RIGA TECHNICAL UNIVERSITY
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METHODOLOGY FOR TRANSMISSION NETWORK DEVELOPMENT PLANNING CONSIDERING ELECTRICITY MARKET

Summary of Doctoral Thesis

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RTU Press
Riga 2014

Obuševs A. Methodology for transmission network development planning considering electricity market. Summary of doctoral thesis.– R.: RTU, 2014.– 32 pp.

Printed in accordance with decision No. 14/14 of RTU Doctoral Board P-05 (Power and Electrical Engineering) dated October 20, 2014

EIROPAS SOCIĀLAIS FONDS

EIROPAS SAVIENĪBA

This work has been supported by the European Social Fund within the project «Support for the implementation of doctoral studies at Riga Technical University».

ISBN 978-9934-10-625-5

DOCTORAL THESIS IS PROPOSED FOR ACHIEVING *DR. SC. ING.* DEGREE AT RIGA TECHNICAL UNIVERSITY

Doctoral Thesis is proposed for achieving *Dr. sc. ing.* degree and will be publicly defended at 15:00 on the 27 of November, year 2014, at Faculty of Power and Electrical Engineering of Riga Technical University, 12/1 Azenes street, in room 306.

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CONFIRMATION STATEMENT

Hereby I confirm that I have worked out the present Doctoral Thesis, which is submitted for consideration at Riga Technical University for achieving *Dr. sc. ing.* degree. This work has not been submitted to any other University for achieving scientific degree.

Artjoms Obuševs …………………………….

Date: ………………………

The Doctoral Thesis is written in English language, it contains introduction, 3 chapters, conclusions and recommendations for further work, list of references, 4 appendices, 28 tables and 43 figures, total number of pages is 110. The list of references includes 70 sources of information.

CONTENTS

TOPICALITY OF THE WORK

To foster 2020 climate targets and estimate the technical and economic impact of renewable energy sources (RES) accommodation to transmission networks, several theories based on the social impact of the investments in competitive markets and marginal pricing are created. Electricity market and Smart Grid Technology's (SGT) integration in energy sector of many countries presents completely new problems from different perspectives, such as:

- System operation and reliability issues;
- Network planning including future uncertainties;
- RES integration in different voltage levels;
- Completion of the Internal Energy Market in EU;
- Implementation of novel information and communication technology (ICT) and SGT solutions.

Many transmission expansion planning methodologies and tools have been proposed to obtain the optimal solution for the transmission expansion problem: mostly using classical optimization techniques such as linear programming, dynamic programming, nonlinear programming, mixed integer programming, optimization techniques like Benders and hierarchical decomposition etc [1,2].

Methodologies for transmission network development find an optimum expansion plan by using a calculation procedure that solves a mathematical formulation of the problem. Due to the impossibility of considering all aspects of the transmission planning tasks, to obtain result in form of optimal plan, significant simplifications have to be considered, thus – it should be technically, financially, and environmentally verified, among other examinations, before the planner make a decision. In the formulation of these models, the transmission planning is posed like an optimization problem with an objective function (a criterion to measure goodness of each expansion option), subject to a set of constraints. These constraints attempt to model a great part of the technical, economic, and reliability criteria imposed on the power system expansion [1].

The great majorities of researches describe only one-time static problems investment models and do not consider additional factors that can affect the network expansion in future. The new network operation conditions create new requirements for transmission planning, which include new methods and algorithm elaboration and implementation. A transmission network planner's need to aggregate regional system, defined areas, or subsystems, capacity between areas, including a mixture of supply and demand. The fairly detailed and widely used created model can be implemented for various purposes including expansion planning and energy security analyses.

The main point of this work is to demonstrate the new methodology based on the deterministic concept with a dynamic transmission expansion planning in a perfect competitive electricity market with technical and market economic regulation principals.

OBJECTIVE AND TASKS OF THE DOCTORAL THESIS

The objective of the doctoral thesis is development of transmission development planning methodology with a long-term focus on technical regulation and market – economic regulation principles.

A coordinated approach including optimal power flow implementation for capacity calculation will show the best use of the electricity transmission lines to interconnect Europe, which will open additional opportunities for development planning with social welfare estimation.

To achieve the objective, the following main tasks have been addressed:

1. Transmission planning methodology development according the needs for new methods and tools for planning of the future European power system with considerable integration of renewable energy sources;
2. Elaboration of the transmission network analysis model, including intermitted generation and market conditions within alternating current model;
3. Consideration of the complexity and dimension of development and optimization tasks in long-term, with appropriate method elaboration for the steepest calculation of optimal power flow simplified by direct current method;
4. Alternating current (AC) and direct current (DC) optimal power flow (OPF) models compilation for development planning techniques elaboration.

The methodology has to be as scientific and practical basement, when addressing transmission expansion problem in conditions of free electricity market.

