для светодиодных светильников. Так как интеллектуальная система освещения состоит из нескольких датчиков и местных устройств управления, то разработка устройств коммуникации блоков управления, может быть проблематичным из-за различных помех и шумов, поэтому в будущих исследованиях особое внимание будет уделено электромагнитным помехам для их уменьшения и оценки воздействия на различные модули светильника.

Toward Intelligent Lighting Systems with Power LED

Ansis Avotins (*M.Sc.ing., Riga Technical University*), Leonids Ribickis (*professor, RTU*)

Abstract **– the given paper estimates requirements for development of intelligent lighting system, using power Light emitting diodes, power supplies, control method, different EU and local standards, communication technology in the context of EU energy efficiency policies and situation in Latvia.**

Keywords **– Light emitting diodes, intelligent networks, lighting.**

I. Introduction

As the lighting systems are meant to deliver comfort and safety, they are used in two type areas – buildings and street lighting. If some commercial buildings already have intelligent management systems, the most of the households and street lighting systems – doesn't.

European Union at year 2008 adopted an integrated energy and climate change limitation policies to be implemented by year 2020. With this policy is intended to develop the sustainable and energy efficient economy of the Europe with low carbon emissions, by implementing such events as greenhouse gas reduction by 20% (or 30% if according international agreement will be reached); energy consumption reduction by 20% (improving energy efficiency); 20% of EU energy obtain from renewable sources.

More than 40% of energy consumption in Europe is related to buildings (residential, public, commercial and industrial buildings) [2]. Energy Efficiency Action Plan predicted that the biggest cost-effective energy savings potential is found in residential buildings (around 27%) and commercial buildings sector (around 30%), therefore, a special emphasis on energy efficiency and need of integration of alternative energy sources, must be made [5], as it is introduced also in SmartGrid or intelligent power grid concept. The aim of article is to describe existing situation in Latvia, possible contribution of EU policy implementation, existing regulating norms that could be applied also for intelligent street lighting systems and tasks for further research.

A. Situation in Latvia

At the same time, load growth forecast for the housing sector shows that, due to raising the quality of life, households are becoming increasingly available to a wider range of household electrical appliances, thus contributing to the electrical load increases, actualizing the problem. For example, after A/S Latvenergo and Riga Energy Agency data, comparing the year 2007 with year 2003, the electrical energy consumption has increased by 11%. There can be defined some problems regarding to inefficient use of electrical energy in Latvia, for basic dwelling and commercial buildings sector.

Existing dwellings consume about 3 times more energy than it is prescribed in the current Latvian building regulations. Since the regulations were developed before households became available with wide range of electrical appliances, the classification of average consumption per device type has been changed. The Table I shows results of experimental measurements of average consumption of 7 people, 120m2 household per month. The results show that average consumption per month is 10,2 kWh/m2 (by older regulations 6 kWh/m2) or 174,6 kWh/person. The lighting system, which already includes incandescent, CFL and halogen luminaries, estimates just 7% of total consumption, where most consumption (~80%) gives incandescent and halogen lamps.

It can be concluded that one of the fundamental problems in electrical household is non-saving energy consumer. In order to solve this problem, the consumer must be informed about his possibilities to save energy, which could be reached by implementing smart metering systems with visualization on PC and intelligent real-time help guide.

TABLE I

Average energy consumption of the household per month.

Consuming devices	Average consumption, kwh/month	Average consumption, %
Heating system	341	29%
Kitchen household	331	29%
Lighting system	81	7%
PC and utilities	71,21	6%
TV and utilities	64,85	6%
Bathroom utilities	270	23%
Total:	1159,06	100%

If climate control devices mostly are equipped with regulating contour, then lighting devices has it very rare. This fact is related to certain current lighting technology problems - difficulties in regulating the light of gas-discharge lamps. Similar problem exists in street lighting systems, where energy saving potential is much higher than in households. Illustrating the lighting effects on the overall energy balance, it must be noted that in Riga city street lighting system is 44 thousand luminaries and costs for electricity are 1,9 million LVL (or 2,47 million EUR) per year [7].

The next problem as well in households and street lighting system is non-uniformity of load thus resulting phase asymmetry and overload of electricity infrastructure. The difference between the phase loads can differ even 5 times, and often result in voltage loss, heat-up of cable insulation and in lasting overload cases it endangers people. Asymmetrical phase load leveling with SMART GRID control systems, for single-phase part of the consumer by changing their feeding phase, would allow low-cost optimization of 0.4 kV city district section internal network loads [6]. It also would help to implement use of alternative energy sources - because their nature is not only irregular, but also less predictable.

All these problems clearly describes the need of SMART lighting systems, to achieve the EU energy efficiency policy, but these lighting systems are based on new dimming possibilities, given by new and uprising power LED technology. However they should be considered as a part of SMART GRID for the future integration in distributed network.

Also growing development of computer control and automation technology, shows that both existing electrical and lighting grids have reached their capabilities of performance, for the further development, they need real-time response, fewer outages and power quality disturbances, better use of existing capacity, enhancements that enable new power supplies, also from distributed energy sources [3],[4].

II. Requirements for LED

It is important to understand characteristics of LEDs in order to understand how to drive them properly. One of the LED characteristics is its colour, with very narrow band of wavelengths, which determines the voltage drop across the LED, while it is operating. The current level determines the light output level, the higher the current, the higher the luminosity of a LED, and also a temperature.

Due to production variations, a LED wavelength and thus also voltage drop has variations, typically ±10 %. As the temperature rises, the voltage drop reduces by ~2mV per degree. From the equivalent scheme of LED, where in series is ESR (equivalent series resistance), which means that voltage drop will increase the current. As the power LEDs are very expensive, for LED driver testing, appropriate Zenner diode can be used.

A constant current load needs a constant voltage source, but a LED, which is constant voltage load, needs a constant current source. In that case some voltage limiting arrangements should be considered, just in case of disconnections and short-circuits. A voltage monitoring, doesn't affect current level, and if the circuit failed to open, the voltage would rise to the limit of the open-circuit protection level, so it could be preferred failure detection method.

Since the LED brightness changes almost linearly with the current, the brightness of the LED can change drastically from small changes in voltage. Therefore, a much tighter control over the LED brightness is achieved if the driving circuit controls the current delivered to the LED as opposed to the voltage delivered across the LED.

For HB-LED (High bright) and UB-LED (Ultra bright) driving a simple linear regulator can be used, but in most cases a switching power supply with a constant current output is required. Linear driving is inefficient and generates too much heat, with a switching power supply, the main issues are EMI and efficiency, and costs. The problem is to produce a design that meets legal requirements and is efficient, with minimal costs.

Passive components and semiconductor devices can withstand high temperatures for long time period, but HB-LEDs are getting vulnerable. The experiment shows that LED luminary (~1,5W) with linear regulator has very high case temperature, if operated 6-8 hours without interruption, leading to LED damage after 360-400 working hours, where regulator is still intact. The same problem could occur if used in street lighting luminaries, as they work 5-9 hours without interruption.

High ambient temperatures inside the lamp can lead to LED driver failures, when an electrolytic capacitor is used in driver circuit, which eventually loses capacitance due to high temperatures.

III. Requirements for power supplies

A. Generally

It is very important to carefully choose the power supply converter type from the topology. It can give a major impact on the end product parameters and features, like brightness, EMI radiation levels, input/output voltages, currents, regulation possibilities, efficiency, power losses, temperature ratings, sensors, component selections and fault protections, communication, e.t.c.. The power supply topologies suitable for LED driving are shown in Fig.1.

B. Linear power supplies

Linear power supplies produce no EMI radiation that should be considered as advantage. Disadvantage is their low efficiency, when supply voltage is higher than LED voltage, in this case it could cause thermal problems and thus a need for bulky heatsink. If the difference between voltages is small, then linear regulator could have higher efficiency as switching regulator, especially when operated from low voltage DC power source, like photovoltaic. If operated from AC mains, linear regulator will have a large size, due to need of step-down transformer and smoothing capacitor, unless LED string voltage is near to peak AC voltage.

C. Switching power supplies

It is obvious, that for street lighting with SMART LED luminaries, its power supply should convert 220 AC mains voltage to the appropriate LED string DC voltage, ensure constant output current and enable dimming possibilities. Due to switching elements in circuits EMI must be limited by careful circuit design, screening and filtering. For LED driving a Buck circuit for AC input or flyback topology can be used. When using Buck topology, efficiency can reach 90-95%, when long string of LEDs is controlled. The output current of LED string should be:

$$I_{out} = \frac{V_{TH}}{R_{sense}} - \frac{1}{2}\Delta I_{out} \qquad (1)$$

Where V_{TH} is the current sense comparator threshold, R_{sense} the current sensing resistor and ΔI_{out} is output ripple current designed to be 20-30% of I_{out}. Conduction power loss in the MOSFET can be calculated as:

$$P_C = D I_{out}^2 R_{ON} \quad (2)$$

Where D is the duty ratio and R_{ON} is the ON resistance.

$$D = V_{out} / \eta V_{in} \quad (3)$$

When the input voltage could be lower or higher than output voltage, the buck-boost topology is necessary. It is often used in automotive applications, and can be used if powered by wind generator. The SEPIC and Cuk topologies are very common, they need over-voltage protection, but require minimal external filtering, due to shunt capacitors.

The fly-back topology also can reach 90% efficiency, but with PWM has limited dimming capabilities, due to storage capacitor [1].

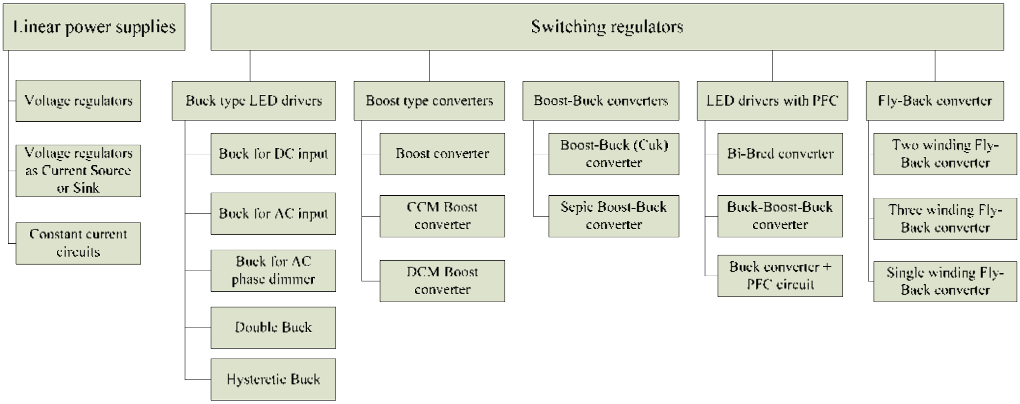

Fig. 1. Power supply topologies suitable for LED driving.

IV. STANDARDS

A. Lighting

Compliance of LED luminaries to lighting class is very important for municipalities which manage the city lighting system. For LED luminaries there is no special standard of their performance, a parameters and norms defined in existing standard EN 13201-2:2004, which include recommendations from CEN and CIE, can be applied to choose an appropriate LED luminary.

TABLE II

LIGHTING CLASS VS ROAD MAINTENANCE CLASS IN LATVIA

Average traffic intensity (cars per day)	Municipality roads	Lighting class
above 5000	A	M1, M2, M3
from 1000 to 5000	A1	M1, M2, M3
from 500 to 1000	B	M1, M2, M3
from 100 to 500	C	M2, M3, M4, M5
below 100	D	M4, M5

These standards are recommendations, some other standards or government rules can be mandatory in Latvia, like road maintenance class [8]. If, road maintenance class defined by traffic intensity, is used for choice of lighting class, then combining it with EN 13201-2:2004 classes, a Table II can be developed. Most of the small municipalities are able to measure an illuminance with lux meter, and chose appropriate values from Table III.

TABLE III

LIGHTING CLASS, MINIMAL LUMINANCE AND RECOMMENDED ILLUMINANCE OF ROAD CLASS

Lighting class	Minimal luminance, L_{min} (cd/m^2)	Minimal illuminance amount, E (lx)
M1	2,0	30
M2	1,5	20
M3	1,0	15
M4	0,75	10
M5	0,5	7,5

B. EMI and EMC

Any LED driver circuit using MOSFET switch connected to AC mains should meet the limited harmonic current emissions specified by standard IEC/EN 61000-3-2. Within this standard the Class C corresponds to the lighting. Harmonic emission limits are given in Table IV.

TABLE IV

SPECIFIED HARMONIC LIMITS UP TO 40TH HARMONIC

Harmonic order No	Maximum current, Class C (% of fundamental current)
2	2%
3	(30 x Power Factor)%
4 – 40 (even)	Not specified
5	10%
7	7%
9	5%
11-39 (odd)	3%

Conducted emission limits in the 150kHz to 30MHz frequency range are specified in the standard IEC/EN 61000-

6-3 (covers 20MHz to 1GHz). The emission levels to meet EN55022/CISPR22 Class B are 30dBµV/m in the frequency range 30MHz to 200MHz.

C. Communication standards

The ZigBee stack architecture, which is based on the standard Open Systems Interconnection (OSI) seven-layer model but defines only those layers relevant to achieving functionality in the intended market space. The IEEE 802.15.4-2003 standard defines the lower two layers: the physical (PHY) layer and the medium access control (MAC) sub-layer.

Companies developing products regarding to SMART GRID, mostly for communication purposes prefer to use ZigBee protocol, cause of its compatibility and possible integration with other protocols, like 802.15.4-2003.

V. CONTROL OF SMART LED LUMINARY

To develop smart LED luminary, the control unit must have access to lots of sensor and programming control inputs. Twilight switch or small photovoltaic could be used to obtain correct statistical data for switching lighting calendar method. Movement sensor should be used to measure traffic intensity during day-time, for central statistical agency, and as a control signal for LED luminary in night time, to improve dimming. Temperature sensor to measure readings during the day for central statistical agency and to switch on/off luminary to prevent it damage if temperature inside the case reaches critical value. Voltage and current sensor should be used to obtain power consumption, waveform and other electrical data. From energy reading data is possible to extrapolate how much LED are intact, and when they reach maintenance limits, the control unit can send signal about its state. The inputs from communication unit received from central remote management unit should include dimming ratio signal for different luminary classes (according to street class), as well as adjustment for on/off triggering by calendar plan. In cases with alternate energy sources like wind, or photovoltaic, a weather prediction from central unit could be possible, for energy usage calculations.

VI. EXPERIMENT WITH IRS2541 LED DRIVER

There are lots of manufacturers, who have lately produced a LED drivers also for power LEDS. IRS2541 (see Fig.2.) has been chosen as the first to be tested for development of 70W LED luminary (see Fig.3). Further tests are planned to improve EMI and EMC ratings.

VII. CONCLUSIONS

Still the main problem is to build efficient power supply and control system, which also in dimming stage preserve good efficiency, and has low EMI and EMC radiation levels. The further research tasks should focus on experimental evaluation of other power supply topologies and appropriate control hardware, to decrease emitted EMI values for laboratory prototype, and develop distant control hardware for power supply control via ZigBee protocol.

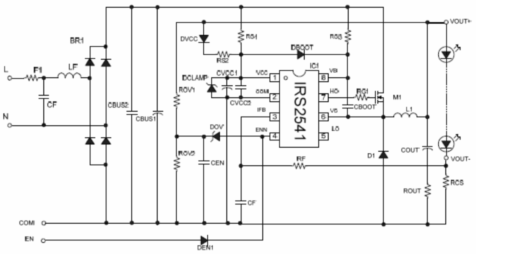

Fig.2. Electrical circuit of IRS2541 LED Driver.

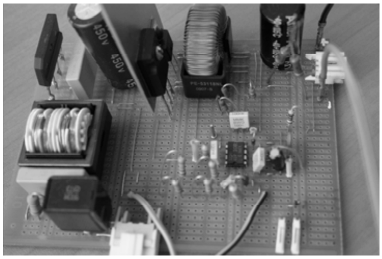

Fig.3. Laboratory experimental prototype for IRS2541 LED Driver.

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Appendix 19

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WIRELESSLY CONTROLLED LED LIGHTING SYSTEM

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ABSTRACT

Intelligent LED dimmer demand in lighting market is increasing due to energy saving potential, environment protection as well as great possibility of control and management of lighting systems. An internet web browser controlled LED lighting systems is developed and described in the article. The 1st is radio-wave and internet implementation between LED light source (lamp) and control point. The 2nd are ZigBee network and internet implementation. Special Hall effect based LED dimmer circuit is developed. FileMaker database implementation in the computer controlled electrical technologies still is rare.

Index Terms — LED lighting; LED dimming; ZigBee network; automatic control; ICT control.

1. INTRODUCTION

Nowadays a demand for more energy efficient devices also in lighting industry is increasing, as there is a great potential for energy savings and CO2 emission reduction to contribute to European Union (EU) Action Plan for energy efficiency, where EU in the year 2008 adopted an integrated energy and climate change limitation policies to be implemented by the year 2020. The street lighting system is a necessity for city traffic and citizen safety, and in most of the cases the lighting systems are as wide as the city street layout, therefore it has a lot of luminaries, consuming a significant amount of electrical energy.

Solid-state lighting still is a new technology for street lighting application and its main advantage is the ability to regulate light output within full range - from 0% to 100% with no photometric parameter changes, where conventional lighting with high intensity discharge (HID) lamps, could be regulated just from 50% to 100%, and can cause color shift and color rendering index (CRI), as well as significant drop of luminous efficiency (lm/W).

As a new technology LEDs still are in the development process, and the main obstacle for wider application of LED luminaries is the initial cost of LEDs, which tends to be much higher than HID sources. According to a DOE study, LED technology has been experiencing steady rates of improvement not only in efficiency (approximately 35% annually) but also in cost (approximately 20% annually). When looking at some economic aspects from engineering - economic analysis made in [2], which indicates that white solid-state lighting already has a lower levelized annual cost (LAC) than incandescent bulbs, and will be lower than that of the most efficient fluorescent bulbs by the end of this decade.

To compare different illumination technologies with different lifetimes by economical means, not only net present value should be compared, but rather LAC, which includes such parameters as initial capital investment, discount rate, years of lifetime and expected annualized cost of operation and maintenance.

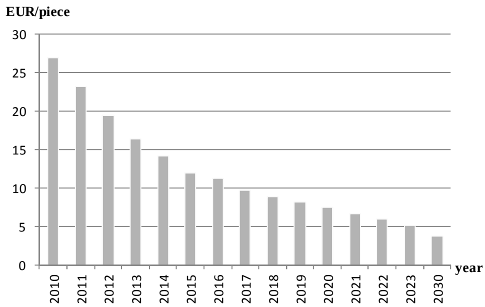

Fig. 1. Projected cost of 1000 lumen (60W equivalent) LED light fixture

According to Fig. 1, a significant price reduction could be achieved in near future for LED fixtures and this trend is proportional also for single LED chip [1], in meantime the luminous efficiency of the chip is also increasing. It indicates, that countries with limited budget should be careful by planning investment in retrofitting existing street lighting lanterns with high pressure sodium vapor (HPS) lamps to new solid-state lighting with light emitting diode (LED) technology, unless the retrofitting is technically and economically justified or subsidized with additional investments.

Currently the implementation of LED luminaries is not driven with green or clean energy thinking (except special government financial subsidies), but more with technical and economical aspects, therefore an investment price is a significant matter for retrofitting existing high-pressure sodium vapor lamps to more efficient LED luminaries. Therefore a street lighting system can be considered as non-saving energy consumer, as the investment payoff in saved energy mostly exceeds 15-20 years, compared to sodium vapor lamps. In order to solve this problem, the consumer must be informed about his possibilities to save energy, which could be reached by implementing smart lighting systems with decentralized control, individual lamp consumption metering, visualization on PC and intelligent software.

2. DESCRIPTION OF EXISTING SITUATION

One problem for 0.4 kV feeder (transformer) of street lighting system is non-uniformity of load thus resulting in phase asymmetry and overload of electricity infrastructure. The difference between the phase loads can achieve even 5 times, and often result in voltage loss and voltage drops at the end of long lighting lines, heat-up of cable insulation and in lasting overload cases lighting system failures. Asymmetrical phase load leveling with SMART GRID control systems, for single-phase part of the consumer by changing their feeding phase at the connection points (Fig.2.), would allow low-cost optimization of 0.4 kV city district section internal network loads [6]. It also would help in future to implement the use of alternative energy sources - because their nature is not only irregular, but also less predictable.

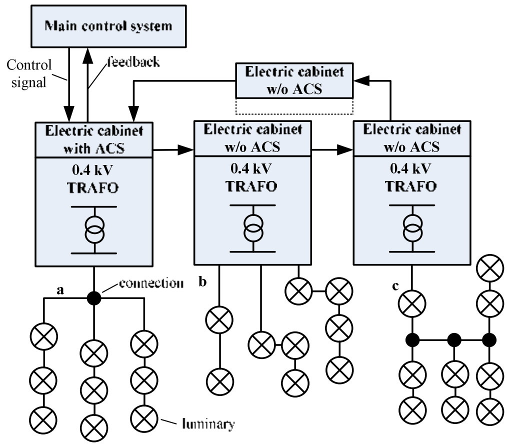

Fig.2. Loop based control system

Some cities still use lighting system with control method as shown in Fig.2, where Main Control System (MCS) is controlling one electric cabinet (trafo) equipped with Automated Control System (ACS) and current measurement devices, which then can give feedback signal, back to MCS through radio frequency communication signal (other cases use GSM or GPRS signal). Other cabinets are connected in series and turned on one-by-one with specific time relay. Such method can save money on ACS, but if some cabinet is without (w/o) ACS fails, then maintenance operators do not know which cabinet has to be repaired. This system is suitable for small cities with relatively low number of luminaries.

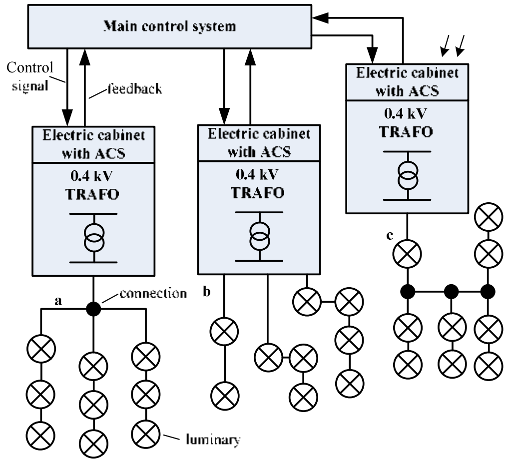

Fig.3. Automated control system

For the cities, like Riga, with significantly larger amount of lighting units, where 44 000 luminaries are installed, the control method shown in Fig.2 is not suitable, therefore each electric cabinet is equipped with ACS, with integrated photo sensor, on/off indication, burglar alarm, energy readings, a special voltage regulator (up to 30% high pressure sodium dimming) is also possible. As the connection point can have other point connected (see Fig.3-c) in parallel, thus the connection point cabinet is equipped with additional time relays, especially for large lighting lines.

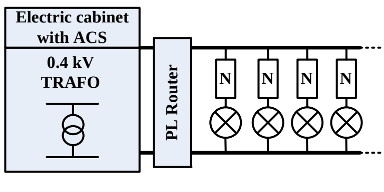

Figure 4. Power Line communication system

Automated control system shown in Fig.3 could also use Power Line communication devices – Router – which controls each luminary through N-Node, installed into luminary or luminary pole. Both Power Line devices are typically based on Echelon or Yitran integral circuits. The main challenge in Power Line implementation into street lighting control system is the inductive elements – like transformers or relays, as the signal cannot be transmitted through them.

3. PROPOSED SOLUTION

Recent advances in internet web browser, WiFi, ZigBee/XBee network, communication tool and web scripting language (HTML) development, open new opportunities for LED lightning control systems. At the same time consumers still are looking for less expensive and more efficient solutions. Street lighting luminaries with high power LED light sources still are expensive and financially not attractive, thus a power supply with “dimming” capability is a sustainable solution.

LEDs are powered from special power devices - LED drivers, which can regulate current in different ways [3]-[5]. Different Integrated Circuit manufacturer application notes for LED drivers are already known, for example [6], where mainly voltage step down (buck) or step up (boost) or combination of both topologies is used. Advanced topologies for LED current control increases a LED driver price, where only one chip costs 8-10 EUR [7]. Combined with additional external elements, total price of a driver is high enough for wider application in LED street lighting luminaries or luminaries for auditoriums.

Therefore a simple Hall Effect based current sensing-regulating driver is proposed for the use in conjunction with ZigBee or radio wave network control. LED luminary light output intensity, as well as monitoring of each luminary/light source power consumption, efficiency and fault detection is measured and analyzed by means of FileMaker Pro based database. Lighting systems each LED luminary is connected to the main control point via ZigBee or radio-wave connection (for indoor application a WiFi internet and ZigBee). Electric cabinet has a ZigBee main access point, which can also publish information over public internet.

System is based on well known electronic modules, ICs and software: Atmel microcontrollers, Arduino family boards, FileMaker database software, Apple ICT, C programming language, FileMaker scripts and AppleScripts etc.

3.1. LED dimmer

LED dimmer is based on Continuous-Time Linear Hall Effect Sensor IC A1301. Sensor provides a voltage output that is proportional to an applied magnetic field: output value is ~2,5V for magnetic field zero value.

Comparator compares sensor output voltage VS (Fig.5.) and 8-bit digital-analog converter (DAC) output voltage VDAC and control transistor switch. Switch load includes LED array and inductance. Magnetic field in inductance determines Hall sensor output voltage. Switch is ON if VS is lower than VDAC and current of the load increases until VS is higher than VDAC, then switch turns OFF. IC allows digitally set average LED current (48-50V power supply voltage) by changing 8-bit DAC input value. Current value is controlled between 0 and 1,25A by 50-60mA steps.

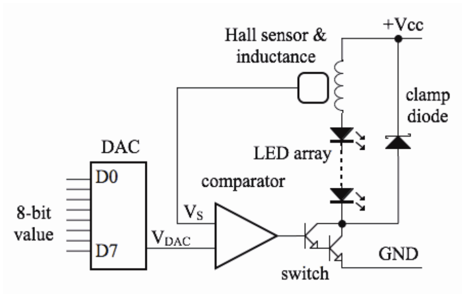

Fig.5. Schematics of LED driver circuit

Inductor and Hall Effect sensor is combined into one element (Fig.6). Small air gap is applied to avoid core saturation under DC current through the coil. Magnetic hysteresis of the inductance core must be taken into account.

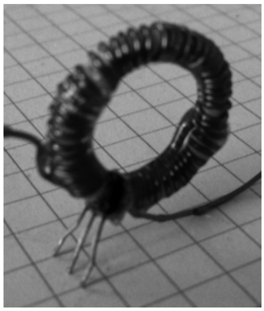

Fig.6. Inductor and Hall Effect sensor

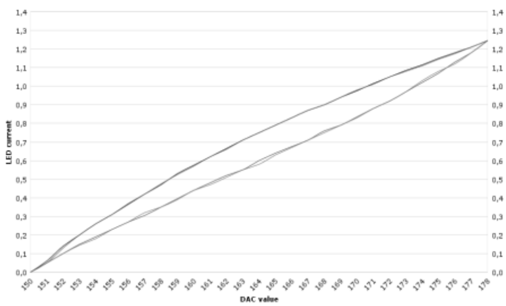

Fig.7. LED current vs DAC output value of developed Hall Sensor

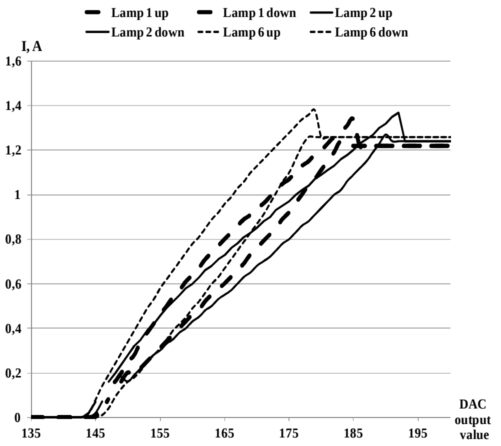

Fig.8. DAC output value of various LED Lamps

Arranged from 56 1W LEDs, a 60W LED luminary consumes 1,25A from 48V DC source. Here overall LED circuit inductance must be about 1mH. Necessary inductance is achieved via connecting additional inductance into the circuit.

In this example 28 illumination steps from zero to maximum allow to change illumination smoothly enough for human eye. Due to the effective and smooth current regulation there is no stroboscopic effect (light blinking), usually caused by simple PWM.

Digitally set output or LED current value stability is approximately +/-0,5 % (+/-6mA).

3.2. Network structure

The main (but not the only) elements of the system are:

- web-server (the well known Apache web-server);
- FileMakerPro database with enabled Instant Web Publishing engine. FileMaker stores information, perform calculations, activates commands to drives, displays readings;
- separate LED driver for each LED lamp (luminary);
- bi-directional ZigBee module for each LED luminary;
- ZigBee router for each system branch. In this example router is located near to computer;
- Atmega328 microcontroller based Arduino board as interface between ZigBee network and Apple OS X based Filemaker Pro 11 and Apache web server.
- GSM module for SMS information to administrator in case of fault.

Several network structures can be implemented.

The simplest are radio-wave link to send commands to LED lamps to change illumination (Fig.9.). The solution is similar to that described in [8]. LED luminary light output level is changed by sending 6-bit code over 415 MHz radio-links. 6-bit code is received from Arduino board and compiled by SC 2262 IC. The received code is decoded by SC2262-L6 IC and directly controls LED driver DAC. 6-bit application is possible because most significant bits D7 and D6 constantly are digital 1 and 0 during full scale dimming.

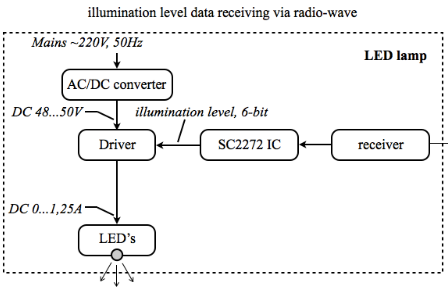

Fig.9. Radio wave link as control signal

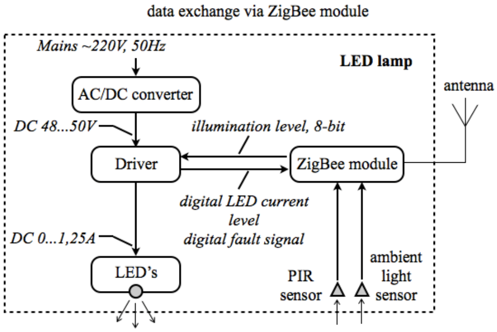

Fig.10. ZigBee PAN Network structure

ZigBee PAN (Personal Area Network) based and locally controlled network structure are shown in Fig.10.

Typically ZigBee PAN allows 16-bit addressing so practically LED lamp count is not limited. ZigBee network provides bi-directional data flow: the commands are sent to lamp driver DAC and measurements as well as fault signals are sent back to the main point, containing Arduino board, OS X driven Apple computer. Bi-directional data flow is controlled via FilMaker Pro 11 software based application.

PAN area based but controlled over internet network structure is shown in Fig.11. Main difference between the described above networks is Arduino Internet board application for sending data from ZigBee network to the main point over the internet.

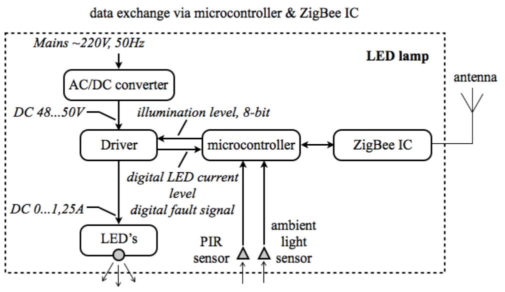

Fig.11. Internet and ZigBee PAN control network

3.3. Criteria for equipment, devices and software

LED light lamps control must be turned on and accessible 24 hours per day and, possibly, all the year. This requires carefully selected and matched hardware and software components of the system. Described LED lightning system employs:

- A stable and secure computer/server UNIX based operating system - Apple OSX10.6;
- FileMaker Pro11 database software. Beside database functionality, it comprises well developed command, script and calculation level as well as instant web publishing option.
- Since the control equipment (not LED's) is turned on all the time, low energy consumption is crucial. Apple Mac Mini computer running OSX 10.6 consumes less than 13W in idle mode.
- Arduino platform (Atmega 328 based Arduino Uno board) is one of the best options on the market.

3.4. Experimental tests and results

ZigBee controlled LED Dimmer circuit was tested with typical industry manufactured LED luminary power supply and the original LED layout. The efficiency of original LED luminary power supply is only 86% at full load.

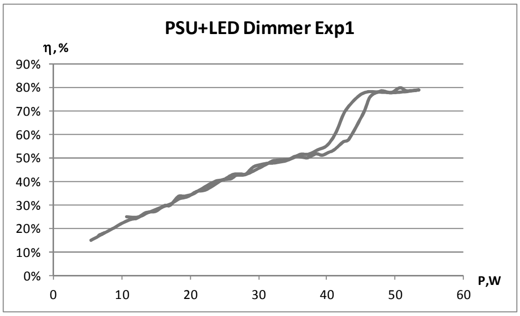

Fig.12. Efficiency of LED power supply with Dimmer

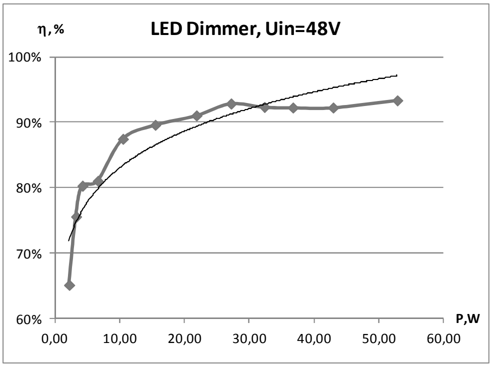

Fig.13. Efficiency of LED Dimmer

4. CONCLUSIONS

The low efficiency of industrial power supply influences the total efficiency of the LED luminary, decreasing it to 80% (Fig.12), also LED Dimmer shows a good efficiency – 96% therefore a new design for PSU is needed.

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Appendix 20

Avotins, A., Suzdaļenko, A., Galkins, I. A Project-Based Learning Approach to Improve Quality of Power Electronic Courses. 2013 7th IEEE International Conference on e-Learning in Industrial Electronics (ICELIE 2013), Austria, Vienna, 10–13 November 2013.

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A Project-Based Learning Approach to Improve Quality of Power Electronic Courses

Methodologies and processes for education

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***Abstract*—This papers describes practical implementation of instructional design methodology, by means of practical workshops, for such industrial engineering study courses, like computer control and power electronics. RTDI development serves as improvement of FPGA workshop, which has increased quality of teaching methods and student satisfaction.**

***Keywords*—power electronics; FPGA; e-learning; teaching methods; instructional design.**

I. Introduction

Energy efficiency nowadays is one of the topical issues in different areas, thus a demand for the enabling technologies and qualified engineers with appropriate knowledge and practical skills, is increasing. Power electronics have wide application in home appliances, indoor and outdoor lighting fixtures and their controls (dimmers), smart grid, smart meters, automation and process controls, robotics, electrical cars, GHG friendly energy production and conversion, etc., with different technical specifications and challenges. Thus it is already uneasy task to prepare qualified engineer in power electronics, covering all those application fields, in mean time facing the problem that it is hard to attract young students, as engineering education is typically a “hard work” and not easy to understand without proper knowledge and basic practical skill background.

As the future trend, in context with smart grids and more advanced power electronic controls, is to integrate Information and Communication Technologies (ICT’s) in power electronics controls, it becomes even more complicated for education, so the teaching methods and courses should be revised or even study curricula should be restructured accordingly. Also microcontroller and microprocessor latest developments in integrated circuit industry and availability (in respect to low costs) of products like Arduino boards, MSP430 LaunchPads, with extensive free libraries and projects, during the latest years enable new teaching methods and approaches, or carry out even more complex control algorithms for additional functions.

In meantime also different processors, for example AVR architecture based Cortex for FPGAs, different products of CPLDs etc, have evolved from 1995, both in speed and bit operations as well as other technical parameters and additional capabilities. Similarly also programming languages are changing, and new are emerging and some of them become more and more popular among engineers, for example light-weight scripting language – Squirell, which is object-oriented programming language, became public in 2003 and in November 2010, the license was changed to free software license.

Therefore students and engineers in industry have to implement lots of time and learning in order to satisfy new demands, but universities have to reorganize their education system or methods, which raise many practical problems and challenges that need to be solved, and they can be different depending on country or university.

To reorganize traditional study process methods [1]-[3] where each course has its plan with lectures and practical works (either calculations or laboratory works), in order to implement methods and tools like e-learning, virtual LABs, problem based learning and application of instructional design theories, several study courses must be analyzed and areas of interaction must be found using available resources and keep expenditures for education on an acceptable level.

In this article, a problems and challenges are analyzed, that are common to Riga Technical University (RTU) bachelor and master study program in “Computerized Control of Electrical Technologies” (CCET) focusing on possible reorganization of subjects related to computer control.

II. Study Course Overview

RTU bachelor, master and doctoral study program CCET is thought by Institute of Industrial Electronics and Electrical Engineering (IIEE). Academic studies are organized according to Bologna declaration, using common system of European higher education – a three-year bachelor study, followed by a two-year master study (known as 3 + 2 year study). Study course structure is modular and is based on the common credit point (CP) system and European credit point transfer system (ECTS), which allows accept evaluation grades for students learning subjects within ERASMUS exchange program.

If speaking about the needed skills and knowledge of graduates, then there always will be different point of view for industry and research institutions. Industry typically demands graduates with certain practical skills and design abilities, more close to technology application in order to solve different automation problems in industry or new product development.

The research institutions need graduates that have deeper and wider knowledge about the theoretical aspects of the field and problems, as well as ability to carry out research and development (Fig.1.) for new technology development, as well as write scientific papers and attract funding from industry as well. Therefore it is important for research institution to carry out study program in order to get qualified researchers in future, in meantime also fulfilling the needs of industry.

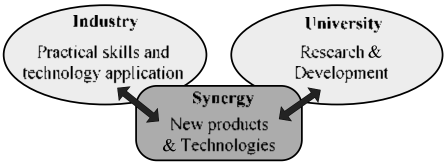

Fig. 1. Demanded skills of graduates.

If looking from student point of view, they have interest to finish their studies faster and get their first job in industry, the 3+2 year studies therefore is attractive for them, but in those 3 years they have full-time learning and therefore they lack practical and work experience.

In year 2004 IIEE set-up a "professional bachelor study program", where (3+1) years they spend to do the classes as academic bachelors, and in additional +1year they do praxis and engineering work, after successful completion, they have possibility to finish their master studies in 1 year, so they still finish their 3+2 year studies according to Bologna principles. These studies became very popular among students and now 90% of bachelor students choose learning at professional studies rather than in academic profile. Higher education system in Latvia still allows realization of both academic and practical study programs, that confuses foreign experts when evaluating the study program, but in meantime both the students and industry appreciates the results, also these graduates can continue their PhD studies and, due to their practical skills, typically make good contribution in industry or science related projects done in RTU.

The professional bachelor study program totally has 240 ECTS credit points (CP), where 30 CP are general study courses, 54 CP are industry and IT related courses, 60CP are industry specialization courses, 30 CP for specific specialty courses, 9 CP for free student choice courses, 39 CP for industry praxis (last 3 semesters) and 18 CP for development of bachelor thesis with project part which includes engineering calculations and drawings. Within transition program students have praxis and development of engineer work (like practical part of professional bachelor thesis).

III. Problems and Solutions

As the professional bachelor study program is being realized several years, and it includes also mandatory praxis at industrial companies, it is possible to obtain evaluative feedback not only from students or teaching personnel, but also from industry engineers and company managers. Thus gathering all information, several problems can be identified that are related to:

- Insufficient budget
- Personnel overload
- Education level of secondary school graduates
- Teaching methods applied

Some years ago, also other problems were topical, like access to new literature and digital on-line libraries, modern laboratory equipment and technology, but due to attracted funding from European projects and Industrial research projects, this could be solved to provide education close to average European level.

A. Insufficient budget

In the field of Electrical Engineering, it is hard to attract students, and in Latvia it could be a big problem if student should pay full price for his studies there, therefore government is giving budget paid places, but in mean time demands to deliver minimum quantity of graduates per year, and in case of CCET bachelor study program it is 50 per year. The money amount allocated by Latvian government for education is one of the lowest in Europe, and due to the global economical crisis, CCET suffered around 50-70% decrease within latest years. Different activities like internal self-evaluating, modernization of infrastructure and courses, experience exchange, invited lecturers from abroad, financing of student practical development projects, stipendiums has been minimized.

To solve this problem it is needed to attract additional funding, which can be done by attracting additional students that pay full price, for example foreign students, another way is to attract more industry funded research projects, or even small engineering projects for students from SME. Also modular type courses or special workshops for students and industry specialists can serve as additional income and contribute to long-life-learning concept. Therefore different public relation activities must be carried out and new teaching methods implemented.

B. Personnel overload

The teaching personnel is the key element for quality education and their salary is determining the quality and skill of personnel or whether it is working in one or more research projects, thus getting overloaded, and discontinuing course improvements, due to lack of time, and also less time available for student consulting.

An appropriate balance between hours spent for teaching and research projects, must be determined, as research is the key that enables for teaching personnel to be up-to-date in the field. Another possibility is to attract help from the students, for example PhD students can help to lead courses for Master students or Bachelor students, and Master students can help with laboratory works for Bachelor students, if properly prepared for this task. This approach is already tested and works fine, if used time to time only. Also it gives possibility to look at those tasks from other point of view, thus giving additional feedback and possible improvements.

C. Education level of secondary school graduates

An overall problem in Latvia is the education level of the secondary school graduates that enroll at university. Their knowledge background is different as they come from different parts of country, where in case of CCET they lack basic understandings of electricity, programming, electronics and typically some practical skills, like soldering or even simple mechanical tasks.

To improve these skills and knowledge, without overloading teaching personnel, e-learning tools and instructional design methods can be applied, in order to stimulate students do more practical work after the course classes. Older course students can become free-willed mentors for younger class students, thus helping to transfer the knowledge, working in team and solving real practical tasks. Currently it is done by means of Student Lab, which is equipped with materials and tools, and every student can get access to it and do their own projects, for example from “youtube.com” or “instructables.com”, or some easy projects developed by teaching personnel.

D. Teaching methods applied

For the academic branch studies, lectures are presented by using MS Power-Point, at the same time teachers always give out handouts or share materials electronically in RTU MOODLE e-learning platform, preventing students to write down bulky information, like block diagrams, tables or schematics. This approach helps to save time, but as a result the "repetition" phase is skipped and not well remembered, which must be complied within interesting home works or practical tasks. Some of the courses have some hours for laboratory works that mainly use predetermined instructional guidelines for given task. The main problem is that those tasks are very specific to the course, and when student needs to interlink that knowledge from different courses, he typically fails, as he didn’t understands why he was doing the LAB works, and where this knowledge is applied in real life problems. Thus Problem Based Learning (or Project-Based Learning) can greatly contribute to solve this problem.

Several universities are changing their teaching methods, giving more focus on practical skill improvement. The PBL is already implemented in different universities of engineering field, for different courses. The Project-Based Learning is also very common term, and sometimes it is hard to draw a strict line between Project or Problem based learning, as in case of application in engineering studies, as the goals and results are the same, where Problem can be more of virtual nature, but the Project is something more of practical nature.

The latest results of University of Oviedo (Spain) [4], where they implied PBL in Power supply course, reveal that experience is positive and students are more motivated, as they deal with real problems and projects. Experience of the University Carlos III (Spain) [5] also reveals that traditional methods: lectures + some laboratory sessions leave some basic knowledge gap. Implementation of PBL method in their course “Wind energy conversion systems for electricity generation”, where both virtual (Matlab) and real setups were used for teaching, also showed improvements in grades regarding the traditional method. Also Electronic Engineering Department at Myongi University (Korea) [6] redesigned its Microprocessor course and implemented PBL method. In the result students were motivated to participate more actively and spend more time on their learning activities, thus highly increasing their understanding and ability to implement gained knowledge and practical skills. A Project-Based Learning has been also applied to Programmable Logic Design course in University of Newcastle (Australia) [7], where as the result this uneasy PLD course is one of the best evaluated courses in this university, and greatly has helped for students to understand digital logic and computer architecture.

For the first year course students the problems they should solve in their free time, should be kept as simple as possible, so in case of success they can feel, the pride and emotions, that goal is achieved, and thus step-by-step the difficulty of the projects should be increased. To evaluate the steps of the difficulty, the student feedback is needed, and then students can be given a very interesting and attractive special tasks, for example “Electromagnetic levitation of a Disc” [8], where they will need to learn how to search literature or scientific publications in databases.

Another such example is described in [9], where PID regulator has been adapted to control DC motor current of an electric cart in order to stabilize motor torque and monitor motor current to protect power converter from dangerous current overshoots. If students work in team, they even succeed to develop such electric-cart and their stimulus is to drive and test it in the field, where starts the fun.

In case of [10] a passive cell balancing for electric vehicle battery pack is realized using MSP430G2153, practically applying the obtained knowledge from course Digital Electronics. Also speech recognition system to control electrical technologies, described in [11] can be interesting project, (http://www.youtube.com/watch?v=Blgff14e_Fk).

Practically oriented workshops can be implemented also into a study process. Formerly they were organized as 4-6 day company pre-paid special courses, to improve knowledge and skills of their employees. Such approach can be used also for teaching students after the course classes, where only costs are for the hardware and materials, if lecturer – volunteer and free time gap is found for both sides. For example workshops of [11],[12] have implementation of e-learning tools, where practical solutions must be carried out, and specific knowledge and practical skills about communications, sensors and power electronics is obtained.

Utilization of modern and promising technologies attracts students, especially when these technologies are presented during practical exercises. A special workshop "LED dimmer as versatile hardware platform for practical exercises in power electronics and control courses" [13] was created to interlink different courses with the proposed task with utilization of LED related equipment is possible to enable that. As the student groups sometimes can be very large for one lecturer, a cost-effective approach with implementing new methods of e-learning for tasks possible to be done also at home or work, or even contribute to life-long learning.