METHODOLOGY OF RESEARCH

To be able to practically achieve the proposed goal, the following assumptions were accepted:

1. This study focuses on perspective development strategies, which are elaborated by given methodology that could contribute to future electricity supply;
2. The given methodology does not attempt to fully and reliably analyse the power system that includes addressing sub-hourly, transient, and distribution/ transmission system requirements;
3. This work presents the new methodology for Modern Transmission System Planning based on common Power System and electricity market characteristics required to reach 20-20-20 targets with address to SRA 2035, R&D Roadmap ENTSO-E and EC Directives;
4. A long-term development planning methodology was developed taking into account uncertainties associated with data assumptions and limitations, which can be reflected by the created methodology.

The algorithms proposed in the thesis consisted of AC/DC OPF models and were realized by the mathematical (numerical) simulation in the environment of MatLab software. The approved algorithms of development processes modelling were used in multi-step development planning tasks.

A consideration of details in the present work is chosen with respect to the applicability of approaches, algorithms and methods: moreover, to keep the contents readable, as well as to avoid its early fall out of use. Another issue is to leave some level of adjustability or partial upgradeability, which would be beneficial in cases when progress can be made due to the new knowledge.

SCIENTIFIC IMPORTANCE OF THE DOCTORAL THESIS

The scientific novelty includes the methodology for transmission network development planning in liberalized conditions. The new object that was investigated was a power system with an increased share of intermitted generation. The main results cover the strategic bidding analysis and price formation mechanisms, optimal power flow techniques and comparison between AC and DC models, development of optimal power flow methods and development process algorithms, which were implemented in the mentioned above methodology for the transmission network development planning in electricity market. Subsequently, the practical implementation of the planning will allow to perform the following: long-term energy balance evaluation, long-term perfect competition electricity price and welfare forecasting for different scenarios.

PRACTICAL VALUE OF THE DOCTORAL THESIS

The EU energy strategy sets ambitious goals for the energy systems of the future that foresees a substantial increase in the share of renewable electricity production. The whole-sale deployment of RES connected to the network at all voltage levels will require radically new approaches for transmission system modelling that could accommodate the coordinated operation of millions of devices and various technologies, at many different scales that are dispersed across EU grid.

The developed methodology algorithms and methods can be used in power system planning practice. The potential stakeholders are the decision makers and planners who require a proper instrument for transmission development planning, as well as a comprehensive understanding of the impacts on the entire System's operation, electricity market as well as generating and transmission capacity requirements in advance, to secure optimal development solutions.

The proposed methodology is intended to be implemented into a software tool appropriate for the application in the development planning.

APPROBATION OF THE DOCTORAL THESIS

The results obtained in the frames of development of the thesis were reported and discussed at 8 international conferences:

1. Interstate DC Line Performance Assessment Methods // The 3rd International Youth Conference on Energetics 2011 // Leiria, Portugal, July 7–9, 2011.
2. Modeling of Zonal Prices with Application in Long-Term Development Planning Strategies // Conference of Young Scientists on Energy Issues "CYSENI 2012", Kaunas, Lithuania, May 24–25, 2012.
3. Assesment of the Network Reliability Calculation in Transmission System Development Tasks// PMAPS`2012 (12th International Conference on Probabilistic Methods Applied to Power Systems). Istambul, Turkey, June 10–14, 2012.
4. Dynamic Management of Power System Sustainable Development with application for Smart Grids // Proceedings of the 5th International Conference on Liberalization and Modernization of Power Systems: Smart Technologies for Joint Operation of Power Grids. Irkutsk, Russia, August 6–10, 2012.

5. Assessment of Wind Production Impacts to a Power System and Market Formation in Baltic // Riga Technical University 53rd International Scientific Conference dedicated to the 150th anniversary and The 1st Congress of World Engineers and Riga Polytechnical Institute / RTU Alumni. Rīga, RTU, 2012.
6. Assessment of optimal power flow application in long-term development planning // 4th International Conference on Power Engineering, Energy and Electrical Drives (PowerEng'2013) Istanbul, Turkey, 13–17 May 2013 ISBN:978-1-4673-6390-7.
7. AC and DC optimal power flow models for long-term development planning // Conference of Young Scientists on Energy Issues "CYSENI 2013", Kaunas, Lithuania, May 29–31, 2013.
8. Transmission Expansion Planning Considering Wholesale Electricity Market and Integration of Renewable Generation // 11th International Conference on the European Energy Market "EEM14", Krakow, Poland, May 28–30, 2014.

PUBLICATIONS

The results obtained in the frames of development of the thesis are includes in 11 publications in international proceedings:

1. A. Obushevs, M. Turcik, I. Oleinikova. Interstate DC Line Performance Assessment Methods // The 3rd International Youth Conference on Energetics 2011 // Leiria, Portugal, July 7–9, 2011.– Conference Proceedings (on CD 7 pp.). ISBN 978-1-4577-1494-8
2. A. Obusevs, I. Oleinikova. Modeling of Zonal Prices with Application in Long-Term Development Planning Strategies // Conference of Young Scientists on Energy Issues "CYSENI 2012", Kaunas, Lithuania, May 24–25, 2012 – Conference Proceedings ISSN 1822-7554
3. A. Obushev, M. Turcik, I. Oleinikova, Kolcun. Probabilistic Method for Wind Production Forecasting and Energy Markets Trades Optimization in Power System with Large Wind Specific Gravity// PMAPS`2012 (12th International Conference on Probabilistic Methods Applied to Power Systems). Istambul, Turkey, June 10–14, 2012.– Symposium Proceedings (on USB 5 pp.).
4. A. Obushevs, I. Oleinikova, Z. Krishans. Assesment of the Network Reliability Calculation in Transmission System Development Tasks// PMAPS`2012 (12th International Conference on Probabilistic Methods Applied to Power Systems). Istambul, Turkey, June 10–14, 2012.– Symposium Proceedings (on USB 5 pp.).
5. I. Oleinikova, M. Turcik, A. Obusev, Dynamic Management of Power System Sustainable Development with application for Smart Grids // Proceedings of the 5th International Conference on Liberalization and Modernization of Power Systems: Smart Technologies for Joint Operation Of Power Grids. Irkutsk, Russia, August 6–10, 2012. ISBN 978-5-93908-081-1.
6. I. Oleinikova, M. Turcik, A. Obushev Dynamic Management of Power System Sustainable Development with Smart Grids application on Transmission Level // The 3rd IEEE International Conference on Sustainable Energy Technologies (IEEE ICSET 2012) Kathmandu, Nepal, 24–27 September 2012. ISBN: 978-1-4577-1869-4

7. A. Obushevs, M. Turcik, I. Oleinikova, G. Junghans. Assessment of Wind Production Impacts to a Power System and Market Formation in Baltic // Riga Technical University 53rd International Scientific Conference dedicated to the 150th anniversary and The 1st Congress of World Engineers and Riga Polytechnical Institute / RTU Alumni. Section of Power and Electrical Engineering Paper 8 of Subsection of Power Systems. Rīga, RTU, 2012. ISSN 1407-7345
8. A. Obushevs, I. Oleinikova. Assessment of optimal power flow application in long-term development planning // 4th International Conference on Power Engineering, Energy and Electrical Drives (PowerEng'2013) Istanbul, Turkey, 13–17 May 2013 ISBN:978-1-4673-6390-7.
9. A. Obushevs, I. Oleinikova. AC and DC optimal power flow models for long-term development planning // Conference of Young Scientists on Energy Issues "CYSENI 2013", Kaunas, Lithuania, May 29–31, 2013 – Conference Proceedings ISSN 1822-7554
10. A. Obushevs, I. Oleinikova. Transmission Expansion Planning Considering Wholesale Electricity Market and Integration of Renewable Generation // 11th Internationa Conference on the European Energy Market "EEM14", Krakow, Poland, May 28–30, 2014
11. A. Obushevs, I. Oleinikova, A.Mutule. Infrastructure of Baltic Region Transmission System: Analysis of Technical and Economic Factors of it's Development // Latvian Journal of Physics and Technical Sciences, 2014, No 4, P. 3–14. DOI: 10.2478/lpts-1014-0023

STRUCTURE AND VOLUME OF THE THESIS

The Doctoral Thesis is written in English language, it contains introduction, 3 chapters, conclusions and recommendations for further work, list of references, 4 appendices, 28 tables and 43 figures, total number of pages is 110. The list of references includes 70 sources of information.

In the first chapter the new network operation conditions are considered, which create new requirements for transmission planning.

In the second chapter the main drivers for the whole transmission grid and well market functioning is analyzed from development perspectives point of view and the need for transmission expansion planning techniques and model has been proposed.

The main point of the third chapter is to demonstrate the new methodology based on the deterministic concept with a dynamic transmission expansion planning in a perfect competitive electricity market with technical and market economic regulation principals.

1. TRANSMISSION PLANNING CONSIDERATIONS

Transmission planning can be classified as static or dynamic according to the tasks that are to be solved. In the static planning tasks, the planners seek the optimal set for the single time period (for instance, single year) with a focus on the final optimal network state for the pre-defined future single period. This thesis will focus on the multiple years' consideration of optimal development strategy identification for the whole planning period, which is classified as dynamic (see Fig. 1.):

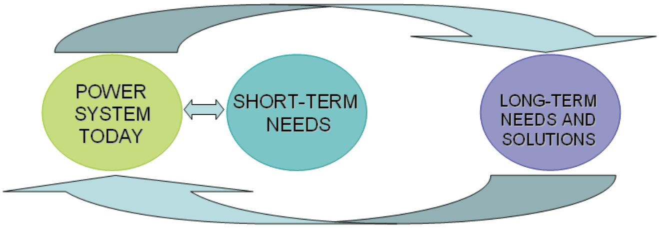

Fig. 1. Planning horizons

The optimal development strategy consideration makes it necessary to apply systems analyses and dynamic multi-step optimisation methods in order to observe reciprocal interconnections of system elements over time and space. A characteristic feature of network analysis is that for selecting an optimal solution, sophisticated systems and various variable parameters must be investigated during the development process.