Project based workshop on LED dimmer control with FPGA development kit [14], is aimed to increase practical skills for engineering students of RTU study program CCET. Workshop consists of lectures and various laboratory works, which implements widely used industry tasks as examples, like indication with 7 segment display, serial communication, and specific timer module for PWM generation and proportional regulator for power converter control. Laboratory works improve students' design and practical skills as well as decrease the time spent on solving such simple tasks. Those skills are well received from industrial companies when students do their practice during the Bachelor study course.

IV. Improvements of Workshop

This section describes an improvement proposal to workshop [14], a real-time debugging interface (RTDI) for FPGA boards implemented by means of Piccolo LaunchPad and integrated analysing tools of Code Composer Studio IDE that allow to monitoring or and changing internal FPGA parameters in real-time. Three topologies of RTDI are described identifying fields of suitable applications.

A. Description Of Hardware

The proposed idea of RTDI was implemented by means of Piccolo Launchpad. It is the development board available from Texas Instruments based on C2000 series digital signal controller. It has powerful peripheral devices on board with SPI module among others, which is considered for communication with FPGA board. Another advantage of the Piccolo LaunchPad is that it has built in XDS100v2 USB emulator with fully isolated digital interface between DSC and programmer that eliminates the need for additional safety devices.

The main criteria for choosing this type of DSC however was the real-time debugging module that allows monitoring the internal parameters and variables from Code Composer Studio (CCS) without pausing the application firmware of DSC. It is realized as low priority interrupt, that is held in DSC to communicate with the integrated development environment (IDE) for data exchange with certain refresh rate (>100 ms). The monitored data is viewed through the watch list, or in case of big data arrays, analyzing tools that are integrated into CCS: graphs, FFT analyzers etc.

The FPGA board has Cyclone III chip (EP3C5E144C8N) on board, as well as 125 MHz clock, 8 channel analog to digital converter (ADC - MCP3008) and 8 DIP switches for choosing pin's analog or digital function. The layout is pin-to-pin compatible with TI's Piccolo LaunchPad, enabling stacked-connection of boards suitable for any application.

B. RTDI interface

As it was described before the RTDI is realized by means of Piccolo LaunchPad and Code Composer Studio that enables real-time monitoring of DSC. Thus, the SPI interface has to be implemented between FPGA board and Piccolo controller, enabling bidirectional data exchange for internal parameter and variable monitoring via CCS.

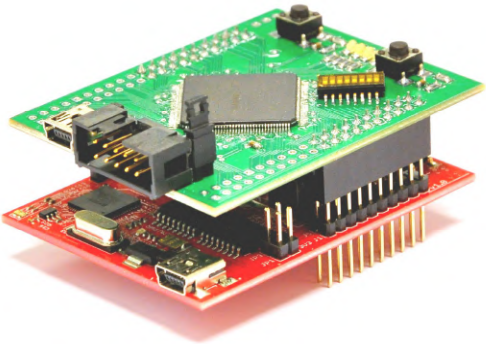

Fig. 2. Stacked connection of FPGA and Piccolo LaunchPad boards.

Three RTDI topologies are considered for implementation in Quartus software: centralized RTDI; multiplexed slave select signal and global RTDI interface.

<u>Central RTDI</u>

The central RTDI module is realized in single block, to which all monitored parameters should be connected. It communicates to the Piccolo via realized SPI interface as a slave. The outputs of the RTDI block could be connected directly to input or output terminals operating with bits of information, or it could be bytes or words of data defining or reading parameters from other blocks (divider for prescaler, threshold value for PWM, etc).

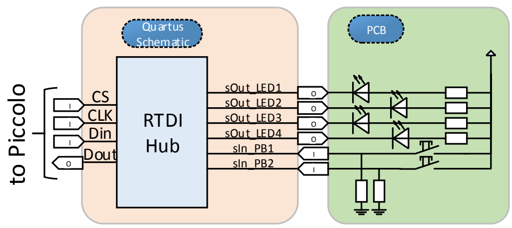

Fig. 3. Quartus block scheme for central RTDI.

<u>Multiplexed Slave Select signal</u>

The multiplexed SS signal RTDI is implemented with two types of blocks – RTDI SS multiplexor and RTDI parameters' block. The multiplexor analyses the header of data frame, where the index of RTDI parameter block is been transmitted, selects the required module by activating certain SS output and then operates as transparent bridge, transmitting CLK, Din and Dout signals.

TABLE I. DETAILS OF SPI PROTOCOL FOR CENTRAL RTDI

Din/Dout	Bit num.	Name	Function
Din	1	R/W	0 – read, 1 – write
	2-7	Ind	0-63 – parameter index
	9-16	Data	0-255 – data, if write operation requested
Dout	8	Err	Erroneous combination of R/W and Ind bits on Din
	9-16	Data	0-255 – data, if read operation requested

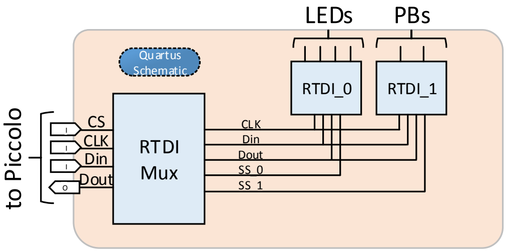

Fig. 4. Quartus block scheme for multiplexed RTDI.

The SPI protocol is a bit different, as it now requires index of parameters' block to be at the beginning of the frame. The following bit defines read/write operation and rest 4 bits of the first control byte select the parameter. The length of data field is variable (byte word, double word) as each separate RTDI parameters' blocks can have different length of data bits.

TABLE II. DETAILS OF SPI PROTOCOL FOR RTDI WITH MULTIPLEXED SS SIGNALS

Din/Dout	Bit num.	Name	Function
Din	1-2	B_Ind	0-3 –block index
	3	R/W	0 – read, 1 – write
	4-7[a]	P_Ind	0-15 – parameter index
	9-16[a]	Data	0-255 – data, if write operation requested
Dout	8	Err	Erroneous combination of R/W and P_Ind bits on Din
	9-16[a]	Data	0-255 – data, if read operation requested

a. extendable length of field for different blocks

Global RTDI

The global RTDI is implemented as separate parameters' blocks connected to single SPI bus. The data transmission protocol should have common header for the data frame to identify the active RTDI parameters' block, as SS signal activates all blocks simultaneously and do not functioning as in classical SPI interface. The data transmission from FPGA to Piccolo is configured as bidirectional pins transmitting only high level signals, but zeros are formed with tri-state input with weak pull-down resistor. This precaution measures are intended to avoid short-circuit conditions, in case if two blocks are transmitting data with different polarities. Additional arbitrage function can be implemented in all blocks by monitoring the Dout signal during zero transmission period (which is considered as tri-state input with weak pull-down). Thus, if high level is sensed during rising edge of clock signal, then error flag is raised (which is transmitted between all blocks connected in daisy chains) terminating the transmission. Additional block with zero address can be used to identify arbitrage conditions.

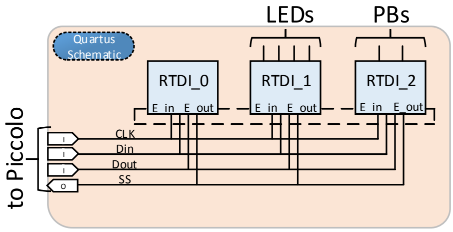

Fig. 5. Quartus block scheme for global RTDI

The SPI protocol implemented here is similar to previous case, when different parameters' blocks can have different lengths of fields, considering only common headers of data frame that helps to activate only one block in a transaction period.

V. SURVEY EVALUATION

To provide feedback to presenter, evaluate quality of course materials, and understand possible improvements to meet life-long-learning requirements, a long term evaluation is needed. For this purpose a questionnaire of three parts (A, B, C) was made, for the workshop [14].

For long term evaluation Part A collects information about participant, like gender, age, grade level (see Fig.6.) and general knowledge background, similar to [13]. Part B of survey collects information about specific knowledge background, covered by this workshop, asking participants to evaluate given statements using 5-point Likert scale (1 - strongly disagree, 2 – disagree, 3 – neither, 4 - agree , 5 - strongly agree). Survey parts A and B are filled before the workshop.

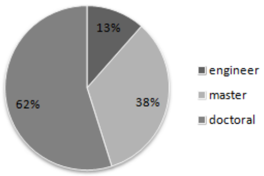

Fig. 6. FPGA Workshop participant education grade.

Part C consists from 12 statements and is supposed evaluate after four day workshop (see example in Table 3.).

TABLE III. WORKSHOP QUALITY EVALUATION RESULTS.

C	Survey about workshop	Mean	STDEVP	VARp%
C.1.	The real content of the workshop met my expectations	4,13	0,60	15%
C.2.	Training staff covered all topics of the program and available time was spent efficiently	4,13	0,78	19%
C.3.	Topics of workshop were good structured and well understood	4,13	0,60	15%
C.4.	Teaching method of the workshop was interesting and exciting	4,25	0,43	10%
C.5.	Topics covered by workshop I already learned previously	2,63	0,99	38%
C.6.	Topics covered by workshop I understood best from:			
A	*Presentation and lectures*	4,00	0,71	18%
B	*Course materials*	3,67	0,47	13%
C	*Practical experiments*	3,88	1,05	27%
C.11	It was difficult for me to understand and realize workshops practical tasks			
A	*Practice 1A: Decoder for 7 segment LED matrix*	2,14	1,36	63%
B	*Practice 1B: Dynamic Display Controller*	2,14	0,99	46%
C	*Practice 2A: Interfacing ADC MCP3004*	2,29	1,03	45%
D	*Practice 2B: Single Channel PWM*	2,00	0,53	27%
E	*Practice 3A: Open Loop SEPIC System with Multiple-channel shifted PWM*	2,75	0,97	35%
F	*Practice 3B: Closed Loop SEPIC System*	2,43	0,90	37%
G	*Practice 4: Basics of Embedded Processors (NIOS II)*	2,50	0,76	31%
C.12	Survey statements and questions were clear and understandable	4,57	0,49	11%

VI. CONCLUSIONS

The FPGA chips become popular in control applications due to flexibility and computational potential of the PLD. However the debugging tools are limited with only simulation of the VHDL code. This however is insufficient in real-time applications, when internal coefficients of the program code should be adjusted. Additional user interface (visualization, buttons) can be used to monitor internal parameters, however it makes the system bulky. Thus, the article proposes an idea of using Piccolo LaunchPad and Code Composer Studio’s integrated analyzing tools to implement RTDI by using only SPI communication between FPGA and Piccolo boards. The central topology of RTDI is suitable for simple applications, controlling a few parameters or input/output bits. The RTDI with multiplexed SS signal is applied for bigger amount of transmitted data, as it allows using different length of fields for different parameters’ modules. The global RTDI is also flexible as it allows connecting several of parameters’ modules operated at different protocols (common packet headers are required helping to activate only one RTDI block), however the arbitrage function should be implemented helping to identifying collisions on the common Dout line.

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Appendix 21

Avotins, A., Ribickis, L. Analysis of GHG Reduction Possibilities in Latvia by Implementing LED Street Lighting Technologies. Civil Engineering '11: 3rd International Scientific Conference: Proceedings, Latvia, Jelgava, 12–13 May 2011. Jelgava: LLU, 2011, pp. 209–214.

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CONTENT

IV ENGINEERING OF ENVIRONMENTAL ENERGY

ANALYSIS OF GHG REDUCTION POSSIBILITIES IN LATVIA BY IMPLEMENTING LED STREET LIGHTING TECHNOLOGIES

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ABSTRACT

This manuscript deals with the EU policy in energy efficiency and CO2 emission reduction from the perspective of possible improvements in Latvia street lighting system. The paper also shows the results of examination of the existing situation, estimation of further street lighting development possibilities, and experimental measurements in real conditions.

Key words: street lighting, GHG emissions, solid-state lighting, energy efficiency

INTRODUCTION

Nowadays a demand for more energy efficient devices also in lighting industry is increasing, as there is a great potential for energy savings and CO2 emission reduction to contribute to the European Union (EU) Action Plan for energy efficiency, where the EU in 2008 adopted an integrated energy and climate change limitation policies to be implemented by 2020. With this policy it is intended to develop the sustainable and energy efficient economy of Europe with low carbon emissions, by implementing such events as greenhouse gas reduction by 20%, energy consumption reduction by 20% (or improving energy efficiency), 20% of the EU energy obtained from renewable sources. Street lighting systems have a high potential for improving the energy efficiency, which are identified as significant energy consumers, but they are needed for traffic and citizen safety and security.

Solid-state lighting still is a new technology for street lighting application and its main advantage is the ability to regulate light output in full range - from 0% to 100% with no photometric parameter changes, where conventional lighting with high intensity discharge (HID) lamps, could be regulated just from 50% to 100%, and can cause color shift and color rendering index (CRI), as well as significant drop of luminous efficiency (lm/W).

As a new technology LEDs still are in the development process, and the main obstacle for wider application of LED luminaries is the initial cost of LEDs, which tend to be much higher than HID sources. According to a DOE study, LED technology has been experiencing steady rates of improvement not only in efficiency (approximately 35% annually) but also in cost (approximately 20% annually). When looking at some economic aspects from the engineering - economic analysis done in (Azevedo et al., 2009), which indicates that white solid-state lighting already has a lower levelized annual cost (LAC) than incandescent bulbs, and will be lower than that of the most efficient fluorescent bulbs by the end of this decade.

To compare different illumination technologies with different lifetimes by economical means, a LAC should be compared rather than just the net present value.

$$LAC = I \frac{d}{(1-(1+d)^{-n})} + O \& M$$

where I is the initial capital investment in the lighting system, d is the discount rate, n is the number of the years of lifetime, and O&M is the expected annualized cost of operation and maintenance.

It indicates that countries with limited budget should be careful by planning investment in retrofitting the existing street lighting lanterns with high pressure sodium vapor (HPS) lamps to new solid-state lighting with light emitting diode (LED) technology, unless the retrofitting is technically and economically justified or subsidized with additional investments.

MATERIALS AND METHODS

Description of LED luminary

It is important to understand the main characteristics of LEDs in order to understand how to drive them properly. One of the LED characteristics is their colour, with very narrow band of wavelength, which determines the voltage drop across the LED, while it is operating. The current level determines the light output level, the higher the current, the higher the luminosity of a LED, and also the temperature. Due to production variations, the LED wavelength and thus also the voltage drop has variations, typically ±10 %

(Winder, 2008). As the temperature rises, the voltage drop reduces by ~2mV per degree. When operating LED at maximal parameters, small changes in voltage can make significant changes in the current value and possibly damage the LED, thus appropriate power supply must be used.

To obtain a correct value of CO_2 emissions for street luminary, which is mainly obtained from the consumed electrical energy value, not only the light source efficacy (lm/W), but also the ballast and fixture efficiency (lm/W) should be taken into account, as they can significantly influence the total efficacy (lm/W). Also electromagnetic ballasts typically consume 10-15% more electrical energy than similar electronic ballasts.

Table 1

Efficacy of lighting devices and fixtures

Light source efficacy [lm/W]	Ballast efficiency [%]	Fixture efficiency [%]	Total efficacy [lm/W]
Incandescent 4 to 18 lm/W	100	40 - 90	2 -16 lm/W
Halogen 15 to 33 lm/W	100	40 - 90	6 - 30 lm/W
Fluorescent tubes 60 to 105 lm/W	65 - 95	40 - 90	16 - 90 lm/W
CFL 35 to 80 lm/W	65 - 95	40 - 90	9 - 68 lm/W
HID 14 to 140 lm/W	70 - 95	40 - 90	4 - 120 lm/W
White LED 60 to 188* lm/W	75 - 95	40 - 95	18 - 170 lm/W

*188 lm/W is a target for white LED at 2015 of US DOE

Table 1 shows a comparison of different light source luminaries, thus the total efficacy ranges differ from the light source efficacy (Azevedo et al., 2009).

Standards

Another important topic for public and street lighting luminaries is compliance with different local and EU standards, which help municipalities to avoid low quality products and ensure sustainable lighting. The compliance of LED luminaries to lighting class is very important for municipalities which manage the city lighting system. For LED luminaries there is no special standard of their performance, the parameters and norms defined in the existing standard EN 13201-2:2004, which includes recommendations from CEN and CIE, can be applied to choose an appropriate LED luminary.

These standards are recommendations, but some other standards or government rules can be mandatory for the municipalities in Latvia, like the road maintenance class. If, the road maintenance class defined by traffic intensity, is used for the choice of the lighting class, then combining it with EN 13201-2:2004 classes, Table 2 can be made.

Table 2

Lighting class vs road maintenance class in Latvia

Average traffic intensity (cars per day)	Municipality road **class**	Lighting class
above 5000	A	M1, M2, M3
from 1000 to 5000	A1	M1, M2, M3
from 500 to 1000	B	M1, M2, M3
from 100 to 500	C	M2, M3, M4, M5
below 100	D	M4, M5

Table 3

Lighting class, minimal luminance and recommended illuminance of road class

Lighting class	Minimal luminance, L_{min} (cd/m^2)	Minimal illuminance amount, E (lx)
M1	2,0	30
M2	1,5	20
M3	1,0	15
M4	0,75	10
M5	0,5	7,5

Most of the small municipalities are able to measure illuminance with a standard lux meter, and chose the appropriate values from Table 3.

Any LED driver circuit using the MOSFET switch connected to AC mains should meet the limited radiated, emitted and harmonic current emissions specified by the standard IEC/EN 61000-3-2. Within this standard the Class C corresponds to the lighting.

The conducted emission limits in the 150kHz to 30MHz frequency range are specified in the standard IEC/EN 61000-6-3 (covers 20MHz to 1GHz). The emission levels to meet the EN55022/CISPR22 Class B are 30dBμV/m in the frequency range 30MHz to 200MHz.

RESULTS AND DISCUSSION

Survey of lighting systems in Latvia

To obtain data about the existing situation in the lighting systems in Latvia, an intensive survey of 44 public lighting managing companies, agencies and Latvian municipalities was done by help of the Latvian Ministry of Environment.

The survey indicates that most lighting systems in Latvia have not been reconstructed since their installation date (some of them are more than 30 years old), most of the street lighting managing institutions (municipalities, agencies, private companies) in the survey admit that some part of their lighting system is in bad technical condition. Mostly it deals with old poles for luminaries, that have reached the end or are very close of their depreciation period, for materials like reinforced concrete, steel, wood, in average 35% of the system (see Fig.1.).

Also lots of cables are very old (see Fig.1.) and in bad condition, due to damaged isolations during road reconstructions and repairs.

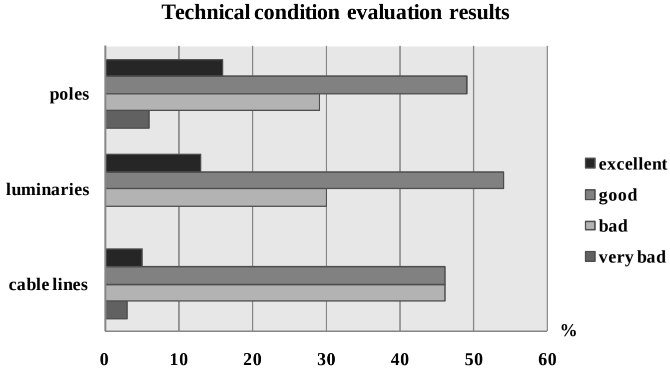

Figure 1. Overall technical condition of poles, luminaries and cable lines of lighting systems.

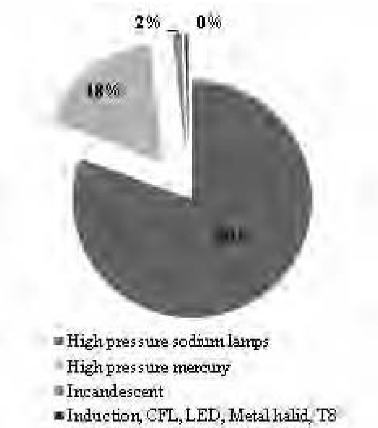

Figure 2. Total rated power versus light source used.

Implementation of power line communication for dimmable LED luminaries would be a challenge in this situation.

As the change of luminaries is the easiest way to reduce the energy consumption, most of the managing institutions of lighting systems, are in the process to change or already have changed old luminaries with mercury vapour lamps to luminaries with High Pressure Sodium (HPS) vapour lamps, thus admitting in the survey, 33% (see Fig.1.) of the luminaries to be in a bad technical condition in an average lighting system. The payoff of investment (change to HPS) will be reached in the next 2-4 years, depending on the system operating hours per year, giving the time and opportunity to develop intelligent power LED luminary. From the survey data the total rated power of luminaries installed at the lighting systems in Latvia is 12,148 MW, which is calculated from the indicated light source technology, capacity and number at the survey questionnaires. Fig.2. shows the percentage of the total rated power of the installed light source technologies. It is obvious that the HPS lamps dominate at street lighting systems, as it is still one of the most efficient light sources, but surprising is that there still are 18% of mercury vapour lamps and even incandescent lamp light sources, and that gives a great opportunity to change these 19% to LED technology luminaries, as the retrofitting investment payoff would be more cost-effective, than retrofitting HPS lamps with LEDs.

As it can be seen from Table 4, the total costs and energy consumption from 2008 to 2009 has decreased, despite the continuously growing electricity rates.

Table 4

Total power of lighting installations and costs

		Latvia Total	Riga	Other cities
Power of lighting installations		MW	MW	MW
Total power of light installations	2008	13,543	7,3	6,243
	2009	13,757	7,2	6,557
Consumption of electrical energy		MWh per year	MWh per year	MWh per year
Electrical energy consumed	2008	46 228	28 203	18 025
	2009	36 497	21 966	14 532
Costs		10^6 LVL per year	10^6 LVL per year	10^6 LVL per year
Consumed electrical energy	2008	2,706	1,410	1,055
	2009	2,136	1,286	0,851
Annual O&M *excluding* energy consumption	LVL	1,958	1,014	0,944
Annual O&M costs *including* energy consumption	LVL**	4,095	2,300	1,795

Table 5

Results of calculation of CO_2 savings

Retrofitting Scenario Description	Average rated power per lamp	lamp count	Electrical energy savings	CO2 savings per year (0,397)	Electrical energy savings per lifetime	CO2 savings per lifetime (0,397)
	W	pc.	MWh/year	t/year	MWh/life	t/life
Incandescent	133	1 196	0	0	0	0
LED w/o dimming	27	1 196	534	212	10 626	4 218
LED + dimming	27	1 196	590	234	11 734	4 658
HME	239	9 069	0	0	0	0
LED w/o dimming	70	9 069	6 478	2 572	128 915	51 179
LED + dimming	70	9 069	7 573	3 006	150 702	59 829
HPS	137	72 568	0	0	0	0
LED w/o dimming	70	72 568	20 363	8 084	405 216	160 871
LED + dimming	70	72 568	29 123	11 562	579 553	230 083
Total possible savings w/o dimming			27 375	10 868	544 756	216 268
Total possible savings with dimming			37 286	14 803	741 990	294 570

It was possible due to the implemented "light saving" measures, like turning off the lighting at night hours due to mechanical timer, turning off two phases, where both methods are not preferable as no light would be available, or changing to more effective lamps or luminaries, where the survey indicates that it was the best method for most of the managing institutions of the lighting systems.

Calculation of possible CO_2 savings

The Latvian lighting systems have present luminaries with incandescent lamps, high pressure mercury lamps (HME), high pressure sodium lamps with very wide range of rated power of lamps, so more than one retrofitting scenario is possible.

To calculate the potential CO_2 savings of retrofitting the existing light souces to LEDs, an average rated power per lamp light source type is calculated, and according to the survey data, totally 1196 incandescent lamps are installed with the average rated power 132,9W per lamp, and the total rated power 158,94kW, as these lamps are mainly installed in parks and decorative lighting, where the pole height is around 6m, an appropriate average LED lamp of 27W can be used to reach similar luminous output. Also 9069 HME lamps, with the average rated power of 239,44W per lamp, are available and the total rated power is 2171,5kW and an appropriate LED lamp would be 70W (average value).

The total number of HPS lamps is 72568, with the average rated power of 136,56W and the total rated power of 9909kW and an appropriate LED lamp would be 70W (average value). For calculations it is assumed, that the lighting system is working 11 hours daily, but when using dimming 4 hours have 100% of light output, 1 hour - 70% and 6 hours - 30% of light output.

According to the method for calculation of GHG emissions from the Latvian Ministry of Environment, 1MWh = 0.397 t CO_2 GHG emissions, when saving electrical energy.

On-site optical measurements of LED luminaries

Nowadays at the market lots of simple LED (without embedded dimming capability) luminaries are already available, but the technical data about the optical and electrical properties are mostly not full, or little technical info, as it is the result of aggressive marketing strategy. To compare production variations and specified optical parameters of several LED luminaries available on the market, on-site testing was done with the method, which can be repeated by every municipality with an ordinary luxmeter.

In order to evaluate the illumination level of the street more accurately, LED luminaries were placed in series, as shown in Fig.3, where HPS luminary is equipped with a 250 W high-pressure sodium vapor bulb. The selected layout allows switching off HPS luminaries, thus the illumination measurements are not affected by adjacent luminaries. The measurements are performed by Hagner "EC-1" luxmeter, (lx 0.1-200000 range, and accuracy +/- 3% (+/- digit).

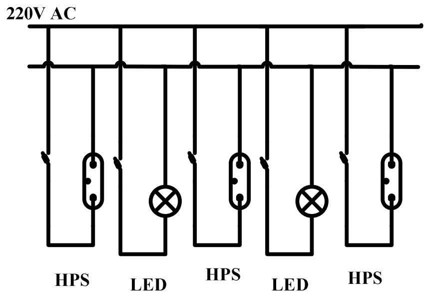

Figure 3. On-site luminary layout..

The experimental street lane is typical M3-M4 class, with the width of 12 m, pole height of 8-10 m. The distance between the poles typically is around 30-35m. Thus according to the measurement method described in the CIE standards, a measurement point of 2x2m intersection was selected, and accordingly the lux value measured. The obtained data are shown in Figure 4, where the darkest color represents the value close to 0 lux and lighter color – closer to 20 lux, an exception is LED 2, LED 7 and LED 8, where the central grey dots represent 40-50 lux. From the obtained graphs the optical properties can be evaluated and compared with HPS luminary. As it can be seen, LED 1, LED 3-5 does not meet the requirements to replace the HPS 150W luminary, but it shows better uniformity, thus it allows to place these luminaries in parks or places where the poles are less than 6 m high. LED 6-8 are supposed for different distances between the poles and lane widths, so to get better uniformity, a careful selection must be done.

Electrical parameter measurements of LED luminaries

Also electrical properties are mostly unclearly described in the LED luminary technical datasheet, not telling if the active power value includes the power supply consumption and losses. To evaluate the electrical properties of LED luminaries, LED1-8 was tested, where LED9 is floodlight, which optical performance is not comparable with HPS streetlamps.

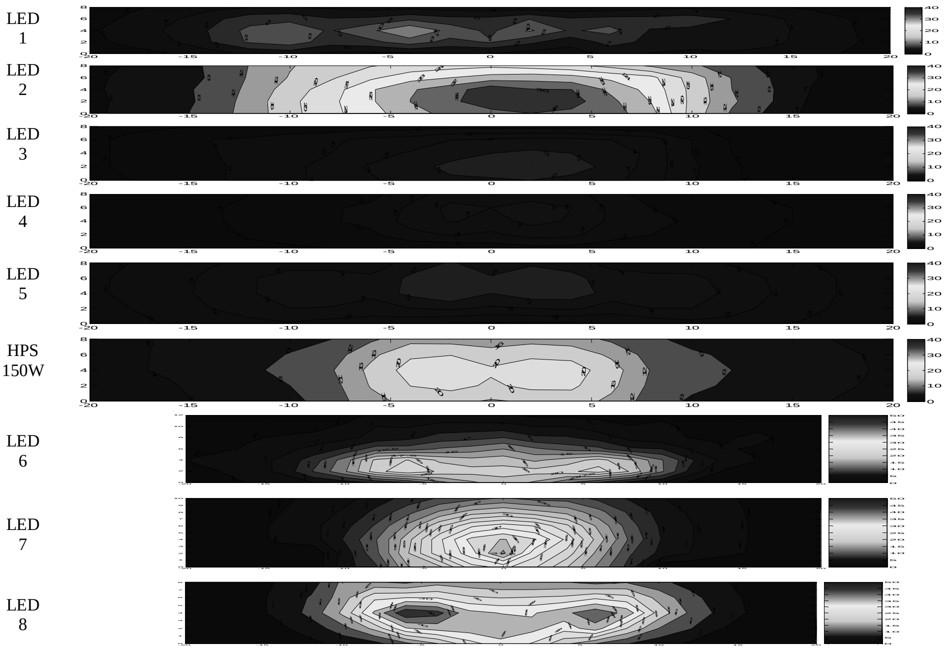

Figure 4. Comparison of different LED luminary photometrical performance at ~ 45 lux scale.

Table 6

Comparison of different LED luminary electrical parameters

Parameter / Luminary	U [V]	I [mA]	P [W]	$\phi1$	cos(ϕ1)	I1 [mA]	THDi [%]	S [VA]	Q [var]
LED1 50W	225	390	51	19	0.95	240	128	87.2	70.7
LED2 225W	224	1020	221	12	0.98	1010	16	228.4	57.6
LED3 35W	225	170	35	21	0.93	160	17	38.2	15.2
LED4 25W	225	110	25	-3	1.00	110	29	26	7
LED5 50W	228	210	47	14	0.97	210	26	50	17
LED6 140W	221	683	150	3.7	0.998	679	11.2	151.3	19.5
LED7 112W	222	564	124	0.75	0.999	561	10.9	125.3	13.7
LED8 84W	221	489	107	2.59	0.999	486	11.9	108.3	13.7
LED9 24W	216	114	24	11.3	0.98	112	15.3	24.6	6.1
HPS 400W	225	1730	369	-14	0.97	1670	28	395	141
HPS 150W	226	780	165	-18	0.95	770	20	176	63

Appendix 22

Galkins, I., **Avotins, A.**, Suzdalenko, A. LED Dimmer as Versatile Hardware Platform for Practical Exercises in Power Electronics and Control Courses. Proceedings of the 14th European Conference on Power Electronics and Applications (EPE 2011), Lielbritānija, Birmingham, 30 Aug. – 1 Sep. 2011.

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LED dimmer as versatile hardware platform for practical exercises in power electronics and control courses

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Keywords

Education tools and e-learning

Abstract

This paper discuss the problems regarding to traditional teaching methods and possible improvement of student practical knowledge base in RTU study program "Computerized Control of Electrical Technologies" by offering interlinked task between many courses and utilization of Light Emitting Diode (LED) related equipment in the course of power electronics, microprocessor control engineering and control theory as a industrial task example.

Introduction

Lighting systems is one of the areas where energy efficiency is especially important – [1] and [2]. There are two basic ways of its improvement: increasing the self-efficiency of lighting equipment and excluding it from unnecessary operation – making it "smart". Utilization of Light Emitting Diodes (LEDs) successfully combines these two ways in lighting systems.

However, elaboration of the intellectual lighting system faces few significant problems. The first one is development of efficient dimmer for LED lamp. Since the amount of light produced by an LED is proportional to its current two light control methods becomes obvious [3]: 1) fluent regulation of LEDs current and 2) Pulse Width Modulation (PWM) of LEDs current. Another light regulation method is based on small rated power of LEDs. Due to that LED luminary include a number of LEDs and it is possible to divide them into groups and control each group separately [3]. Some previous researches [4]-[6] have shown that various DC choppers can be used as the regulators: buck, boost, buck-boost [4], [5] and Cuk [6]. Each of these converters may be driven in different ways and from various control hardware [4], [5]. One more task is overall control of the intellectual lighting system and communication between luminaries, sensors and central control element (if it exists). Since very often installation of new wires is not desirable only two way of communication are possible – through the existing supply cables (Power Line Communication – PLC) or some kind of wireless [7].

It is seen that the implementation of the intellectual lighting system involves a lot of control hardware and software that requires cooperation of experts from different fields. At the same time, existing intellectual lighting system may provide a complete hardware and software platform for practical training in various disciplines - [8] and [9].

Description of study program

Implementation of LED dimmer as versatile hardware platform for practical exercises in power electronics and control courses is supposed for Riga Technical University (RTU) professional bachelor study program "Computerized Control of Electrical Technologies" (CCET), thought by Institute of Industrial Electronics and Electrotechnologies (IIEE). The professional bachelor study program is quite new, started just in year 2004, and became very popular among students and now 90% of bachelor students choose learning at professional studies. Higher education system in Latvia allows realization of both academic and practical study programs, thus it is possible for students to choose the path of learning as it is shown in Fig. 1, and getting PhD degree anyway.

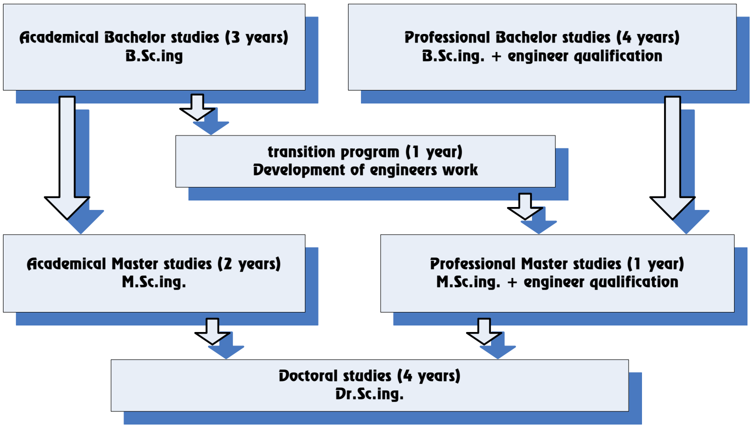


Fig. 1: Structure of degree levels of study program.

The professional bachelor study program totally has 160 Credit Points (CP) (1CP-1.5 ECTS), where 20 CP are general study courses, 36 CP are industry and IT related courses, 40CP are industry specialization courses, 20 CP for specific specialty courses, 6CP for free student choice courses, 26CP for industry praxis (last 3 semesters) and 12CP for development of bachelor thesis with project part which includes engineering calculations and drawings. Within transition program students have praxis and development of engineer work (like practical part of professional bachelor thesis).
Utilization of modern and promising technologies attracts students, especially when these technologies are presented during practical exercises. Thus for professional bachelor study program, LED dimmer can greatly contribute in several courses, like power electronics, control theory and microprocessor control. Hardware platform of the LED dimmer is implemented within new special course – study project at Digital Electronics (2 CP), which is realized at third study years spring semester. By that time students already know related topics of this course (like Fundamentals of Electrical Engineering Theory, Electron Devices or Electronic Equipment, Programming Technologies in Industrial Electronics, Fundamentals of Digital Electronics, Computer Studies, Electrical Measurements, Electrical Engineering and Electronics, Fundamentals of Regulation Theory, Fundamentals of Power Electronics), that is why this new course will greatly help to evaluate their existing knowledge in mentioned topics, and use steps and key terms described in Bloom's Taxonomy.

Identification of problems

Common or traditional teaching method [10]-[12] is used at RTU IIEE, where each course has its plan with lectures and practical works (either calculations or laboratory works). Nowadays lectures are presented by using MS Power-Point, at the same time teachers always give out handouts or share materials electronically in MOODLE, preventing students to write down bulky information, like block diagrams, tables or schematics. This approach helps to save time, but as a result the "repetition" phase is skipped, which must be complied within interesting home works.

This problem can be solved within new course, in which student must make a preparation to laboratory works at home, by calculating some initial parameters of the system, describing theoretical results or solving some other small tasks. Another approach is to give them some small test, during which students must find answers on test questions from previous courses and topics. Knowing their grades of particular course previously, which can be easily obtained in RTU ORTUS system, the student knowledge can be evaluated before and after the course.
Mostly due to large student groups and lack of time, practical works in laboratory mainly use predefined and predesigned laboratory handouts with defined sequence for carrying out the experiment, correct and detailed outline of wiring, and limited amount of sockets for safe plugs. Thus there is no possibility to make errors during composition stage excluding measurement and analysis of wrong data making false conclusions on experimental data or understanding that it was an error and what was the cause. The observation shows that students mostly don’t ask question whether obtained data is correct or not, unless specifically guiding questions are not asked, helping students to make link between knowledge from theoretical course and experimental data obtained in laboratory.
Prepared experimental stands mostly are used for practical works in laboratory, with limited possibility of problem or task variations, thus it decreases students creativity, finding their own new solution for given task. If LED dimmer is used as an example, then due to frequently appeared new LED driver ICs, which is realized with different pin-outs, rising for students new problems to solve them individually, like new PCB design, new elements must ordered and soldered. Some part of the job can be prepared at home giving opportunity for students to work in team.
As the experimental stand becomes very flexible and easy customizable at the end, it is possible to eliminate the problem that arises from repetitive process, using the same task and experimental stand year by year, when students can get final reports from elder course students.

Course methodology and equipment

During recent years RTU implemented e-learning system using RTU website ORTUS which is based on e-learning program MOODLE (Modular Object-Oriented Dynamic Learning Environment) for all study programs at university. Key terms of Bloom’s Taxonomy were used for course description to unify it criteria for potential local and foreign students, the description of course is given in Table 1.

Table 1. General overview of proposed task methodology using Bloom's Taxonomy key terms [13,14].

Bloom’s Taxonomy key terms	Task starting conditions	Performed task	Task result
Evaluation	Experimental setup and plan, measurement equipment (oscilloscope, current clamp, IR camera, etc), access to scientific paper databases	Perform practical measurements and tests. Analytical estimation of measurement error, losses, efficiency. Compare obtained practical results with theory. Consider thermal management and EMC process (at least theoretically if possible).	Ability to plan experiments, use laboratory measurement equipment, analyse measurement errors. Ability to work and make decisions independently. Ability to analyse and select best choice.
Synthesis	TI LaunchPad development board or RTU designed development board based on MSP430F1232 microcontroller control system, needed pulse modulation methods	Integrate closed loop for LED current stabilization. Compose program code. Propose possible equivalent hardware or upgrade to existing design.	Ability to interlink regulation theory with power electronics. Ability to apply programming in Assambler or C code for practical task.

Analysis	OrCAD PSpice, MatLAB,	Compare developed schematics and PCB layout with predesigned variant, analyse both designs.	Ability to run simulations and evaluate obtained results.
Application	OrCAD PSpice, soldering iron, industrially manufactured PCB (without elements) or circuit board plotter (LPKF Protomat S62), Ordering information (links, catalogues, etc)	Calculation of schematic parameters and element values. Ordering elements and analyse economical and packaging aspects. Design of PCB layout, identify places for PCB manufacturing or making them with LPKF Protomat. Braze scheme.	Ability to use OrCAD PSpice. Ability to find necessary components and work with catalogues and order them. Ability to perform and understand practical and industrial application tasks. Ability to work in team.
Comprehension	Topologies of DC/DC converters, pulse modulation methods	Recognize converter topology, explaining differences of converters and pulse modulation methods.	Ability to implement theoretical knowledge for realisation of practical task.
Knowledge	Defined U_{in} and U_{out} and I_{out} of dimmer. LED description and setup.	Analysis of given task, literature. Remember examples showed by lecturer.	Ability to find and use information like, lecture materials or technical documentation.

Configurations of testbench

Four dimming circuits have been discussed: buck, boost, buck-boost and Ćuk. Their basic schematics are well known from the literature. However, their practical implementation has certain features (Fig. 2). First of the all controllable switches are placed so that their control signals are referred to the same grounding as their supply voltage attached through its contacts XI1 (+) and XI2 (–). This makes driver circuits for these switches very simple – control voltage (from XC1 and XC2) is then attached through a gate resistor. It is also easy to install a transistor current sensor at such configuration because its power supply also has to be referred to the same ground. The converters also include an output current sensor that provides feedback to the control system (through XFB1 and XFB2).

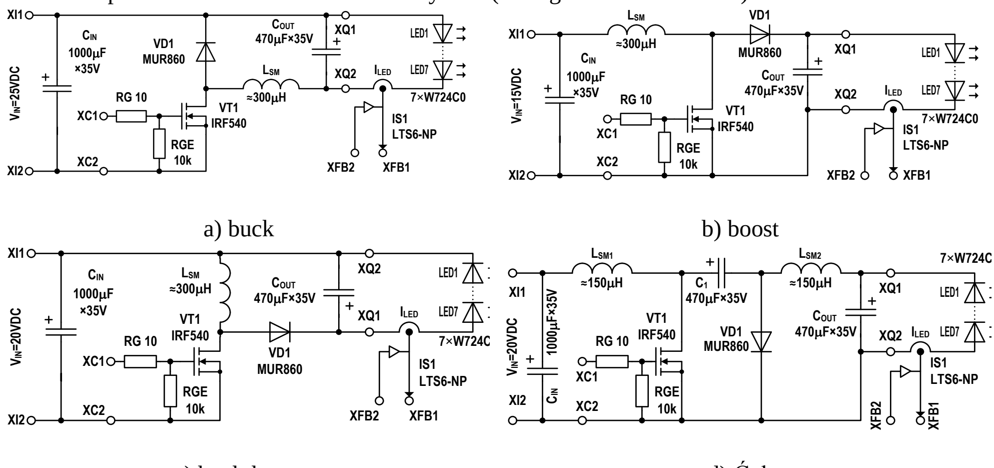
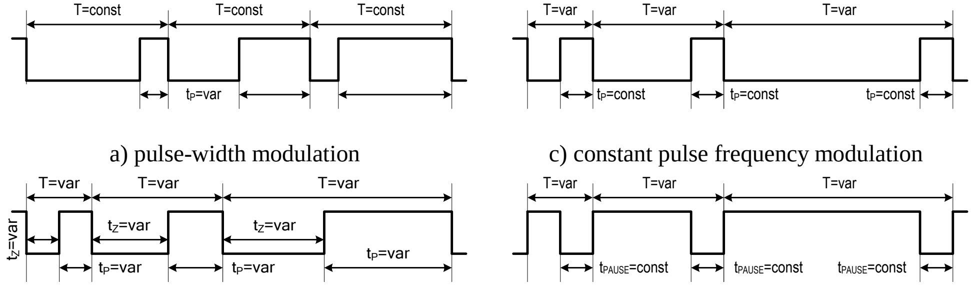


Fig. 2: Dimming DC/DC converters for light regulation with LEDs.

The value of the input voltage is chosen so that the voltage across the LEDs is within its working range while the range of duty cycle is as wide as possible. This gives the value of maximal LED voltage (25V) for buck dimmer, minimal LED voltage (15V) – for boost dimmer and value from the middle of the range (15V) for buck-boost and Cuk converters.

Pulse modulation methods

The discussed dimmers are pulse mode circuits. The transistor of these converters has to be controlled by a pulse signal whose duty cycle defines the amount of energy transferred from the input of the converter to its output. There a several approaches of generation of such signal depending on a control command.



a) pulse-width modulation c) constant pulse frequency modulation

b) variable pulse variable pause frequency modulation d) constant pause frequency modulation

Fig. 3: Pulse modulation methods for LED dimmers.

The most widely used is Pulse-Width Modulation (Fig. 3**Error! Reference source not found.**-a). Then the required duty cycle is obtained with the same period of all pulses. In case of PWM the value of the carrier frequency has significant impact on the losses in the converter. That is way this method has been tested with two values of the frequency (80 and 10kHz).There are plenty of control hardware and software solutions for PWM generation.

Another approach is Frequency Modulation (FM) at which the required duty cycle is obtained with variable period or frequency. At FM pulse and pause width may be variable or one of them may be constant. This produces the following sub-modes: Variable Pulse and Pause Frequency Modulation (VPZFM – Fig. 3**Error! Reference source not found.**-b); Constant Pulse Frequency Modulation (CPFM – Fig. 3**Error! Reference source not found.**-c); Constant Pause Frequency Modulation (CZF M – Fig. 3**Error! Reference source not found.**-d). CPFM provides very high accuracy of regulation at duty cycles close to 0, CZFM – close to 1, while VPZFM is preferable at 0.5. This makes CPFM advantageous with boost converter, CZFM – with buck, but VPZFM – with buck-boost and Ćuk converters.

Implementation of digital control

As it was described previously digital control circuit based on microcontroller should be used to allow students to use their programming skills on practice. For this reason some custom designed versatile and easy reprogrammable microcontroller control board should be developed. A microprocessor system with MSP430 could be utilized because of availability and as equipment that is widely utilized in the author’s department for training purposes and is well studied for this reason. Some disadvantages of this solution should be mentioned – it has relatively big expenditures for development and additional device should be used for programming of microcontroller which requires LPT port on PC. This puts some limitations on use of this equipment; because student will not have possibility to make some test programs on their private notebooks (which rarely can be seen with LPT port).

Another solution for control board implementation is based on utilisation of TI LaunchPad development board, which costs about 5 USD and includes the development board with removable MCU, two LEDs and two pushbuttons and USB programmator integrated on the development board. This solution has excellent price-functionality ratio due to simplified connection with PC (only USB cable is required) and moderate functionality that is suitable for implementation of the control loop for

LED dimmer. To prevent wrong connection of control and power boards the generated PWM signal and analogue feedback signals are galvanically isolated from power supply block of LED dimmer, thus making safer connection of PC to dimmer circuit.

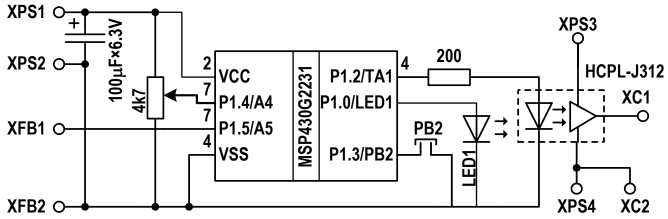


Fig. 4: Pulse modulation methods for LED dimmers.

This development board has its own 3.6 V power supply powering by USB port. XFB1 point (see Fig. 4) is used to acquire current value signal from Hall sensor (see Fig. 2) or output voltage value via optically isolated circuit that is seen on figure below (see Fig. 5), which transfer analogue value from voltage divider through optically isolated circuit with amplifier ratio about 1. Values of resistors are selected to drive HCNR200 IC in nominal mode in which signal to noise ratio is high enough to provide stable operation of circuit.