The basics of the step-wise Power System development approach are established from the following main factors (see Fig. 2.) [3, 4]:

- Time levels / voltage levels / loads, generation etc. modelling;
- Decision-making for advance stage (horizontal information flow) in uncertain conditions only for the nearest time period of 2–5 years;
- Estimation period shall correspond to average life-circle period, approximately within 20 to 30 years;

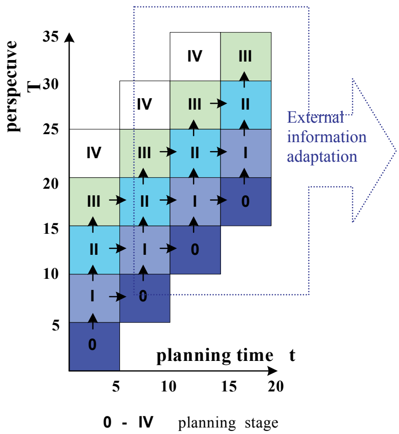

Fig. 2. Development Planning Structure

To realize this particular approach, modelling methods of the existing system development were supplemented with new technical regulation and market economic regulation criteria's and functionalities.

The modelling methods must adequately reflect real systems characteristics as much as possible, as well as include flexible generation incorporation, and perform system technical, economic and ecological criteria calculation. Moreover, effective optimization methods are required to solve optimization tasks with discrete variables [4].

1.1. Transmission Planning in Liberalized Environment

The deregulation of the electricity industry leads to global developments toward the commoditization of electric energy [5, 6]. The liberalization and privatization of the electricity sector began in Chile in 1982 and the trend spread to Latin American countries and the rest of the world in the 1990s [7]. This tendency has increased in Europe and North America, where market forces have pushed policymakers to begin removing artificial obstacles that have shielded electric utilities from competition. The electricity price is far more volatile than that of other commodities normally noted for extreme volatility [6]. Relatively small changes in load or generation can cause large changes in electricity prices in a matter of hours (with real-time dynamic prices in seconds or minutes) [8]. Unlike in other financial markets, electricity is traded every hour of the year; however, it cannot be stored efficiently. Thus, the balance between generation and consumption must be kept every hour of a year [9]. However, electricity differs from other commodity markets. Reason for the obvious difference in markets would be the variety as regards costs/expenses of electricity production. There is nearly no variable cost in hydro, solar and wind generation, however variable costs of power generation from coal, gas and another fossil fuel are considered on a wider scale. To satisfy the demand for low cost power, a great variety of generation sources is needed. Some power generation units are expensive to build; however, they can be operational all year round, continuously sustaining the generation process [10]. Other types like combined heat and power plants are used mostly to cover wintertime heating and consumers' needs during high price periods of the year. Gas powered turbines are used only for certain periods of high price and electricity demand because of their energy intensive nature [11]. Despite different deregulation processes, market concepts are relatively the same. The main tasks of a market are: to unbundle the competitive functions from the monopoly functions and to establish a free wholesale and retail electricity market.

Before liberalisation, most European electricity networks were interconnected for the purpose of mutual assistance and in some cases with a view to carrying out long term import/export contracts for electricity [12]. However, in today's liberalised electricity markets, the role of interconnections has been extended. By providing physical connection between electricity markets, interconnections form the key to the international trade. The European Commission concluded that more interconnection is needed to facilitate companies to extend their activities into other regions outside their traditional areas in order to increase competition [13].

Due to the high levels of concentration of electricity markets, strategic bidding has been deeply analyzed in the last decades by means of game theory simulation models. Current literature points out four major models in use for electricity markets: Bertrand based models, Cournot-based models, Stackelberg-based models, supply function-based models. The supply function equilibrium model applies very well to the market structure of many restructured electricity markets, such as New Zealand, Australia, Pennsylvania-New Jersey-Maryland Interconnection, California Power Exchange. In these markets, the bid format is precisely a supply function [14]. Typically, all of these models simulate the results of electricity markets with strategic suppliers exerting market power, requiring the solution of complex mathematical problems with a considerable computational time. This usually does not fit with the long term analyses for transmission expansion problem that should rely on fast and robust tools that perform market simulations over extended time horizons [15]. The typical approach applied to transmission planning is to consider a perfectly competitive market, where all suppliers bid at their marginal costs.

Integrating transmission networks, building trans-European infrastructures, and creating a single and fully integrated energy market ask about the 218.5 bn.EUR. [The Commission estimates in 2012 that the current total investments requirements for energy networks infrastructure].

1.2. Modern Power System Expansion including Renewable Energy Sources, Europeans Targets and Developments Transmission

Current European legislation defines two different rules related to integration of the European power market [16]:

1. Electricity should flow according to price differentials through the use of market-based capacity auctions, and that cross-border capacities shall not be reduced in order to solve a country's internal congestions;
2. Priority should be given to access for renewable energy sources.

The above-mentioned rules need to be taken into account since they both are crucial for future transmission planning solution, which nowadays depended on market structure (see Fig. 6.).