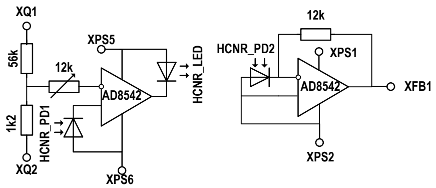


Fig. 5: Optically isolated feedback circuit.

b c

Fig. 6: Laboratory assembly: a) LED dimmer controlled by LaunchPAD; b) power board TOP; c) power board BOTTOM

Realization of control algorithm for LED dimmer requires understanding and repetition of many theoretical courses presented for students previously. This practical example will help them to build strong relation between studied materials and encourage understanding them. Within this course students are toughed to realize control algorithm for process, starting with simple examples, helping them to get familiar with use of particular microcontroller. Then the basic idea of interrupt-driven programs is being presented and additional examples are shown. Within following example students write its own programs to generate PWM signal in respect to some analog value acquired from ADC module. At the end of this course regulation theory is applied on practice by realizing stable operation of LED dimmer on input parameter change. On the picture above (see Fig. 6) example of workbench equipment is presented, consisted of two boards – TI LaunchPAD (the smaller one) that can be mounted on top of power board (Fig. 6-b,c), which has all DC/DC converter elements and additional ICs to provide galvanic isolation and internal power supply.

Evaluation

Student Survey

To provide feedback to presenter, evaluate quality of course materials, and understand possible improvements to meet life-long-learning requirements, a long term evaluation is needed. For this purpose a questionnaire of two parts was made, where part A collects information about participant, like gender, age, grade level and existing knowledge background. This part is needed for long term evaluation and for different type of students, as this study program allows full-time, part-time (extramural) and evening division studies, where students are with different age, gender, even different country, thus having different theoretical and practical knowledge background, for example - second degree in economics. Part B of survey (see Table 2) collects information about course or all workshops (if course is split in several workshops), asking participants to evaluate given statements using 5-point Likert scale (1 - strongly disagree, 2 – disagree, 3 – neither, 4 - agree , 5 - strongly agree).
The first evaluation was done during the first workshop named “Microconrtollers for Power Electronics Applications” at Tallinn University of Technology. Together there were 8 participants, with 7 males and 1 women, average age was 26,6 years, 38% are students from master study program and 62% from doctoral studies, where two of the participants had also second degree in economics. The group has previous knowledge background in some topics, where 62% of group has background in Fundamentals of Electrical Engineering Theory, in Electron Devices or Electronic Equipment – 38%, Programming Technologies in Industrial Electronics – 62%, Fundamentals of Digital Electronics – 50%, Computer Studies – 38%, Electrical Measurements – 62%, Electrical Engineering and Electronics – 88%, Fundamentals of Regulation Theory – 50%, Fundamentals of Power Electronics – 62%, Microprocessor - based Automation Systems – 75%.
The part B is supposed to get feedback about the course or specific workshop and to evaluate the training staff, where first evaluation shows that some improvements are needed, because average evaluation of statements is 3-4 with average variation from 20 - 25%. The most problem was lack of available time (just 8 hours), thus more time is needed, especially for practical tasks (additional 8 hours), and some material to prepare students before the workshop.

Table 2. Survey questions of part B.

B.	**Survey about workshop**	**Mean**	**STDEVP**	**VARp, %**
B.1.	The program of the workshop met your expectations	4,00	0,71	18%
B.2.	Training staff covered all topics of the program and available time was spent efficiently	4,50	0,50	11%
B.3.	Topics of workshop were good structured and well understood	4,00	1,22	31%
B.4.	Teaching method of the workshop was interesting and exciting	4,50	0,50	11%
B.5.	Topics covered by workshop I already learned previously	3,38	0,86	25%
B.6.	Topics covered by workshop I understood best from:			
a	*Presentation and lectures*	3,86	0,64	17%
b	*Course materials*	4,00	0,76	19%
c	*Practical experiments*	4,71	0,70	15%
B.7.	Workshop significantly improved my knowledge and understanding of:			
a	*Power electronics*	3,00	0,76	25%

b	*Regulation Theory*	3,57	0,90	25%
c	*Programming*	3,86	0,83	22%
d	*Microprocessor application*	4,29	1,03	24%
e	*Electron Devices*	3,14	0,83	27%
B.8.	Workshop significantly improved my ability to:			
a	*find and use information*	3,43	0,90	26%
b	*implement theoretical knowledge for realisation of practical task*	3,86	0,83	22%
c	*perform and understand practical and industrial application tasks*	3,86	0,99	26%
d	*apply programming in Assambler or C code for practical application*	4,00	0,93	23%
e	*interlink regulation theory with power electronics*	3,57	0,90	25%
f	*analyse and select best choice*	3,43	0,73	21%
g	*work and make decisions independently*	3,43	0,90	26%
h	*plan experiments, use measurement equipment, analyse measurement errors*	3,57	0,90	25%

Evaluation of knowledge with Test

Additionally it is possible to get student evaluation (grade/test result) from previous courses and compare them with test results after the workshop/course evaluation of specific knowledge and abilities, thus it will show the improvements in student skills or a very valuable feedback for lecturers of previous courses, to make a deeper focus on some specific topics. The test results of workshop are presented in the table 3. Students were not allowed to use course materials and correct answer was deducted only if all multiple choice questions were answered correctly. It should be taken into an account that students were with different knowledge backgrounds and most of them were not familiar with MSP430 MCU family, so it was hard for them for example to remember the names of registers or information about basic clocking system.

Table 3. Test questions and answer analysis.

Question	**Absolutely correct**	**Partly correct**
1 Emphasize main features of MSP430	*25%*	*55%*
2.What is benefit of free choice of clock frequency for peripheral devices:	*0%*	*38%*
3. Please, check the main system clock signals available of MSP430 (at which CPU and peripheral devices are synchronized);	*0%*	*28%*
4. Please, write correct C instruction to stop WatchDog timer:	*13%*	*13%*
5. Establish correct link between the name of register and its function:	*75%*	*83%*
6. Please, choose correct statements about Timer A2:	*0%*	*54%*
7. Which output mode of Timer_A compare module is best suitable for PWM generation:	*38%*	*48%*
8. Which sentence is the most complete definition of interrupts?	*75%*	*79%*
9. Which configuration bits must be set to enable maskable interrupt "x"?	*0%*	*46%*
10.Please, write the model of MCU used in the course:	*63%*	*63%*

Student evaluation from industry

As the students start their praxis at industry on third study year (spring semester) with 5 CP, they also have study project at Digital Electronics (2 CP), with proposed methodology, and 21 CP praxis continues next two semesters, it is possible to obtain evaluation of student abilities according to Bloom's Taxonomy key terms (see Table 1.) from practice manager in industry. The on-line survey can be realized electronically using either support of RTU Moodle system or Google Docs or traditional paper format questionnaire, asking to evaluate student abilities, for example using same statements a-h of question B.8. (see Table 2.), but changing the heading to "Student has ability to:", and praxis manager must choose 5-point scale – strongly agree to strongly disagree. This evaluation is very valuable for all sides – student, industry and university study program, for implementing long-life-learning methods.

Conclusions

Existing teaching methodology in RTU study program "Computerized Control of Electrical Technologies" is mainly based on theoretical calculations and simulations, thus students lack the possibility be creative and build something from "scratch" and thus to be acquainted with full design process. With the proposed interlinked task between different courses with utilization of LED related equipment is possible to enable that. As the student groups sometimes can be very large for one lecturer, a cost-effective approach with implementing new methods of e-learning for tasks possible to be done also at home or work, or even contribute to life-long learning.

Successfully finishing the task, students will be able to practically distinguish essential parameters during the design stage, to get better understanding and overall overview of engineering process, and will be more ready to work independently when working on their practice at industry, preparing bachelor or master thesis or doctoral studies.

Next task is to test the workshop on larger group of bachelor study program students, obtain evaluation of previous courses and practice managers at industry, thus it will be possible to develop correct approach of evaluation for next topics and workshops to this course.

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Appendix 23

Avotins, A., Galkins, I., Ribickis, L. Development Challenges of Intelligent Street Lighting System. 9th International Symposium "Topical Problems in the Field of Electrical and Power Engineering. Doctoral School of Energy and Geotechnology II, Estonia, Parnu, 14–19 June 2010.

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Development Challenges of Intelligent Street Lighting System

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Abstract

Abstract – the given paper estimates requirements for development of intelligent lighting system, using power Light emitting diodes, power supplies, control method, different EU and local standards, communication technology in the context of EU energy efficiency policies and situation in Latvia.

Keywords

Light emitting diodes, intelligent luminaries, lighting, communication.

1 Introduction

1.1 EU Policy

European Union at year 2008 adopted an integrated energy and climate change limitation policies to be implemented by year 2020. With this policy is intended to develop the sustainable and energy efficient economy of the Europe with low carbon emissions, by implementing such events as greenhouse gas reduction by 20% (or 30% if according international agreement will be reached); energy consumption reduction by 20% (improving energy efficiency); 20% of EU energy obtain from renewable sources [].

The street lighting networks are significant electricity consumers, for example in Riga lighting system is 44 thousand luminaries and costs for electricity are 1,9 million LVL (or 2,47 million EUR) per year [5], and due to power LED technology it is possible to develop lighting systems with intelligent LED luminaries, thus decreasing energy consumption of system and contributing to implementation of European Union energy saving policies.

1.2 Situation in Latvia

As the most lighting systems in Latvia has not been reconstructed since their installation date (some of them are more than 30 years old), most of the street lighting managing institutions (municipalities, agencies, private companies) in the survey admit that some part of their lighting system is in bad technical condition [9]. Mostly it deals with old poles for luminaries, who has reached end or are very close of their depreciation period, for materials like reinforced concrete, steel, wood, in average 35% of the system (see Fig. 1.).

Also lots of cables are very old (see Fig. 2.) and in bad condition, due to damaged isolations during road reconstructions and repairs. Implementation of power line communication for intelligent LED luminaries would be a challenge in this situation.

As the change of luminaries is easiest way to reduce energy consumption, most of the managing institutions of lighting systems, are in process to change or already have changed old luminaries with mercury vapour lamps to luminaries with High Pressure Sodium (HPS) vapour lamps, thus admitting in survey, 33% of the luminaries to be in bad technical condition in average lighting system. The payoff of investment (change to HPS) will be reached in next 2-4 years, depending of the system operating hours per year, giving the time and opportunity to develop intelligent power LED luminary.

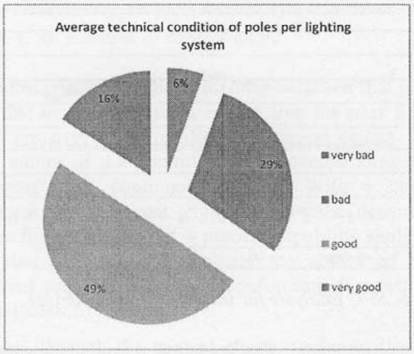


Fig. 1. Technical condition of poles

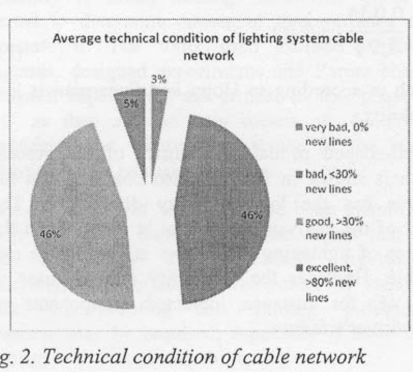


Fig. 2. Technical condition of cable network

1.3 Standards

Compliance of LED luminaries to lighting class is very important for municipalities which manage the city lighting system. For LED luminaries there is no special standard of their performance, a parameters and norms defined in existing standard EN 13201-2:2004, which include recommendations from CEN and CIE, can be applied to choose an appropriate LED luminary.

Table 1. Lighting class and road maintenance class in Latvia

Average traffic intensity (cars per day)	Municipality roads	Lighting class
above 5000	A	M1, M2, M3
from 1000 to 5000	A1	M1, M2, M3
from 500 to 1000	B	M1, M2, M3
from 100 to 500	C	M2, M3, M4, M5
below 100	D	M4, M5

As these standards mostly are recommendations, some other standards or government rules can be mandatory, for example in Latvia, a road maintenance class is strictly defined. If, road maintenance class, which is defined by traffic intensity, is used as basis for choice of lighting class, then combining it with EN 13201-2:2004 classes, a Table 1 can be developed [7].

Any LED driver circuit using MOSFET switch connected to AC mains should meet the limited harmonic current emissions specified by standard IEC/EN 61000-3-2. Within this standard the Class C corresponds to the lighting. Harmonic emission limits are given in Table 2.

Table 2. Specified harmonic limits up to 40th harmonic

Harmonic order No	Maximum current, Class C (% of fundamental current)
2	2%
3	(30 x Power Factor)%
4 – 40 (even)	Not specified
5	10%
7	7%
9	5%
11-39 (odd)	3%

Conducted emission limits in the 150kHz to 30MHz frequency range are specified in the standard IEC/EN 61000-6-3 (covers 20MHz to 1GHz). The emission levels to meet EN55022/CISPR22 Class B are 30dBμV/m in the frequency range 30MHz to 200MHz.

2 Concept of intelligent power LED luminary for street lighting

Existing street lighting system in Riga, as well as other in Latvia, has quite a robust control possibility, and very scarce feedback data. With existing control system it is possible simply to switch ON or OFF three phase electric cabinet via radio signal, and retrieve energy readings from power meter. These electric cabinets are powering a wide branch of streets with HPS luminaries, commutating high currents, and high voltage spikes in lamp ignition stage, thus equipment operating conditions could be described as heavy.

As the LED technology allows dimming the luminary in 100% range, and for powering LEDs an electronic converter and driver is needed, it is obvious, that integrated circuits will be used. Already on the market a simple LED luminaries are available, typically using power LED and Buck type converter with PFC control. Some of the integrated circuit manufacturers offer microcontrollers with PWM input pin, giving a possibility to regulate the output, thus dimming the light. That gives an opportunity to design more intelligent luminary, who could process a lot of sensor signals and send them to the central control and monitoring system (see Fig. 3.).

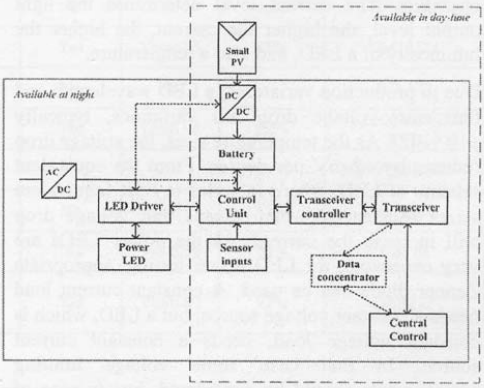


Fig. 3. Basic concept of intelligent LED luminary

By developing new lighting system, we should maximally use existing infrastructure – cables and existing control utilities. Existing control method switches OFF the voltage supply of lighting network lines during the day-time. As the proposed concept includes motion sensor for traffic intensity monitoring for road and pedestrian flow also during the day, the sensor, control unit, controllers, and transceiver circuit should be powered by energy stored in battery, which is charged at night, if it is necessary, and through small photovoltaic, during the day. The control unit monitors the battery charge state. The choice off battery should be made very carefully, by means of power consumption of sensors and control units, as well as lifetime, should be balanced due to long LEDs lifetime. The current consumption of sensors, control unit and transceivers is very low, a small power (<5W) thin-film or amorphous photovoltaic can be used, it will serve also as twilight sensor, and if properly used, can give received solar energy statistical data during the day.

2.1 Power LED

The most expensive material in the intelligent luminary is power LED, and on the market are available different types of them with different characteristics and parameters, so the balance of their efficiency in lm/W and cost of $/W must be found. Some of the manufacturers have produced LED matrix of 70 W, 100 W and more, some of them claim that their laboratory prototypes have reached efficiency 150 lm/W. Preliminary calculations and market explorations show that 3W power LED has most convenient price and efficiency now. The prognosis about LED efficiency from the lighting system manufacturer Philips is that power LEDs will overtake HPS lamps in efficiency by year 2015.

It is important to understand characteristics of LEDs in order to understand how to drive them properly. One of the LED characteristics is its colour, with very narrow band of wavelengths, which determines the voltage drop across the LED, while it is operating. The current level determines the light output level, the higher the current, the higher the luminosity of a LED, and also a temperature.

Due to production variations, a LED wavelength and thus also voltage drop has variations, typically ±10 % [2]. As the temperature rises, the voltage drop reduces by ~2 mV per degree. From the equivalent scheme of LED, where in series is ESR (equivalent series resistance), which means that voltage drop will increase the current. As the power LEDs are very expensive, for LED driver testing, appropriate Zenner diode can be used. A constant current load needs a constant voltage source, but a LED, which is constant voltage load, needs a constant current source. In that case some voltage limiting arrangements should be considered, just in case of disconnections and short-circuits. A voltage monitoring, doesn't affect current level, and if the circuit failed to open, the voltage would rise to the limit of the open-circuit protection level, so it could be preferred failure detection method.

2.2 power supplies

It is very important to carefully choose the power supply converter type from the topology. It can give a major impact on the end product parameters and features, like brightness, EMI radiation levels, input/output voltages, currents, regulation possibilities, efficiency, power losses, temperature ratings, sensors, component selections and fault protections, communication, e.t.c.. The power supply topologies suitable for LED driving are shown in Fig. 4.

Linear power supplies produce no EMI radiation that should be considered as advantage. Disadvantage is their low efficiency, when supply voltage is higher than LED voltage, in this case it could cause thermal problems and thus a need for bulky heatsink. If the difference between voltages is small, then linear regulator could have higher efficiency as switching regulator, especially when operated from low voltage DC power source, like photovoltaic. If operated from AC mains, linear regulator will have a large size, due to need of step-down transformer and smoothing capacitor, unless LED string voltage is near to peak AC voltage.

It is obvious, that for street lighting with intelligent LED luminaries, its power supply should convert 220 V AC mains voltage to the appropriate LED string DC voltage, ensure constant output current and enable dimming possibilities. Due to switching elements in circuits EMI must be limited by careful circuit design, screening and filtering. For LED driving a Buck circuit for AC input can be used. When using Buck topology, efficiency can reach 90...95%, when long string of LEDs is controlled. The output current of LED string should be:

$$I_{out} = \frac{V_{TH}}{R_{sense}} - \frac{1}{2}\Delta I_{out} \quad (1)$$

Where V_{TH} is the current sense comparator threshold, R_{sense} is the current sensing resistor, and ΔI_{out} is output ripple current designed to be 20-30 % of I_{out}. Conduction power loss in the MOSFET can be calculated as:

$$P_C = D I_{out}^2 R_{ON} \quad (2)$$

Where D is the duty ratio and R_{ON} is the ON resistance.

$$D = {}^{V_{out}}/_{\eta V_{in}} \quad (3)$$

Already a lot of power supply topologies based on integrated circuits are available for commercial implementation (see Table 3). It has been found that the most of proposed IC based power supplies operate as the switch mode voltage stabilizers with voltage feedback. They are mostly built as a flyback (1, 3 and 5), truth buck (4, 7 and 8) or half bridge (7 and 9) converter (switch mode or quasi resonant). In fact these topologies are not intended directly for LED application but adjusted for them. One more configuration is simplified buck (2 and 6) without the capacitor and the coil for energy transfer (in Table I entitled "step-down chopper"). If equipped with current smoothing coil this solution is very compatible with LED applications due to current operation mode of the LEDs. From the above mentioned topologies the most energy efficient are the step-down chopper (due to the minimal number of components) and resonant half bridge (due to minimized commutation losses). Power Factor of the presented converters is mostly not controlled or controlled with passive means. Only few examples provide PF correction. Some of them (8) use a separate IC for PF correction. Only few of them are based on one integrated solution either double-stage (3 and 9) or unified (5). Of course these topologies provide better PF.

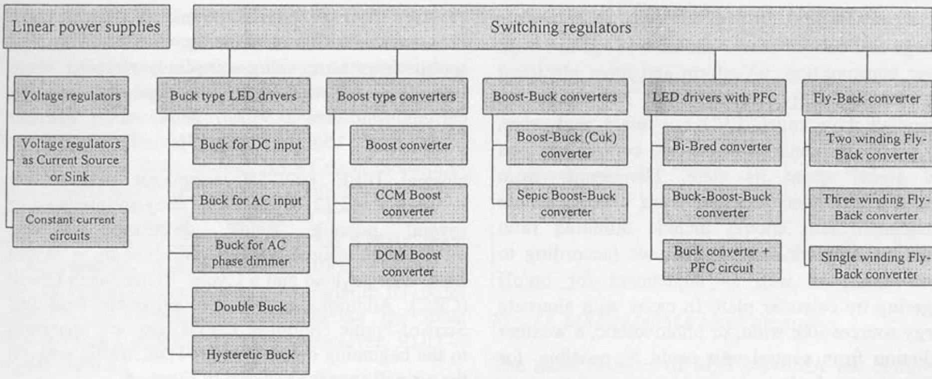


Fig. 4. Power supply topologies suitable for LED driving

Table 3. Some commercially available IC based LED power supplies.

	Mf./IC	Topology	Power/ Current	Dimming method	Isolation	PFC	Efficiency	Reference Design
1	NXP/SSL2101	Flyback	Int. 17W	Triac	Yes	No	78%	UM10341
2	NXP/SSL2101	Step-down chopper	Int. 9W	Triac	No	No	66%	UN10342
3	NXP/SSL1750	Boost + Flyback	Ext.	Triac	Yes	Yes/0.95	85%	UM10321
4	National Semiconductor/ LM3445	buck	Ext.	Triac	No	No	-	RD-172
5	ON Semiconductor/ NLC3000	Flyback	Ext.	Triac	Yes	Yes/0.93	82%	NCL30000LED2G EVB
6	Supertex/HV9910	Step-down chopper	Ext.	PWM	No	No	90%	HB9910BDB2(7)
7	International Rectifier IRS2541	Buck, H-bridge	Ext.	PWM	No	No	85%	AN1131
8	STM/ L6562A (PFC cnt.)	Boost + Buck	Ext	PWM	No	Yes/0.99	90%	U0670
9	Power Integrations/ PLC810PG	Boost, Resonant H-bridge	Ext	-	Yes	Yes/0.97	92%	DER212

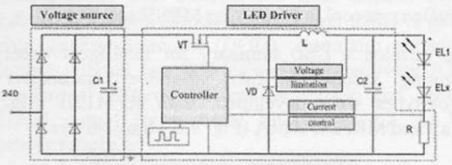


Fig. 5. Functional diagram of LED controlling with IRS2541

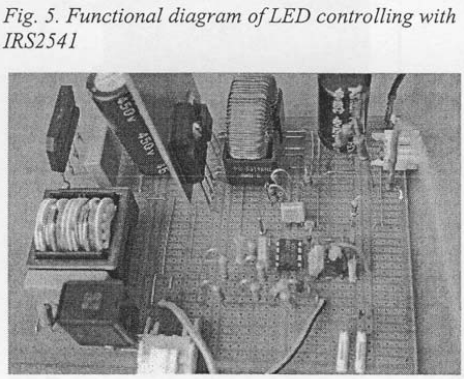


Fig. 6. Laboratory experimental prototype of IRS2541 LED Driver

There are lots of manufacturers, who have lately produced a LED drivers also for power LEDS. IRS2541 (see Fig. 5.) has been chosen as the first to be tested for development of 70W LED luminary (see Fig. 6), as it has a PWM input, and good possibilities to improve EMI and EMC ratings [6]. Still the main issue is dimming control for LEDs, as the controller IRS2541 has PWM enable pin, and simply switches ON/OFF the controller, thus when dimming light to 10%-30%, can lead to stroboscopic effect of light.