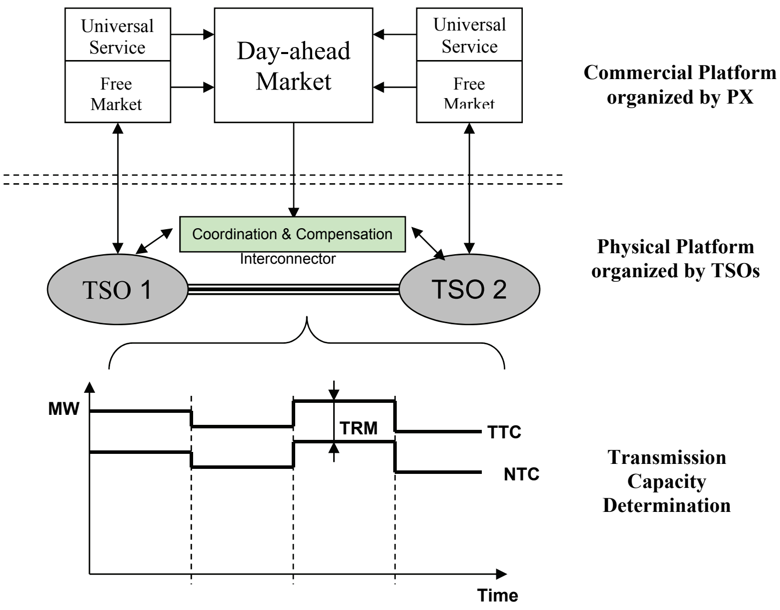

Fig. 6. E-market Environment Structure

Power system should be designed and operated in a way that the demand can be met at all times and under various conditions. Depending on the season, climate, and weather condition, the demand can fluctuate significantly over the single day, week or month. In addition to meeting the variability requirements, there is always some inherent uncertainty about future demand and the future ability of generators. Today there are various operation portfolios with hydro and thermal generation combinations to manage variability.

To set the optimal expansion of the power system – transmission system in particular - under conditions of market environment, forward-looking approaches able to reflect and find balance between requirements (despite often contradictory cases) are necessary.

2. DEVELOPMENT PROCESS MODELLING

2.1 General drivers and Background to the Chapter

In this chapter the main drivers for the whole transmission grid and well market functioning is analyzed from development perspectives point of view.

According to the new requirements it is important to supplement existing transmission planning theory and tools by the following several aspects:

- The attributes to measure the goodness of a solution for each considered scenario (e. g., minimum operation costs, maximum benefits, maximum global welfare, etc.);
- Dynamic pricing;
- The introduction of flexible smart grid technologies;
- Increasing level of uncertainty.

However, this study is made on the large amount of assumptions and there are several relevant aspects that are not taken into consideration. For example aspects of appropriate market design, impact of loss factors on DC/AC interconnectors , etc.

This problem is solved from a position of a system operator, i. e. without any control on the generation planning. The different possible generation mixes and their evolutions over the time horizon are defined through scenarios. Each scenario gives technological solutions for generating units: their capacity, costs and locations (scenarios are based on the different possible energy policy choices).

2.1.1. Social Welfare

To match supply and demand curves in each market area in order to maximize consumer and producer surplus the following Social Welfare concept is used.

Social Welfare is a quantification to assess the potential implications of alternative policy options. The assessment of social welfare shall include a consideration of the additional economic benefit or cost, defined as the sum of the additional individual benefits and costs which are expected to be accrued due to the implementation of the respective policy options compared to the status quo. These benefits and costs shall be analysed independently for tariff customers (as a whole and separated based on their ability to afford the cost of electricity), Market Participants and System Operators. In undertaking this assessment, in all cases, the undertaking party shall clearly specify:

- assumptions about the redistributive effects of an increase of one of the above components for the surpluses of the other groups stated above;

- assumptions about preconditions for market functioning such as market power and liquidity;
- assumptions about implications stemming from external effects

used to undertake the analysis [17].

$$\text{Social welfare} = \text{Producer surplus} + \text{Consumer surplus} \quad (1)$$

Consumer surplus is the difference between what consumers are willing to pay for a product versus what they actually pay. In an energy market, a consumers' willingness to pay can be measured by Value of Lost Load (VOLL). This measure indicates the approximate value of avoiding involuntary energy curtailments. VoLL is the estimated amount that customers receiving electricity with firm contracts would be willing to pay to avoid a disruption in their electricity service [18, 19].

Producer surplus is the difference between what producers are willing and able to supply and the price they actually receive.

2.1.2. Electricity pricing mechanisms

Pricing mechanisms for competitive electricity markets determine either a uniform price (UP), a set of nodal or locational marginal prices (LMP), or only a few zonal marginal prices (ZMP). Each of above mentioned mechanisms is characterized by level of complexity, ability for appropriate allocation of investments as well as rightfully allocates costs for final consumers [20].

Zonal pricing. The zonal pricing method has been introduced as reaction to solve very poor incentive ability of uniform pricing approach. According to the basic principle of zonal pricing, the whole market territory is sub-divided into several zones depending on their respective costs of congestion (Fig. 9.).

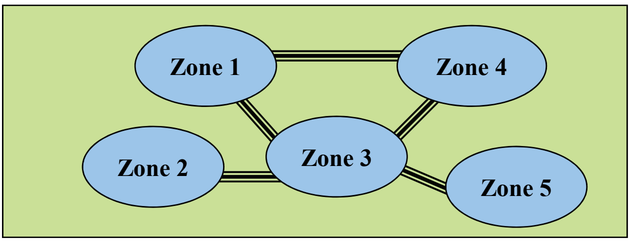

Fig. 9. Zone formation

Higher prices for electricity are paid in zones where demand exceeds transmission capability and vice versa. The price is uniform for entire zone. The zones are usually geographically pre-defined according to expected bottlenecks in grid, however, as in case of Nordic market operation, number of zones can within the year vary according to changes in deployed generating capacities, particularly hydro resources.

Price differences between areas after utilization of transmission capacity between them generate an ownerless income on the spot market, trading flow from the area with a lower price to the area with a higher price. In situations when flow goes from high price area to low price area (towards low price area) due to specific operations or dispatch optimization by transmission system operators (TSOs), generating of ownerless costs occurred [21].

These ownerless costs and incomes are referred as congestion rent (congestion revenue). Within the Nordic region this income is allocated to the TSOs as owners of the transmission grid.

Nodal pricing. Method of determining market clearing prices for a number of locations on the transmission grid – nodes; Node is located in transmission system including generators and loads. Nodal price is equal to the cost of serving the next MW of load at a given location (node):

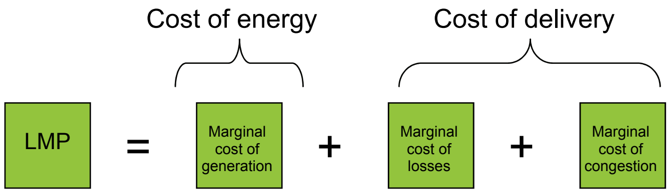

Fig. 11. Nodal price components

Nodal pricing principals:

- Required development of usual equilibrium price determination (include losses, constraints of system);
- Employed bid-based, security-constrained, economic dispatch principle;
- Higher potential for social welfare maximization than UP or ZMP.

The optimization task in a case of zonal and nodal pricing models are based on social welfare maximization of consumers' and producers' surplus areas. The objective function to be maximized could be expressed:

$$\max \sum_{n} \left(\int_{0}^{d^a} D^a(x)dx - \int_{0}^{s^a} S^a(y)dy \right) \tag{3}$$

where (a) represents an zone or node (area), d^a is demand in area (a) and D^a is the demand function in area (a), s^a is supply in area (a) and S^a is the supply function in area (a) and (n) is the number of areas.

Defenders of zonal pricing argue that system based on such principles will be well sufficient to achieve economical efficiency goals with lower complexity and therefore higher transparency to market participants. However, in heavy load periods when congestion is expected exists legitimate concern of market power abuse by market participants. Furthermore, arguable is also ability of right allocation and adequacy of incentives for new investments. Also due to that reasons the evolution of market structures worldwide introduces a nodal pricing principle as the proclaimed benchmark of congestion management, effectiveness and conformity with economic theory and physical laws.

According to aforementioned methods of price determination, the optimal prices in a transmission network are the nodal prices resulting from an optimal power flow performed by a centralized dispatcher.

2.2. Long-term planning methodology under regulation and competition

Development planning is a process to determine an optimal strategy to expand the existing power system transmission network to meet the demand of the possible load growth and the proposed generators, while maintaining reliability and security performance of the power system. The general objective of the power system transmission network development planning task is to determine 'where', 'how many' and 'when' new element/devices must be added to a network in order to make its operation viable for a pre-defined horizon of development planning, with costs minimization and social welfare maximization for optimal expansion/development plan determination.

Main concepts of development planning are based on: Development Action (D-action); Development Step (D-step); Development Plan (D-plan). The essences of the parameters are explained on figure 13.

$$\overbrace{e(t-1)}^{\text{Existing state}} + \overbrace{(\ldots\ldots\ldots)}^{\text{Realized } D-action(s)} = \overbrace{e(t)}^{\text{New state}}$$

Fig. 13. Development state formation

Development plan formation is a complicated process that requires extensive studies to determine many new network elements. Creation of the optimal development plan will ensure adequacy of the grid, generation and demand in the future.

The objective function for the network development plan displays and integrates the technical and economic parameters as well as the power supply reliability [22], ecological, etc. parameters The objective function in (4) represents the social welfare, where the welfare is expressed as the aggregate demand utility bid function minus the aggregate generator offer function, plus aggregated congestion revenue, minus the investment cost in new lines. Objective function is a network development plan g quality criterion, denoted as $F(T,g)$ is calculated by a formula:

$$\max F(T,g) = \max_{g \in \{G\}} \sum_{t=1}^{T} \left(SW(t,e(t),g) + CR(t,e(t),g) - IC(t,e(t),g)\right) \quad (4)$$

where: $t-$ development step serial number; $T-$ number of development steps in estimation period; $g-$ development process; $\{G\}-$ set of all possible development plans; $SW(t,e(t),g)-$ social welfare criterion in development step t, development state $e(t)$ and development process g; $CR(t,e(t),g)-$ congestion revenue aggregated by TSOs in development step t, development state $e(t)$ and development process g; $IC(t,e(t),g)$ – investment costs in development step t and development state $e(t)$ and development process g.

Given that the assumed conditions are observed, $F(t,e(t),g)$ is not dependent on development plan up to development state $e(t)$. Thus, the objective function (4) allows application of dynamic programming.