2.3 Control of intelligent LED luminary

To develop smart LED luminary, the control unit must have access to lots of sensor and programming control inputs. Twilight switch or small photovoltaic could be used to obtain correct statistical data for switching lighting calendar method. Movement sensor should be used to measure traffic intensity during day-time, for central statistical agency, and as a control signal for LED luminary in night time, to improve dimming. Temperature sensor to measure readings during the day for central statistical agency and to switch on/off luminary to prevent it damage if temperature inside the case reaches critical value. Voltage and current sensor should be used to obtain power consumption, waveform and other electrical data. From energy reading data is possible to extrapolate how much LED are intact, and when they reach maintenance limits, the control unit can send signal about its state. The inputs from communication unit received from central remote management unit should include dimming ratio signal for different luminary classes (according to street class), as well as adjustment for on/off triggering by calendar plan. In cases with alternate energy sources like wind, or photovoltaic, a weather prediction from central unit could be possible, for energy usage calculations.

The data exchange between intelligent power LED luminary and central control unit (also data concentrator can be in middle for large systems) can be provided via different communication methods. Due to SMART GRID concept, a Power Line Communication and wireless communications (ZigBee supporting protocol) are tended to be used in near future for various electrical grid and data network.

There are various examples of Power Line Communication (PLC) modems for this purpose, which differs by functionality, availability of internal peripherals, implemented coding algorithm, as well as integrated/supported protocol.

In Smart Grid context, new technologies for smart metering are uprising, for example a Philips Smart Plug, which monitors power consumption of plugged in devices, and sends the data to home desktop PC via wireless communication. Similar approach could be used for street lighting systems, as the costs of Power Line and wireless communication devices are very close.

ZigBee is broadly categorized as a low rate WPAN (Wireless Personal Area Network), where with WPAN is possible to identify and with one command switch on/off whole street or even a large area (district), because max number of PAN is 216 = 65535 ("0" doesn't counts), also a PAN can consist of 65535 objects. It is sufficient for large lighting systems, including all possible sensors, and other objects. ZigBee uses low data rate (20...250 kbps), low power consumption, and works with small packet devices. ZigBee - set of high level communication protocols based upon the specification produced by 802.15.4. As the lighting network with intelligent power LED luminaries is static, the system has lots of devices, infrequently used, small data packets, and some cables are in bad condition, a wireless ZigBee would be a good choice for controlling the network. Wireless communication will also ease access for lighting system maintenance engineers, but the data should be encrypted to prevent unauthorized connections.

ZigBee timing considerations – new slave enumeration = 30 ms typically, thus enabling fast set-up (similar to plug-and-play), sleeping slave changing to active = 15 ms typically (standby current less than 0.3 μA), active slave channel access time = 15 ms typically [9].

Normal IEEE 802.15.4 compliant packets are between 5 and 127 bytes long. They are made up of several possible fields: destination address information, source address information, a length field, data payload and a Cyclic Redundancy Check (CRC). Additionally, a 4-byte preamble field and Start-of-Frame Delimiter (SFD) byte are appended to the beginning of the packet. Thus, traffic seen on the air will appear as shown in Figure 6.

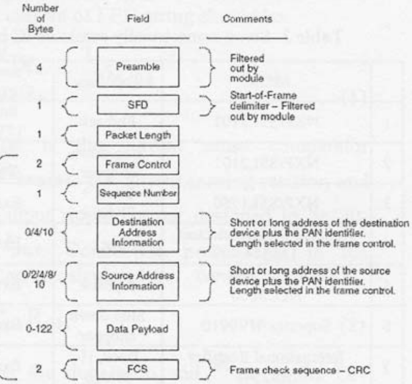
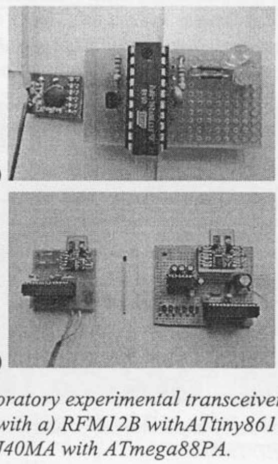


Fig. 7. IEEE 802.15.4 compliant packet format

For street lighting system, a communication network with MESH topology must be used, where each luminary is connected to all closest luminaries, thus providing stable connection in case of damages. The ZigBee protocol is supporting MESH topology.

To develop a LED luminary for intelligent street lighting system, a two laboratory transceiver prototypes were developed, with RFM12B (Fig. 7.a.) and MRF24J40MA (Fig. 7.b.) transceivers.



a)
b)

Fig. 8. Laboratory experimental transceiver prototypes with a) RFM12B withATtiny861V, b) MRF24J40MA with ATmega88PA.

RFM12B ISM Band Sub-GHz RF withATtiny861V Transceiver, has integrated receiver and transmitter in one circuit, and signal receiving and transmitting is realised via microcontroller programme. Interface exchange from ATtiny861V microcontroller to RFM12B interface is shown in Fig. 9., where MISO – Master Input Slave Output, SS – Crystal Selection (active low level), nSEL- microcontroller is active, when level is low/negative ("0"), SCK – synchronization (if microcontroller has 8 MHz, then SCK frequency at least 4x less), nIRQ – interrupt request (when data received, then signal to INT0, to allow microcontroller to start reading the data fromreceiver), nRES – reset for transceiver, VDD – power supply.

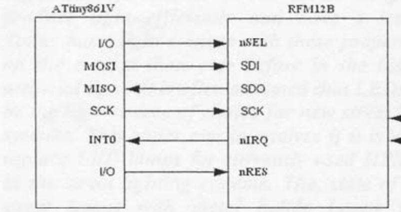


Fig. 9. Microcontroller ATtiny861V to RFM12B interface

RFM12BP is a low costing ISM band transceiver module implemented with 500 mW output power. It works signal ranges from 433/868/915 MHZ bands, The SPI interface is used to communicate with microcontroller for parameter setting.

The main features of RFM12BP are PLL (gives very precise frequency) and zero IF technology, fast PLL lock time, high resolution PLL with 2.5 KHz step, high data rate (up to 115.2 kbps with internal demodulator, with external RC filter highest data rate is 256 kbps), standby current less than 0.3 μA, data quality detection (DQD), automatic antenna tuning, internal data filtering and clock recovery, RX synchronal pattern recognition, clock and reset signal output for external MCU use, 2.2...3.8 V power supply.

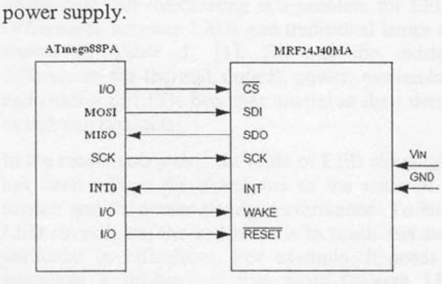


Fig. 10. Microcontroller ATmega88PA to MRF24J40MA interface

MRF24J40MA module is based on the Microchip Technology MRF24J40 IEEE 802.15.4™ 2.4 GHz RF Transceiver IC. The module interfaces to many popular Microchip PIC® microcontrollers via a 4-wire serial SPI interface, interrupt, wake, Reset, power and ground. MRF24J40MA block diagram is shown in Fig. 11.

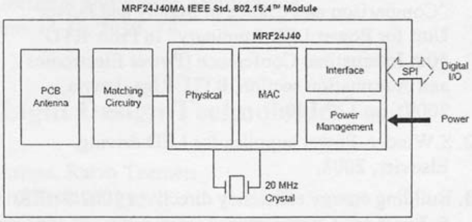


Fig. 11. MRF24J40MA block diagram

The main features of MRF24J40MA are complete IEEE 802.15.4 specification compliant, supports MiWi™, ZigBee™ and proprietary protocols, simple, 4-Wire SPI interface, supports Power-Saving mode, Low-Current consumption (RX mode: 19 mA (typical) receice mode; TX mode: 23 mA (typical) transmit mode (consumption to for transmit length of 25 kbps)), Data transmit speed 250 kbps, Current in sleep mode is 2 μA (typical). For RF/ Analog Features: ISM Band 2.405...2.48 GHz operation, Data rate: 250 kbps (IEEE 802.15.4); 625 kbps (in turbo mode), +0 dBm typical output power with 36 dB TX power control cange, Differential RF Input/Output with integrated TX/RX switch. MAC/Baseband Features: hardware CSMA-CA mechanism, automatic ACK response and FCS check, independent Beacon, Transmit and GTS FIFO, automatic packet retransmit capability (good feature, because in streets are lots of interference, so transmitter can receive acknowledgement that data is received, if not, it sends again with programmed interval x times, until acknowledgement of reception of data packet is received, supports Encryption and Decryption for MAC sublayer and upper Layer (integrated algorithm (for optional usage), for preventing unauthorized access to communication device.

3 Conclusions

Still the main problem is to build efficient power supply, who also in dimming stage preserve good efficiency, and has low EMI and EMC radiation levels. The further power LED development gives new opportunities and new demands to power supply, and it is expected to be next technology used in street lighting systems.

Various LED driver integrated circuits are compared by its internal topology, efficiency, dimming approach, integrated PFC, and it was revealed that the most energy efficient DC converter topology is step-down chopper due to minimal count of components and resonant half-bridge due to minimized switching losses.

A data communication between two MRF24J40MA and two RFM12B based transceivers were established despite programming code guide errors in both RFM12B and MRF24J40 documentations.

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Appendix 24

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TOPICAL PROBLEMS IN THE FIELD OF ELECTRICAL AND POWER ENGINEERING

◆

DOCTORAL SCHOOL OF ENERGY AND GEOTECHNOLOGY II

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City illumination development study

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Abstract

The paper gives estimation of city development study, case study of Riga city describes, implementation of intelligent lighting, and experimental results of measurements of LED luminaries in real conditions.

Keywords

LED, city lighting, street luminaries, development.

1 Situation in Riga

Riga illumination system is largest lighting system in Latvia, with total length of lines 1700 km, it has approximately 44000 luminaries. Without lighting in Riga still are 116.25 km, where most of them are streets with very low traffic intensity. Budget is inappropriate for maintenance and new lighting line construction expenses in Riga city lighting system. Most of Riga city lighting network is in a bad technical condition, causing quite a lot of emergency breakdowns, and still no investments are made to prevent it. From the time, when Republic of Latvia was declared, Riga city lighting agency as a priority has declared, reduction of consumed electrical energy. In year 1995, was started change of out-of-date luminaries to new energy effective luminaries, respectively old and environmentally hazardous high pressure mercury vapour lamps of 400 W and 250 W to 250 W and 150 W high pressure sodium lamps. The luminance level due to sodium lamp technology didn't reduced. So the total active power started to decrease and to pay off investment. At the end of the year 2008 this programme has been finished, and the result is shown in Figure 1, where total power from 12.7 MW has been reduced to 7.2 MW.

The dynamics of energy consumption is shown in figure 2, where statistical data are gathered from year 1993 to 2008. In the years 1996 and 1997 seems that energy consumption is reduced, by means of switching of lighting at nights, this strategy gave almost 50% energy savings, but a lot of discomfort for citizens, operative transport, e.g. ambulance, police. Thus starting from 1997 to 2002 for lighting "austerity measures" was made – just one phase was "switched on". It also gave energy savings, but system also got asymmetrical load, lighting on street was irregular and insufficient, and electrical network was damaged. From year 2002 lighting system works in full regime.

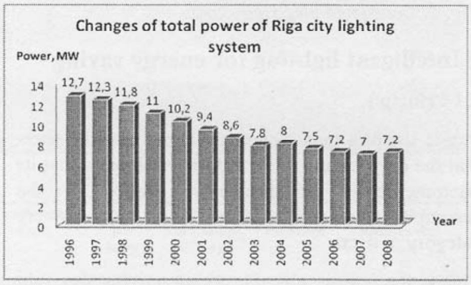

Fig.1. The total power of Riga city lighting system (1996 to 2008)

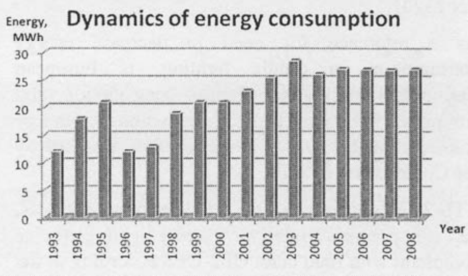

Fig.2. Dynamics of energy consumption per year

But all those energy saving measures, made a little difference, because costs for electricity were endlessly rising. As it is shown in table 1, the rate for consumed electrical energy since 1993 has been increased for 10 times.

Table 1. Changes of electricity rate T-9.

Increased T-9 date	Day rate (Ls/kWh)	Night rate (Ls/kWh)
Year 2004	0,04416	0,03457
1. March of 2006	0,04825	0,03749
1. January of 2007	0,05859	0,04420
1. April of 2008	0,07941	0,06504

The dynamics of costs for electricity are increasing gradually, regardless of drastic increase of electricity rates. That was possible by systematically performing energy saving measures.

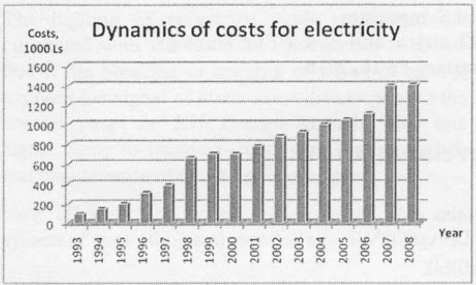

Fig. 3. Consumed electricity costs

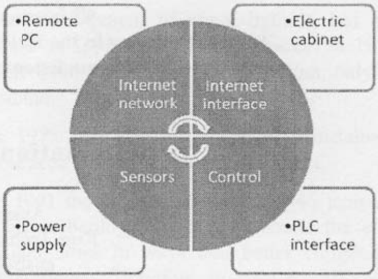

Fig. 4. Principles of the solution

2 Intelligent lighting for energy saving

2.1 Principle

Public lighting must bring much more to the users that the only feeling of "comfort", still needs that its photometric performances allow the accomplishment of the different visual tasks of every category of users.

This is the reason why the notion «giving the right light» is obvious and declines through minimal values of illumination and luminance to support. These values are expressed in the European standard EN 13201.

As a reference for need to decrease energy consumption in public lighting, is European Community policy in energy consumption and aiming at achieving a 20% reduction in energy consumption by 2020. [1] Action Plan adopted by the Commission in 2006.

RTU IEEI experience with LED luminaries shows, that it is possible to deliver a street lighting service compliant with road class CE2-CE5 according to the standard of EN13201. It means that device can be installed in secondary street, access road, commercial access, allotment, pedestrian way, cycle track, residential areas, and most of them are compliant with EN 60598-1 and EN 60598-3 standards for luminaries general requirements and tests. The limitation of the service to class CE2-CE5 roads is due to the use of intelligent light dimming which is not compliant with high traffic roads. But, in another hand, this technology will ensure a quick and significant energy saving.

Mostly power LEDs are used as sources of light. Traditionally, discharge or fluorescent lamps are used for this lighting. Solid State Lighting (SSL) technology is now getting competitive compared to other sources. If they are still less powerful compared to the other sources, they have several advantages, among others the quality of light, the durability, the hardiness. In the existing technologies of street lighting, the LEDs are limited to the lighting called residential where it requires less power. Even in this type of application, LEDs might be one of the best solutions if their use is optimized to reduce energy consumption.

The principle of intelligent micro grid for energy saving, based on LED technology is shown in figure 1. The luminary is composed of a matrix of LEDs, a power supply, sensors, a power line communication (PLC) interface and a power supply control device. Data of light intensity, of movement, of temperature, and of current are sent by the sensors to the smart control device, then processes by the embedded control software, a dimming signal is sent to the power supply in order to regulate it providing thus the gradation of the light emitted by the LEDs. A power line communication system provides the connection of the luminary to the electric cabinet and then to the Internet network allowing the remote management of system [2].

The residential areas allow easiest dimming because they are less subject to security traffic problems.

2.2 Consumption

The following table show the comparison between the three technologies, former, latest and LED. The HME-125 produces a light flux of 6500 lumen, the TC-L55 a flux of 4800 lumen and the LED-50, a flux of 5000 lumen. The difference between technologies is that older technologies were losing a lot of flux along the time, to the contrary of new technologies. Furthermore, the new technologies have a lifespan very superior. The LED in particular has a lifespan estimated to 50,000 hours. The average duration of lighting is 11 hours per night during the year. During the night it is possible to apply a dimming. This dimming is limited by the discharge lamps technology to 70% that is why we force dimming to 30% for LEDs and thereby limit even more consumption [2],[3].

2.3 Maintenance cost

The maintenance has no major difference. Though the replacement cycle of LEDs is much longer, it requires a longer intervention, and the cost of the lamp is higher. Of course, the price of LED is going to reduce, but the manufacture of the LED cards will keep more expensive than traditional lamps. The value of 100 € per unit is only given as a rough guide.

In this comparative, we do not take into consideration the cleaning of the optics, which has to be performed every year to keep a correct light efficiency. This operation reduces even more the differences between the technologies.

Table 2. Calculations to compare consumption.

Description of lamp	Type of lamp	Luminary wattage	Number of lamps	Total system wattage	Average lighting hours per day			lighting hours / year		electric work [kWh/y]			cable loss	Total consumption
		W/unit	unit	kW	100 %	70 %	30 %	100%	reduced	100%	reduced	total	%	kWh/y
Old technology	HME 125	142	50	7,1	11	0	0	4015	-	28507	-	28507	5	**29932**
Old technology (with dimming)	HME 125	142	50	7,1	6	5	0	2190	1825	15549	9070	24619	5	**25850**
New technology	TC-LE55	62	50	3,1	11	0	0	4015	-	12447	-	12447	5	**13069**
New technology (with dimming)	TC-LE55	62	50	3,1	6	5	0	2190	1825	6789	3960	10749	5	**11287**
LED technology	LED-50	55	50	2,75	11	0	0	4015	-	11041	-	11041	5	**11593**
LED technology (with dimming)	LED-50	55	50	2,75	5	0	6	1825	2190	5019	1807	6826	5	**7167**

Table 3. Calculations for maintenance comparison.

Description of lamp	Type of lamp	Operation hours (100% power)	Operation hours (reduced power)	nominal life of lamp	exchange cycle	price per lamp	labour costs lamp exchange	costs lamp exchange	total maintenance costs
		h/y	h/y	h	unit/y	unit	unit	unit	y
Old technology	HME 125	4015	-	8000	0,50	5	30	17,57	**878,28**
Old technology (with dimming)	HME 125	2190	1825	8000	0,50	5	30	17,57	**878,28**
New technology	TC-LE55	4015	-	8500	0,47	7,5	30	17,71	**885,66**
New technology (with dimming)	TC-LE55	2190	1825	8500	0,47	7,5	30	17,71	**885,66**
LED technology	LED-50	4015	-	50000	0,08	100	60	12,85	**642,40**
LED technology (with dimming)	LED-50	1825	2190	50000	0,08	100	60	12,85	**642,40**

2.4 Summary

The comparison is made between a currently used solution and the LEDs solution. It highlights an important energy saving over the year. That is the main objective. It is certain that this objective cannot be achieved only by using LEDs. The global management of the system is therefore necessary to optimize the consumption. By using 50 LED 55 W luminaries with dimming possibilities instead of 50 HPS 150 W luminaries, it will reduce electrical energy consumption by 22765 kWh per year.

3 LED luminary measurements in real conditions

RTU campus at island "Kipsala" in Riga is chosen as appropriate test place for LED luminary testing in real conditions. LED luminaries of different manufacturers are placed there to obtain photometrical and energy readings. LED luminaries are placed between (see Figure 5) high pressure sodium vapour (NaHPS) lamps, so that it is possible to switch off NaHPS to get readings only of LED luminary.

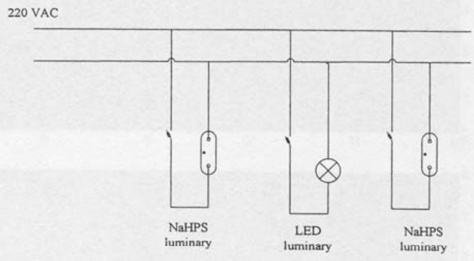

Fig. 5. Connection of luminaries

3.1 Photometrical measurements

Measurements for 51W LED luminary were made in June 16 (see figure 6), weather conditions with no clouds, dry road and waning moon, and in June 30 (see figure 7) with different weather – cloudy, no moon, dry road. For comparison, measurements of 150W high pressure sodium vapour lamps (NaHPS) the same dates and conditions.

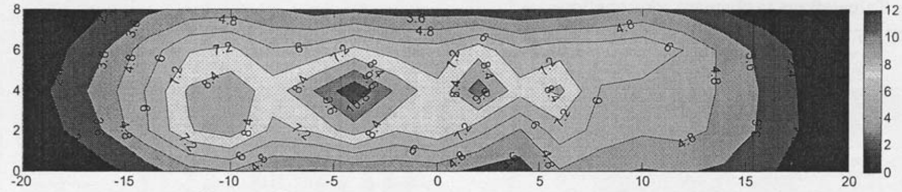

Fig. 6. Measurements for LED luminary at June 16

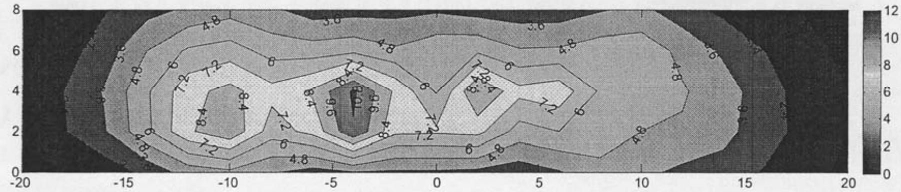

Fig. 7. Measurements for LED luminary at June 30

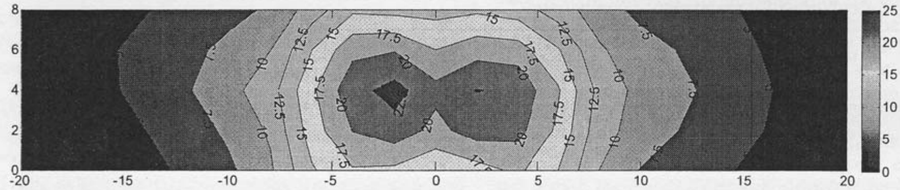

Fig. 8. Measurements for NaHPS luminary at June 16

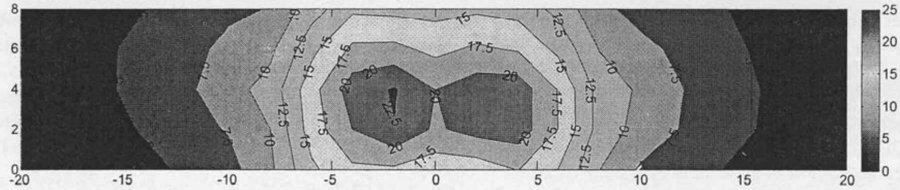

Fig. 9. Measurements for NaHPS luminary at June 30

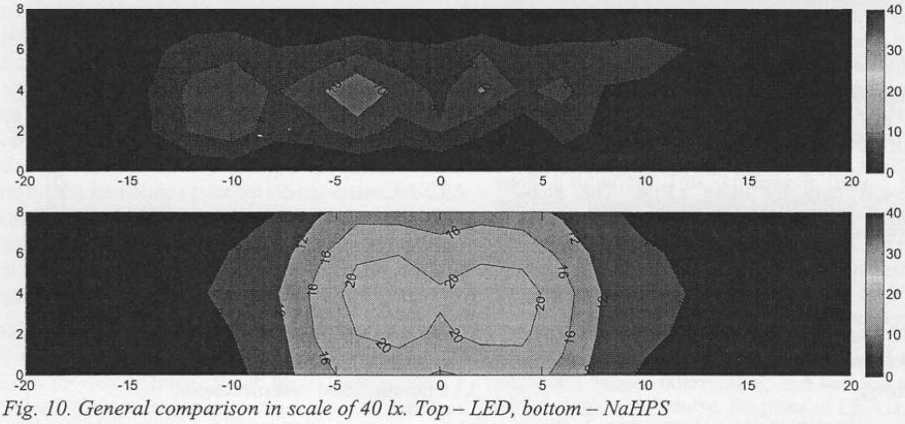

Fig. 10. General comparison in scale of 40 lx. Top – LED, bottom – NaHPS

3.2 Energy measurements

Table 4 shows values from energy readings taken with oscilloscope, as power supply distortion was inessential, for calculation power supply voltage was considered as sinusoidal. From the readings can observe that LED luminary without PFC has very high reactive power, even higher than high pressure sodium vapour lamp. Also total harmonic distortion factor is very high, but cosφ1 is in the range of according requirements of electricity provider. Other tested LED luminaries with similar power have integrated PFC into power supply electronics, thus having cosφ 1 in the range of 0.97 to 1, THD is in the range of 16% to 29% and reactive power Q is in the range of 7 var to 57 var.