To consider the impact of liberalized electricity market to technical and economic criteria each development state should be observed at an hourly base. Application of hourly calculation based on OPF allows taking into account the major trends of production and consumption during the day, taking into account consumption time shifting when considering multiple time zones, demand side management and demand response programs, distributed generation, etc [23-24].

Each development process is characterized by number of realized development actions and its realization moment, as well as by each development action realization type. Fig. 15 represent small example with 2 development actions, development step 1 year and 16 development states. The total number of development plans in this example will be 16.

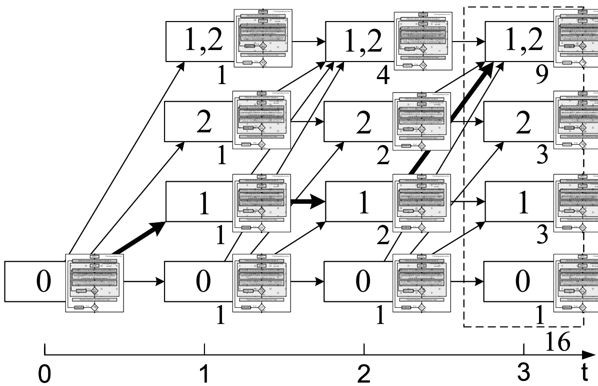

Fig. 15. Development states forming scheme example

In real tasks the number of comparable development plans attains astronomic quantity, therefore it is required to apply specialized dynamic optimization methods in power system sustainable development management process [4]. Within the frame of electric power system dynamic optimization task, power flow calculation must be performed with high-speed and certain accuracy. Due to this factor it is necessary to use specialized methods.

2.3. The AC/DC SCOPF Formulations

This chapter presents the theoretical approach of the optimal power flow method that can be used as a basis for social welfare/price calculation and modelling. OPF includes a security consideration – security constrained optimal power flow. SCOPF is used as a correct basis for transmission pricing, including security constraints by adjusting transfer capacity limits with the Transmission Reliability Margin.

The optimal power flow is a very large and difficult mathematical programming problem. The main aim of OPF is to determine the optimal steady-state operation of a power system, which simultaneously minimizes or maximizes the value of a chosen objective function and satisfies certain physical and operating constraints. To provide complex solutions for the network operation problem analysis and its consideration in development the following mathematical formulations can be implemented.

The objective function of an OPF problem may take many different forms according to the different applications. The general objective is to maximize social welfare which comprises producers' and consumers' surpluses or minimize costs of production. The costs and benefits may be defined as polynomials or as piecewise-linear functions [26-28]. The problem can be formulated schematically as:

$$\max_{x} SW(x) \tag{6}$$

subject to

$$g(x) = 0 \tag{7}$$

$$h(x) \le 0 \tag{8}$$

$$x_{\min} \le x \le x_{\max} \tag{9}$$

where $SW(x)$ objective function of social welfare; $g(x)$ equality constraints of active and reactive power balance; $h(x)$ inequality constraints of power flow limit of line, bus voltage limits; $x_{\min}, x_{\max}$ active and reactive power generation limits. One of the nodes is assigned a zero phase angle by setting its phase angle upper and lower limits to zero (slack bus).

The AC version of the standard OPF problem is a general non-linear constrained optimization problem, with both nonlinear costs and constraints. In a system with n_b buses, n_g generators, n_l branches and n_c consumers, the optimization variable x is defined as follows:

$$x = [\Theta; V; P_G; Q_G; P_L; Q_L] \tag{10}$$

The objective function (6) is a consumers' utility minus producers' cost (represented by function $B_L^i(P_L^i)$ and $C_G^j(P_G^j)$, respectively) shall be maximised subject to equality and inequality constraints:

$$SW(P_G, P_L) = \left\{ \sum_{i=1}^{n_c} B_L^i(P_L^i) - \sum_{j=1}^{n_g} C_G^j(P_G^j) \right\} \to \max_{\Theta, V, P_G, Q_G, P_L, Q_L} \tag{11}$$

The equality constraints (7) consist of two sets of n_b nonlinear nodal power balance equations, one for real power and one for reactive power.

$$g_P(\Theta, V, P_G, Q_G, P_L, Q_L) = 0 \tag{12}$$

$$g_Q(\Theta, V, P_G, Q_G, P_L, Q_L) = 0 \tag{13}$$

The inequality constraints (8) consist of two sets of n_l branch flow limits as non-linear functions of the bus voltage angles and magnitudes, one for the from end and one for the to end of each branch.

$$h_f(\Theta, V, P_G, Q_G, P_L, Q_L) \le 0 \tag{14}$$

$$h_t(\Theta, V, P_G, Q_G, P_L, Q_L) \le 0 \tag{15}$$

The variable limits (9) include an equality limited reference bus angle and upper and lower limits on all bus voltage magnitudes, real and reactive generator and consumption injections.

$$\theta_{ref} \le \theta_i \le \theta_{ref}, \qquad l = l_{ref} \tag{16}$$

$$v_i^{\min} \le v_i \le v_i^{\max}, \qquad l = 1...n_b \qquad (17)$$

$$P_{G,\min}^j \le P_G^j \le P_{G,\max}^j, \qquad j = 1...n_g \qquad (18)$$

$$Q_{G,\min}^j \le Q_G^j \le Q_{G,\max}^j, \qquad j = 1...n_g \qquad (19)$$

$$0 \le P_L^i \le P_{L,\max}^i, \qquad i = 1...n_c \qquad (20)$$

$$0 \le Q_L^i \le Q_{L,\max}^i, \qquad i = 1...n_c \qquad (21)$$

Here l_{ref} denotes the index of the slack bus and θ_{ref} is the slack angle.