Table 4. Energy readings of luminaries

Luminary \ Parameter	U, V	I, A	P, W	φ1	cosφ1	I_1, A	THD, %	S, VA	Q, var
LED luminary w/o PFC	225	0.39	51	19	0.95	0.24	128	**87.2**	70.73
NaHPS luminary with 400 W lamp	225	1.73	369	-14	0.97	1.67	28	**395**	141
NaHPS luminary with 150 W lamp	226	0.78	165	-18	0.95	0.77	20	**176**	63

4 Conclusion

According to electrical characteristics of such LED luminary without PFC, by implementing it into the lighting network, reactive power must be compensated, because it can make difference in rates of consumed electrical energy given by electricity supplier.

Voltage drops and oscillations at the lighting network doesn't affect LED luminary operation, because all of the tested luminaries are equipped with "buck" type converter, and this is an advantage over convenient NaHPS lamps who are flickering at certain voltage value.

Although LED luminary manufacturers declare that their 35W – 50W luminary can replace convenient 150W NaHPS luminary, practical measurements show that it is possible, but not on all roads. Their luminaries are designed for maximal output at 8 meter height, but typical height of pillar in Riga is 9.7 m which is more for NaHPS lamps, also distance between pillars is different. So according existing CIE recommendations, such low power LED luminaries can use on roads of M4 and M5 class and it is not recommended to use them on road classes M1-M3. Potential fastest pay-back time of investment could be at parks, by replacing existing 100W NaHPS lamps with low-power LED luminaries, but according to their price.

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Appendix 25

Galkins, I., **Avotins, A.**, Suzdalenko, A., Ribickis, L. Comparison and Choice of Supply and Driver Unit for Power LED Luminary. RTU, Enerģētika un elektrotehnika. No. 25, 2009, pp. 137–140. ISSN 1407-7345.

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SCIENTIFIC PROCEEDINGS OF RIGA TECHNICAL UNIVERSITY
THE 50TH INTERNATIONAL SCIENTIFIC CONFERENCE „POWER AND ELECTRICAL ENGINEERING," OCTOBER 2009

Comparison and Choice of Supply and Driver Unit for Power LED Luminary

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***Abstract* - the given paper estimates LED lighting technology in the context of development of Riga city illumination system. The main content of the presented report is the analysis of the photometrical and electrical performance of power LEDs at different supply and driving conditions. Possible configurations of the LED luminaries are described, as well as experimentally tested and compared. Conclusions regarding the further development of the LED luminaries are made.**

I. LUMINARIES OF RIGA CITY ILLUMINATION SYSTEM

Riga city lighting system has three main goals to achieve: to provide safety for all type traffic users on road, to provide visibility of pedestrians and their safety, and to improve environment at night.

Main maintenance costs for Riga city illumination system are related with electrical energy consumption. In 1995 Riga started to change high pressure mercury vapor lamps (400W and 250W) to high pressure sodium lamps (250W and 150W). It made possible to reduce energy consumption from 12,7MW to 6,7MW remaining the same illumination level and costs for electrical energy consumption, due to tenfold raise of electrical energy tariff from 1993. As Riga city is growing, the total energy consumption for illumination systems is also growing and a new solution is necessary.

To compare energy efficiency of different light sources, luminous efficacy in lumens per watt (lm/W) should be determined, that means the amount of light produced for each watt of electricity consumed by the light source. Currently, the most efficacious white LEDs can perform similarly to fluorescent lamps, because they have very high correlated color temperatures (CCTs), often above 5000K, producing "cool white" light and "warm white" (2600K to 3500K).

Fluorescent and high-intensity discharge (HID) light sources need ballast, which provides a starting voltage and limits electrical current within the lamp. LEDs are current-driven devices, their brightness and color varies with their forward current, IF and the LEDs forward voltage drop, UF. To solve this problem LEDs require supplementary electronics, usually called drivers. The driver converts line power to the appropriate voltage and current, and may also include dimming and/or color correction controls. Most available LED drivers are typically efficient for about 85%. So LED efficacy should be discounted by 15% to account for the driver. For a rough comparison, the range of luminous efficacies for traditional and LED sources, including ballast and driver losses as applicable, are demonstrated below.

TABLE I
LUMINOUS EFFICIENCY FOR DIFFERENT LIGHT SOURCES [1]

Light Source	Typical Luminous Efficacy Range in lm/W
Incandescent (no ballast)	10-18
Halogen (no ballast)	15-20
Compact fluorescent (CFL) (incl. ballast)	35-60
Linear fluorescent (incl. ballast)	50-100
Metal halide (incl. ballast)	50-90
Cool white LED 5000K (incl. driver)	47-64
Warm white LED 3300K (incl. driver)	25-44

II. BASIC FEATURES OF LED TECHNOLOGY

The fast development of LED (Light Emitting Diode) technology, also called "a light for the 21st century" has a great potential to achieve these efficiency improvements while maintaining high performance and reliability that supersede many currently used sources, like conventional incandescent bulb and fluorescent bulb. This technology is already introduced into a broad range of applications.

Physically, LEDs operate like p-n junction diodes, when a positive differential voltage is applied across the anode and cathode, an electron is recombined with a hole, and it releases energy. The released energy can be in the form of emissions in the optical range, using different p-n junction materials. The wavelength of the emitted light depends on the band gap characteristics of its p-n junction material. LED materials have relatively low reverse breakdown voltages since they have relatively low band gaps. Semiconductor materials used to produce LEDs include gallium phosphide, indium gallium nitride, silicon, silicon carbide, diamond, zinc selenide and some others.

TABLE II
LED WAVELENGTHS OF DIFFERENT DYE MATERIALS

Wavelength (nm)	Color name	Forward voltage (U_F @20mA)	LED Dye Material
940	Infrared	1,5	GaAlAs/GaAs
635	High eff. Red	2	GaAsP/GaP
570	Super lime green	2	InGaAlP
430	Ultra Blue	3.8	SiC/GaN
8000K	Cool white	3.6	SiC/GaN

Basically LEDs are chosen according to their spectra and consumed energy. The important parameters of LEDs are: IF – maximal forward current; VF – maximal forward voltage; Θ - viewing angle. The constructed luminary's working parameters may be calculated from the diagrams, that demonstrate luminous flux dependency on forward current and junction temperature.

Too high temperature can permanently damage LED, or change its luminous flux. The luminous flux values given by LED manufacturers are based on LED junction temperature (Tj) of 25°C, tested under conditions that are different from them in reality. LEDs in a well-designed luminary with adequate heat sinking will produce 10%-15% less light than indicated by the "typical luminous flux" rating.

The average life expectancy of a LED light is 60,000 hours, which greatly reduces the maintenance costs of lighting. Color has high purity and brightness. LED products almost cover the whole spectrum of visible light and have high brightness of the color. LED lights are environmentally friendly, because they have no mercury in light source and no ultraviolet radiation in beam of light, allowing them to meet special illumination quality requirements.

As a kind of solid light source LED is shock resistant. The surface of LED light source can be safely touched. LED light has strong emitting direction and makes good use of luminous flux. LED can be powered with direct current which is safer in use and started up at least in milliseconds with no influence of startup temperature and realizes the full luminous flux instantly.

III. POWER SUPPLIES FOR LED LUMINARIES

LEDs themselves are low voltage semiconductor elements (diodes) that are not directly compatible with common AC networks. Therefore some converter is always required to supply LED luminary.

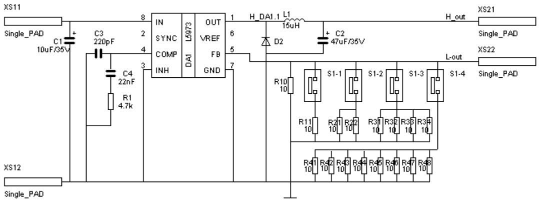
If the luminary must provide some constant amount of light its power supply must ensure the corresponding constant current of the LEDs. This can be done with some traditional equipment like voltage source and series balancing resistor or current regulator (more efficient and preferable solution).

Light dimming is only possible with more complex power supply. Preliminary analysis revealed three basic light control approaches: 1) regulation of value of LED's current; 2) pulse width modulation of the current; 3) grouping and sectional powering of LEDs. Besides that it is possible to combine the first two approaches with the third one.

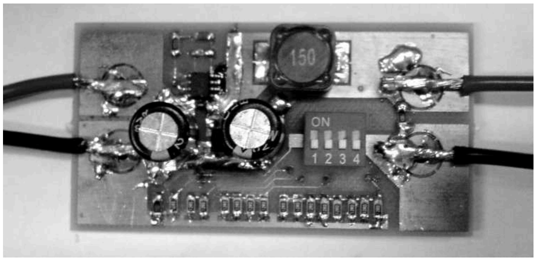
A. *Regulation of current*

The current regulator of the luminary may be based on a typical closed loop that includes a current feedback with current sensor, error amplifier, some PI or PID regulator and power converter. It is, however, more difficult to find an integrated solution for such current loop while discrete implementation is bulky because of the measurement of current. That is why it was decided to adopt an existing voltage regulator to the discussed application [3].

Such voltage regulators are also based on the closed loops, but they include voltage feedbacks. The sensor of the feedback is usually a voltage divider that in steady state keeps 1.235V in its midpoint. The upper and lower parts of such divider may be quite arbitrary chosen, but their ratio defines the output voltage. The divider may be described as the branch with constant current that is set by means of the lower resistor at the level of $1.235V/R_{LOW}$. Then the upper resistor may be even non-linear, for example, series of LEDs – its current will also be stabilized [4].



a) electrical diagram



b) laboratory sample

Fig. 1. The current regulator of LED luminary that is based on an existing integrated voltage regulator.

The proposed example (Fig. 1) is based on the integrated circuit L5973. In order to adjust the current from 0.35A to 2.8A (for tested 70W luminary), lower resistor is changed from 3.5 to 0.44 Ohm (1.235/0.35 and 1.235/2.8 – respectively). Power losses in the lower resistor are changed from 0.43 to 3.46W (less than 5%) that is acceptable for laboratory purposes.

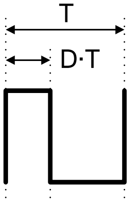
B. *Pulse with modulation of current*

This approach is based on the phenomenon of inertia of the human eye. If a luminary is blinking fast enough then such blinking is recognized as dimming. The depth of the dimming depends on the duty cycle of the signal (Fig. 2-a). There are several possible realizations of this approach.

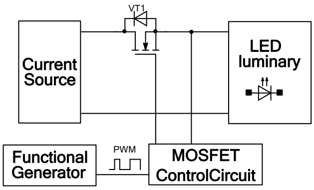
1) Direct PWM signal may be applied to the transistor commutating DC voltage to series connected LEDs and balancing resistor.
2) Inverted PWM signal may be applied to the transistor short-circuiting the series connected LEDs.

3) Direct PWM signal may be used as enable signal for the current stabilizing IC [4][5].

For laboratory testing (Fig. 2-b) the first approach was used. PWM signal was taken from a laboratory signal generator and through a driver circuit applied to the transistor.



a) PWM signal



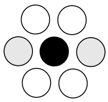
b) laboratory hardware

Fig.2. The current regulator of LED luminary that is based on an existing integrated voltage regulator.

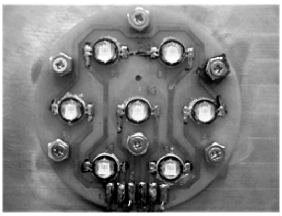
C. Commutation of groups

If the luminary contains few lighting devices (for example, several LEDs) they can be switched on and off separately or in groups thus providing several steps of lighting. Utilization of the binary weighted groups gives more levels of lighting with more constant step between the levels. Of course, each group of LEDs requires its own power supply that, however, may be less complex (3 laboratory power supplies were used in the experiments) [6].

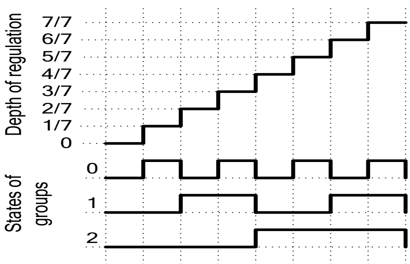
Since in the given research 7 LEDs are used it is efficient to use groups of 1, 2 and 4 diodes (Fig. 3-a and Fig. 3-b). Then there are 7 available levels of power and 7 levels of brightness (Fig. 3-c).



a) configuration



b) laboratory example



c) operation

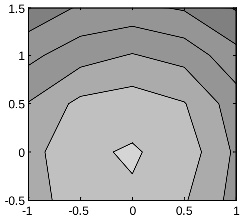
Fig. 3. Grouping of lighting elements in the 70W 7 LED luminary.

IV. EXPERIMENTAL RESULTS

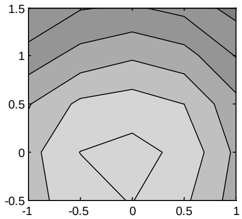
The mentioned approaches were tested with 70W LED luminary that consists of 7 W724C0 LEDs (2.8A, 10W ~80% of which is released as heat), the corresponding heatsink and connectors available for each binary weighted group of LEDs. The experiments were realized in order to find the most energy saving and cost effective solution, as well as to uncover the properties of dimming methods and their efficiency.

The current regulation, current PWM and group switching methods were tested with 1/7, 3/7 and 5/7 of the parameter. Then the current regulation method requires 2.8/7=0.4A, 1.2A and 2.0A levels of the current, PWM – 100/7≈14.3%, 42.5% and 72.5%, values of the duty cycle, but for the group switching – 1, 3, and 5 elements powered with rated current of 2.8A.

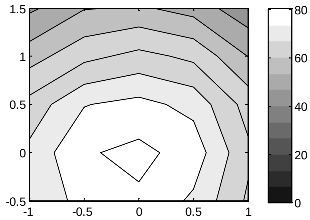
Typical light distribution over the explored surface is presented in Fig. 4. As it was expected the measured brightness is maximal just under the luminary and drop significantly (about 20% per 1m) across the distance. No other significant light spots or shadows are found. In whole this is typical lighting picture for luminary without reflectors, diffusers or other light equalization means.



a) group switching



b) current PWM



c) current regulation

Fig. 4. Lighting at 3/7 of control parameter taken with different types of the dimming

The similar picture could be presented for the other values of the regulation parameter. However, it is more important to compare brightness at different control approaches and at different levels of the corresponding control parameter that is provided in Table IV. It is obvious from this table that switching of groups and PWM provides quite linear regulation (9% and 8% respectively) while current regulation is highly non-linear (24%). This phenomenon could be explained by non-linear lighting characteristic of LED itself. At the same time the current regulation approach gives more light at the same level of the control parameter.

TABLE IV
AVERAGE BRIGHTNESS [LX] AT DIFFERENT POWER SUPPLIES

Value / Type	1/7	3/7	5/7
Group switching	16.4	49.8	74.9
Current PWM	17.0	54.4	91.7
Current Regulation	25.2	66.4	95.2

Another table (Table V) represents the operation temperature of LED package. It shows that in PWM and current control modes the temperature depends on the operation parameter, but in group switching mode the operation LED temperature is about 100°C.

TABLE V
LED OPERATION TEMPERATURES [°C] AT DIFFERENT POWER SUPPLIES

Value / Type	1/7	3/7	5/7
Group switching	96	96	103
Current PWM	36	51	79
Current Regulation	42	63	79

The next significant comparison is comparison of the consumed power (Table VI). This table represents that current the regulation consumes less power for the same level of control parameter while the implemented and tested PWM is the most power consuming. However, these data depend a lot on the power calculation methodology. Also, it must be noted that alternative PWM approaches (for example, methods 2 and 3 from section III.B) might be more effective.

TABLE VI
CONSUMED POWER [W] AT DIFFERENT POWER SUPPLIES

Value / Type	1/7	3/7	5/7
Group switching	11.2	32.0	51.4
Current PWM	10.8 (10.5)	38.3 (34.9)	71.8 (59.9)
Current Regulation	8.5	28.0	49.2

CONCLUSIONS

The first LED's for illumination were available 2-3 years ago, and various products now are available at the market. A year ago high power LED's were developed and soon we can expect next generation of LED products. Also prices for LED luminary for street illumination have been decreased for 20-45% for past years, becoming more attractive for city illumination system managing companies.

So far the described experiments demonstrate the effectiveness of the current control method. This conclusion has two sides. The first one, the lower is current the higher is efficacy of diodes [lm/W]. The second – lower current results in the reduced operating temperature of LEDs and, hence, in higher light output (smaller losses). The efficiency of all control methods is summarized in Fig.5.

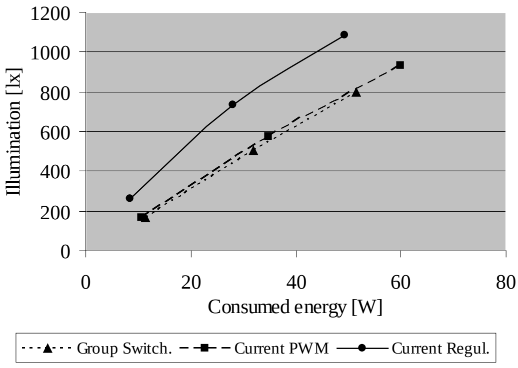


Fig. 5. Efficiency of dimming control methods

All LEDs have the same drawback – their lifetime directly depends on the operating temperature. Therefore the current control and PWM approaches are more preferable also from this point of view.

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Appendix 26

Apse-Apsitis P., **Avotins A.**, Ribickis L., System and method for monitoring real power consumption. WIPO patent WO2013/093554 A1, patent publication date 27.06.2013.

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(54) Title: SYSTEM AND METHOD FOR MONITORING REAL POWER CONSUMPTION

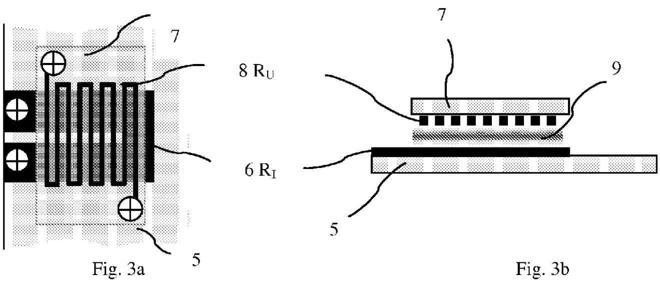

Fig. 3a Fig. 3b

(57) Abstract: The system for monitoring active electrical power consumption by consumers belonging to the same metered group comprises: sensors (1) for measuring real-time load active resistance; a computing device (2) and data transmitting system (3) adapted to transmit data and/or signals between each sensor and the computing device. The sensor for measuring real-time load active resistance used in the offered system is being designed as an electrical shunt and voltage divider and contains: two PCBs (5, 7) - one comprising electric current measuring resistor (6) and the other - voltage measuring resistor (8); said resistors being fixed thermally closely - one opposite another with an electric current non-conductive layer between them; the sensor further comprising a resistor (10) being electrically connected in series with the voltage measuring resistor; microprocessor (11) adapted for reading sensor's measurements and performing operations to calculate real-time active resistance of the consumer.

WO 2013/093554 A1

SYSTEM AND METHOD FOR MONITORING REAL POWER CONSUMPTION

Technical field

The invention relates to methods, systems and devices for monitoring of energy consumption, more particular, to systems for monitoring real electrical power consumption by consumers belonging to the same metered group.

Background Art

Electrical power consumption by consumers belonging to the same metered group or groups typically is metered in one place by one meter (Fig. 1). The electricity charge billed for electrical power consumed by households is calculated for active (real) electrical power consumed. The electricity charge for industrial consumers at high reactive power is calculated for the consumption of reactive power. Such a common metering does not allow monitoring the individual consumer's (e.g. electronic device) electricity consumption, identification of consumers with increased energy consumption or unreasonably connected consumers.

Use of individual electricity consumption meter (electricity meter) for each consumer significantly increases installation and maintenance costs.

Identification of the individual power consumption (W_1, W_2, W_n) can be realized using electrical power distribution monitoring among consumers or electrical resistance monitoring among consumers (Fig. 1). The determination of the power consumption is made using the following formulas:

$$W = P \times T = I \times U \times T = \frac{U^2}{R} \times T \qquad (1)$$

where W is electric power, Wh,

P - consumer's capacity, W,

T - time, when the power P is consumed, h,

I - consumer's current, A,

U - consumer voltage, V,

R - consumer's active resistance, Ω,

$$W_{sum} = W_1 + W_2 + ... + W_n \qquad (2)$$

$$\frac{W_1}{W_{sum}} + \frac{W_2}{W_{sum}} + ... + \frac{W_n}{W_{sum}} = 1 \qquad (3)$$

Voltage and time for all consumers are of equal size. Then ratio of each consumer's power consumption in total consumption is:

$I_1/I_{sum} + I_2/I_{sum} + \ldots + I_N/I_{sum} = 1$; (4)

or:

$1/R_1 + 1/R_2 + \ldots + 1/R_N = 1/R_{sum}$; (5)

Prior art shunts for power consumption measurement being made of material with a low resistance temperature coefficient are expensive. Such resistance is generally determined by the expression (6):

$$R(t) = R(20) \times \{1 + \alpha[t - t(20)]\} \quad (6)$$

where R(t) is resistance value at temperature t, Ω,

R(20) - resistance value at 20°C, Ω,

α - electrical resistance temperature coefficient for the material, K^{-1},

t - temperature, °C,

There are known methods and devices for current measurement, power measurement with exclusion of temperature coefficient impact, as well as for central monitoring of electrical power consumption by consumers belonging to the same metered group.

There is known electric power consumption meter (EP 0161447, DE 10211117) comprising shunt resistance and measuring resistance being coupled with one another thermally closely so that the measuring resistance on temperature changes in percentage terms evenly as does the shunt resistance and thus a temperature compensated voltage signal is provided at the output of the operational amplifier. The known device is relatively complex and expensive in commercial manufacturing.

There is known a transducer for use in a current sensor formed on a PCB (US6414475), comprising a first sense coil and a substantially co-located second sense coils both being formed on a common PCB. The disadvantage of the know device is relative complexity of its electrical scheme, as well as insufficient accuracy of measurement results. The formation of the sensor's elements on different sides of a common PCB decreases accuracy of measurements, because typically the material of PCB is bad thermal conductor. Thus the elements of the sensor do not have the same operating temperature, which negatively affects measurement results. Also the presence of reactive components in the known sensor decrease accuracy of measurements. Further disadvantage of the known device, which negatively affects the precision of the calculation results is that analog-to digital signal corrector is being performed after mathematical processing of measurement results.

Thus the prior art methods and devices increase the total price of power metering equipment due to complex manufacture of its components. Such devices and methods become cost-ineffective if the metered group contains several consumers (e.g. 5 or more). Also the construction of the closest prior art devices does not allow to ensure the sufficient accuracy of measurements.

Disclosure of Invention

The aim of the offered invention is to eliminate drawbacks of the prior art and to develop a cost-effective system and method for monitoring active electrical power consumption by consumers belonging to the same metered group ensuring sufficient accuracy of the measurements.

As used herein the term “consumer” or “consumers” refers to consumers of electricity. The term can refer e.g. to household(s), electrical device(s) or groups thereof. The term “group” in the phrase “one monitored energy consumption group” or “consumers belonging to the same metered group” refers to group of consumers being metered by the offered device and system. The term “group” can refer to e.g. group of households, group of electrical devices within one household or within more than one household, group of distinguishable spaces within one structure (e.g. set of rooms in one apartment).

The offered system and method allows monitoring of distribution of active power (real power) used by consumers of one monitored energy consumption group. The share of power consumption of each consumer in the group’s total consumption is being determined by measuring each consumer’s active resistance in real time.

The system for monitoring active electrical power consumption by consumers belonging to the same metered group comprises: sensors for measuring real-time load active resistance; a computing device and data transmitting system adapted to transmit data and/or signals between each sensor and the computing device. The sensor for measuring real-time load active resistance used in the offered system is being designed as an electrical shunt and voltage divider and contains: two PCBs – one comprising electric current measuring resistor and the other - voltage measuring resistor; said resistors being fixed thermally closely - one opposite another with an electric current non-conductive layer between them (the resistors are made from material having the same or very similar thermal properties); the sensor further comprising a resistor being electrically connected in series with the voltage measuring resistor; microprocessor adapted for reading sensor's measurements and performing operations to calculate real-time active resistance of the consumer.

Brief description of drawings

Fig. 1 represents a diagram of prior art system for metering of electrical power consumption by group of consumers;

Fig. 2 represents a diagram of a system for monitoring active electrical power consumption by consumers belonging to the same metered group;

Fig. 3a is a schematic top or bottom view of the sensor for measuring real-time active resistance;

Fig. 3b is a schematic side view of the offered sensor for measuring real-time active resistance;

Fig. 4 is a scheme for measuring consumer's current and voltage;

Fig. 5 is an electrical scheme of the preferable embodiment of the operating sensor for measuring real-time load active resistance.

Load current measuring resistor (Ri) voltage Ui and voltage measuring resistor (Ru) voltage Uu (if Rsl>> Ri and Rp>> Ru) are determined by the expressions (7) (8):

$$Ui = \frac{Ri(t) \times U}{Rsl} = \frac{Ri(20) \times \{1 + \alpha[t - t(20)]\} \times U}{Rsl} \qquad (7)$$

$$Uu = \frac{Ru(t) \times U}{Rp} = \frac{Ru(20) \times \{1 + \alpha[t - t(20)]\} \times U}{Rp} \qquad (8)$$

Resistors Ri and Ru have very similar operating temperature and are preferably made of the same material (e.g. PCB copper foil). The ratio of voltages Ui and Uu according to the present invention does not depend on the temperature t.

$$\frac{Ui}{Uu} = \frac{Ri(20) \times \{1 + \alpha[t - t(20)]\} \times U \times Rp}{Ru(20) \times \{1 + \alpha[t - t(20)]\} \times U \times Rsl} = \frac{Ri}{Ru} \times \frac{Rp}{Rsl} \qquad (9)$$

The ratio of Ru /Ri is determined by the dimensions of resistors Ru and Ri and its ratio is constant. Resistors for all monitored consumers are chosen identical and their tolerance is ± 0.5 - 1%.

Such conditions allow summarizing a part of an expression (9) with the symbol K, and obtain (11):

$$\frac{Ui}{Uu} = \frac{Ri \times Rp}{Ru} \times Rsl = K \times Rsl \qquad (10)$$

or

$$Rsl = \frac{Ui}{Uu} \times \frac{1}{K} \qquad (11)$$

to rewrite (5):

$$\frac{Uu1 \times K}{Ui1} + \frac{Uu2 \times K}{Ui2} + ... + \frac{UuN \times K}{UiN} = \frac{Uu\_sum \times K}{Ui\_sum} \qquad (12)$$

or

$$\frac{Uu1}{Ui1} + \frac{Uu2}{Ui2} + ... + \frac{UuN}{UiN} = \frac{Uu\_sum}{Ui\_sum} \qquad (13)$$

The monitoring of each consumer's consumption share in total consumption is provided by the monitoring in real time of the appropriate ratio UuN/UiN.

The system for monitoring active electrical power consumption by consumers belonging to the same metered group (Fig. 2) comprises:

(i) sensors 1 for measuring real-time load active resistance (the number of the sensors 1 corresponds to the number of metered consumers of active electrical power);

(ii) a computing device 2, comprising one or more computer-readable media and computer-executable instructions stored on the one or more computer-readable media that upon execution by the computing device, cause the computing device to perform a calculation of each metered consumer's share of active electrical power consumption (UuN/UiN);

(iii) data transmitting means 3 adapted to transmit data (i.a. wirelessly) and/or signals between each sensor 1 and the computing device 2,

(iv) display 4 for displaying results of calculations by the computing device 2 and/or block 4 providing connection (i.a. remote connection by means of data exchange network, including internet) to the computing device 2.

The sensor 1 for measuring real-time active resistance is being designed as an electrical shunt and voltage divider. The sensor's 1 output voltage and power supply voltage match in phase. Each sensor 1 contains:

(a) printed circuit board 5 comprising electric current measuring resistor 6, R_I in the form of conductive pathways,

(b) printed circuit board 7 comprising voltage measuring resistor 8, R_U in the form of conductive pathways; the resistors 6 and 8 are being fixed thermally closely - one opposite another (directed one to another by conductive pathways) with an electric current non-conductive layer 9 (e.g. aluminum foil oxidized at both sides or thermo paste) being put between them (Figs. 3a and 3b);

(c) resistor 10, R_P being electrically connected with the voltage measuring resistor 8, R_U in series,

(d) microprocessor 11 adapted for reading sensor's 1 measurements, conversion of the readings from analogue to digital form, summing up the converted current momentary values, summing up the converted voltage momentary values and dividing sum of the voltage momentary values obtained by sum of the current momentary values obtained.

The design of the sensor 1 ensures practically the same operating temperature t of resistors Ri, Ru (thus excluding influence of temperature to the accuracy of measurements results), and ensures quite high precision of measurements (if compared with prior art devices using different reactive components), as well as allows to provide simple and inexpensive device for monitoring of distribution of consumption of real power among consumers of one monitored energy consumption group.

The number of the sensors 1 corresponds to the number of metered consumers of active electrical power. The system for monitoring active electrical power consumption by consumers belonging to the same metered group is adapted to electrically connect each consumer metered to the electric power supply through the respective sensor 1 (Fig. 4 and 5), such that the respective consumer's resistance Rsl and the current measuring resistor 6, R_I would build one branch of the resistance bridge circuit of each sensor 1, and the resistor 10, R_P and voltage measuring resistor 8, R_U would build the other branch of the resistance bridge circuit of each sensor 1, where the first output of the resistor 10 is connected to the first output of the respective consumer's resistance Rsl and also connected to one electricity network supply voltage wire; the first output of the resistor 6 is connected to the first output of the voltage measuring resistor 8 and also connected to another electricity network supply voltage wire; the second output of the respective consumer's resistance Rsl is connected with the second output of the resistor 6, and the second output of the resistor 10 is connected with the second output of the voltage measuring resistor 8.

The sensor 1 preferably contains voltage and current linear amplifiers adapted to amplify power of signals (measurement results) received from the resistor 6, R_I and resistor 8, R_U and transmit the amplified signal to the microprocessor 11. Electrical circuit of the linear amplifier and resistors Ri and Ru determine that only “positive” current and voltage values are more than zero. Here is assumed that load value is the same during one period of alternating current, so measuring only half period of load current is sufficient.

The method for monitoring active electrical power consumption by consumers belonging to the same metered group comprises the following steps:

(i) determination the beginning and end of the half-period of alternating current from a power supply at value being close to zero (e.g. via voltage 10-bit ADC readings (1024 levels) comparing to some low level value, for example 2 or 3);

(ii) simultaneous periodical reading of current and voltage momentary values each pre-defined period of time from the thermally closely coupled resistors (6) and (8) having the same or very similar thermal properties, where voltage half-cycle is being determined by direct reading of voltage output value without phase offset, and current half-cycle is being determined by direct reading of current output value;

(iii) sending said readings to the microprocessor 11, where the readings are being converted from analog to digital form by analog-to-digital connectors (ADC);

(iv) summing up by the microprocessor 11 all the current momentary values being read within a pre-defined period of time at the previous step (ii), and summing up all the voltage momentary values being read within the same period of time;

(v) dividing sum of the voltage momentary values obtained at the previous step by sum of the current momentary values obtained at the previous step;

(vi) sending by sensor’s 1 data transmitting means 3 the results obtained at the previous step to the computing device 2 for further processing; preferably said results are being sent by the data transmitting means 3 on request of the computing device 2; the computing device 2 preferably sends requests sequentially to each sensor 1 to transmit said results every 1-2 minutes;

(vii) upon obtaining said results from each sensor 1 - displaying by the computing device 2 value and/or share of active electrical power consumption by each consumer belonging to the same metered group; optionally a connection to data exchange network is provided as well, ensuring remote access to the computing device 2 enabling viewing, displaying and further processing the results of measurements by each sensor 1 and/or results of calculations by the computing device 2.

Claims

1. A system for monitoring active electrical power consumption by consumers belonging to the same metered group, comprising:

(i) sensors (1) for measuring real-time load active resistance; wherein each sensor (1) contains:

(a) printed circuit board (5) comprising electric current measuring resistor (6, R_I) in the form of conductive pathways,

(b) printed circuit board (7) comprising voltage measuring resistor (8, R_U) in the form of conductive pathways; the resistors (6) and (8) are being made from material having the same or very similar thermal properties and being fixed thermally closely - one opposite another with electric current non-conductive layer (9) between them;

(c) resistor (10, R_P) being electrically connected with the voltage measuring resistor (8, R_U) in series,

(d) microprocessor (11) adapted for reading sensor's (1) measurements, conversion of the readings from analogue to digital form, summing up the converted current momentary values, summing up the converted voltage momentary values and dividing sum of the voltage momentary values obtained by sum of the current momentary values obtained;

(ii) computing device (2) comprising one or more computer-readable media and adapted to define share of active electrical power consumption by each consumer belonging to the same metered group;

(iii) data transmitting means (3) adapted to transmit data and/or signals between each sensor (1) and the computing device (2);

wherein the number of the sensors (1) corresponds to the number of metered consumers of active electrical power and said system is adapted to electrically connect each consumer metered to the electric power supply through the respective sensor (1), such that the respective consumer's resistance (Rsl) and the current measuring resistor (6, R_I) would build one branch of the resistance bridge circuit of each sensor (1), and the resistor (10, R_P) and voltage measuring resistor (8, R_U) would build the other branch of the resistance bridge circuit of each sensor (1), where the first output of the resistor (10) is connected to the first output of the respective consumer's resistance (Rsl) and also connected to one electricity network supply voltage wire; the first output of the resistor (6) is connected to the first output of the voltage measuring resistor (8) and also connected to another electricity network supply voltage wire; the second output of the respective consumer's resistance (Rsl) is connected with the second output of the resistor (6), and the second output of the resistor (10) is connected with the second output of the voltage measuring resistor (8).

2. The system according to claim 1, characterized in that the sensor (1) additionally contains voltage and current linear amplifiers adapted to amplify power of signals (measurement results) received from the resistor (6, R_I) and resistor (8, R_U) and transmit the amplified signal to the microprocessor (11).

3. The system according to claim 1 or 2, characterized in that the computing device (2) further comprises computer-executable instructions stored on the one or more computer-readable media that upon execution by the computing device, cause the computing device to perform a calculation of each metered consumer's share of active electrical power consumption.

4. The system according to any proceeding claims, characterized in that it further comprises a display (4) for displaying results of calculations by the computing device (2) and/or block (4) providing connection, including remote access to the computing device (2) enabling viewing, displaying and further processing the results of measurements by each sensor 1 and/or results of calculations by the computing device 2.

5. A method for monitoring active electrical power consumption by consumers belonging to the same metered group, comprising the following steps:

(i) determination the beginning and end of the period of alternating current from a power supply at value being close to zero;

(ii) simultaneous periodical reading of current and voltage momentary values each pre-defined period of time from the thermally closely coupled resistors (6) and (8) having the same or very similar thermal properties, where voltage half-cycle is being determined by direct reading of voltage output value without phase offset, and current half-cycle is being determined by direct reading of current output value;

(iii) sending said readings to the microprocessor (11), where the readings are being converted from analog to digital form by ADC;

(iv) summing up by the microprocessor (11) all the current momentary values being read within a pre-defined period of time at the step (ii), and summing up all the voltage momentary values being read within the same period of time;

(v) dividing sum of the voltage momentary values obtained at the previous step by sum of the current momentary values obtained at the previous step;

(vi) sending by sensor's (1) data transmitting means (3) the results obtained at the previous step to the computing device (2) for further processing;

(vii) upon obtaining said results from each sensor (1) - displaying by the computing device (2) value and/or share of active electrical power consumption by each consumer belonging to the same metered group; optionally.

6. The method according to claim 5, characterized in that the results obtained at the step (v) are being sent by the data transmitting means (3) on request of the computing device (2).

7. The method according to claim 6, characterized in that the computing device (2) sends requests sequentially to each sensor (1) to transmit the results obtained at the step (v) every 1-2 minutes;

8. The method according to any claims from 5 to 7, charaterized in that a connection to data exchange network is provided adapted to ensure remote access to the computing device (2).

9. Use of the system according to any one of claims 1 to 4 for monitoring active electrical power consumption by consumers belonging to the same metered group.

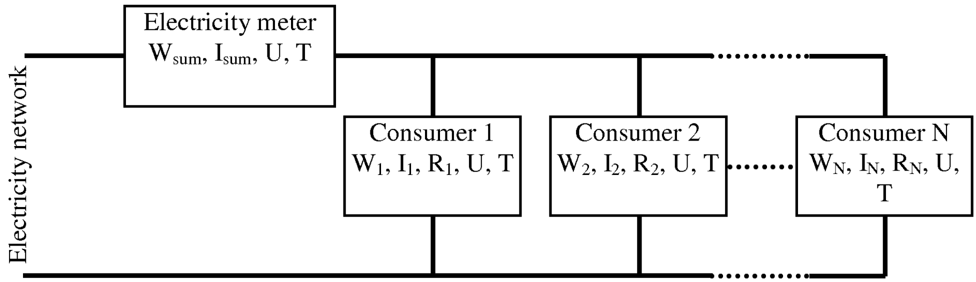

Fig. 1 *(Prior art)*

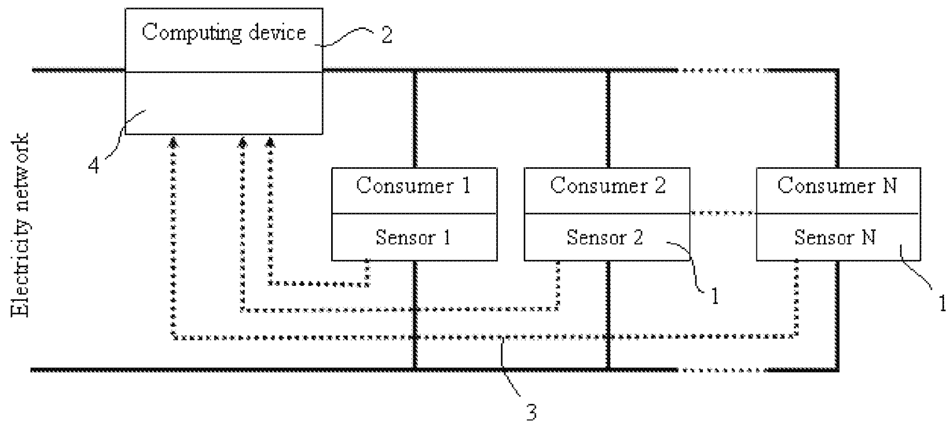

Fig. 2

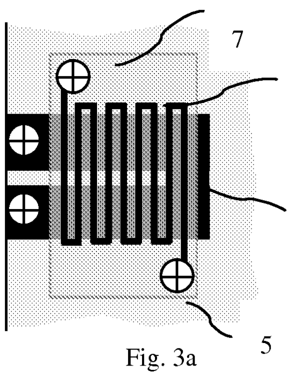

Fig. 3a

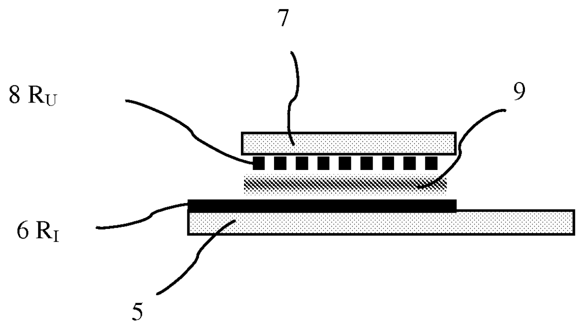

Fig. 3b

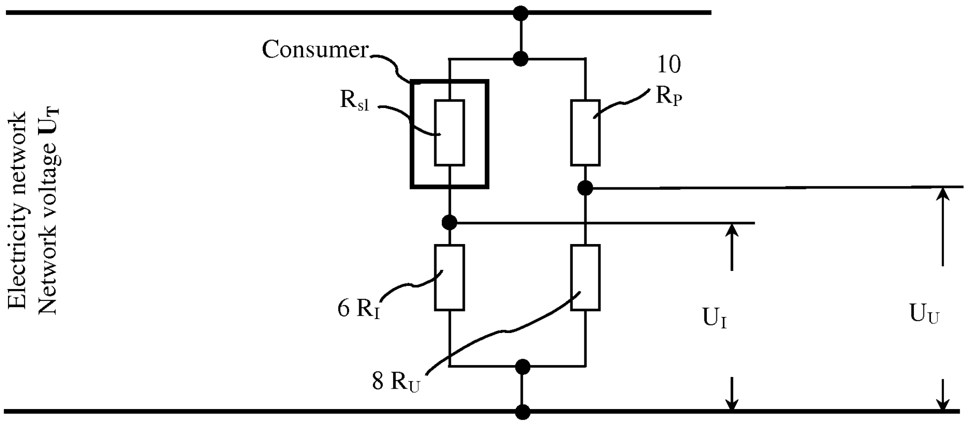
Electricity network
Network voltage U_T
Consumer
R_{sl}
10
R_P
6 R_I
8 R_U
U_I
U_U

Fig. 4

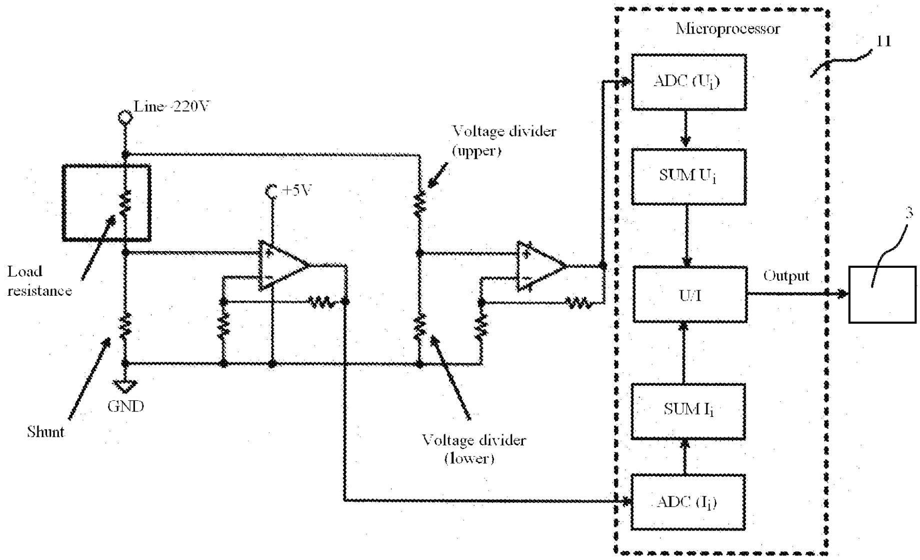
Line 220V
Load resistance
Shunt
GND
+5V
Voltage divider (upper)
Voltage divider (lower)
Microprocessor
11
ADC (U_i)
SUM U_i
U/I
SUM I_i
ADC (I_i)
Output
3

Fig. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2011/055838

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01R21/14 G01R19/32 G01R27/16 G01R27/08 G01R21/00
G01R21/133
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01R H03F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2009/124833 A1 (SIEMENS AG [DE]; NEUMANN BERNHARD [DE]; PROELSS MANFRED [DE]; SCHUMANN) 15 October 2009 (2009-10-15) abstract; claims 1,2,4,5; figure 1 -----	1,5
A	US 2008/018402 A1 (VOGMAN VIKTOR [US]) 24 January 2008 (2008-01-24) abstract; figures 1,3,5 paragraphs [0035], [0036] -----	1,5
A	US 2004/135586 A1 (ZARKHIN MIKHAIL [US] ET AL) 15 July 2004 (2004-07-15) abstract; figures -----	1,5
A	DE 44 03 642 C1 (LICENTIA GMBH [DE]) 8 December 1994 (1994-12-08) abstract; figures -----	1,5
	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 September 2012	24/09/2012

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Fritz, Stephan C.

1

Form PCT/ISA/210 (second sheet) (April 2005)

International application No
PCT/IB2011/055838

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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1

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Information on patent family members

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		EP 0161447 A1	21-11-1985
		FR 2563013 A1	18-10-1985