When using DC network modelling assumptions, the standard OPF problem above is simplified to a quadratic program, with linear constraints. In this case, the dc power flow greatly simplifies the power flow by making a number of approximations including 1) completely ignoring the reactive power balance equations, 2) assuming all voltage magnitudes are identically one per unit, 3) ignoring line losses and 4) ignoring tap dependence in the transformer reactance [26, 29, 30].

OPF development has been closely following the progress in numerical optimization techniques and computer technology. Many different approaches have been proposed to solve the OPF problem. These techniques include nonlinear programming, quadratic programming, linear programming, mixed programming, as well as interior point and artificial intelligence algorithms etc. [31–33]. The most successful interior point methods are based on using a primal–dual formulation and applying Newton's method to the system of equations arising from the barrier method. The theory of nonlinear primal - dual interior point methods (PDIPM) has been established based on three achievements: Fiacco and McCormick's barrier method for optimization with inequality constraints [34], Lagrange's method for optimization with equality constraints, and Newton's method for solving nonlinear equations [35]. This method has been widely used in power system optimization problems because of its favorable convergence, robustness, and insensitivity to infeasible starting points.

The primal-dual interior point method has become the algorithms of choice for long-term development planning strategies. Given an optimization problem in the form of (6), PDIPM formulates the Lagrangian with barrier functions as:

$$L^{\gamma}(x,z,\lambda,\mu) \equiv SW(x) + \lambda^T \cdot g(x) + \mu^T (h(x) + Z) - \gamma^k \sum_{j=1}^{Nineq} \ln(Z_j) \qquad (24)$$

where λ^T , μ^T are Langrage multipliers for the constraints of equations (12)–(15); γ^k is the barrier parameter that is forced to decrease toward "0" as the algorithm iterates to a solution (k is the iteration counter); N_{ineq} represents the number of inequality constraints. The approach taken involves converting the N_{ineq} inequality into equality constraints using a barrier function and vector of positive slack variables Z_j.

The necessary conditions for a stationary point of the constrained optimization problem are that the partial derivatives of the Lagrangian function with respect to each variable must be zero.

The first order optimality conditions are solved using Newton's method. Each Newton step involves the solution of a reduced system:

$$\begin{bmatrix} \nabla_x^2 L^\gamma & 0 & \nabla_x g(x) & \nabla_x h(x) \\ 0 & [\mu] & 0 & [Z] \\ \nabla_x g(x)^T & 0 & 0 & 0 \\ \nabla_x h(x)^T & I & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta Z \\ \Delta\lambda \\ \Delta\mu \end{bmatrix} = - \begin{bmatrix} \nabla_x f(x) + \nabla_x g(x)\lambda + \nabla_x h(x)\mu \\ \mu - \gamma^k [Z]^{-1} e \\ g(x) \\ h(x) + z \end{bmatrix} \tag{27}$$

where $[\mu] = \begin{bmatrix} \mu_1 & & \\ & \mu_2 & \\ & & \ddots \end{bmatrix}$ and $I = \begin{bmatrix} 1 & & \\ & 1 & \\ & & \ddots \end{bmatrix}$

The variables are updated according to:

$$\begin{aligned} \alpha_p &= \min(\xi \min_{\Delta z_j < 0} (-Z_j / \Delta Z_j), 1) \\ \alpha_d &= \min(\xi \min_{\Delta \mu_j < 0} (-\mu_j / \Delta \mu_j), 1) \\ x &= x + \alpha_p \Delta x; \\ z &= z + \alpha_p \Delta z; \\ \lambda &= \lambda + \alpha_d \Delta\lambda; \\ \mu &= \mu + \alpha_d \Delta\mu; \end{aligned} \tag{28}$$

The parameter ξ is a constant scalar with a value slightly less than one to prevent non-negative variables from being zero and it is set to [0.995−0.99995]. During the Newton-like iterations, the perturbation parameter must converge to zero in order to satisfy the first order optimality conditions of the original problem. The barrier parameter can be evaluated by uses the following rule to update at each iteration, after updating Z and μ:

$$\gamma^k = \sigma(\mu^T Z) / Nineq \tag{29}$$

where σ is a scalar constant between [0−1] and is called center parameter, usually one can get satisfactory convergence by setting parameter around 0.1.

2.4. Comparison of ACOPF and DCOPF models for development planning

To compare the different methods, two approaches were applied: the hourly calculation (considered the whole year as a whole), and the typical schedules for consumption and production by months (monthly characterize trends for 24 hours). Therefore, to determine the criteria for one development state it is necessary produce 8760 calculations using the first approach, and 288 calculations using the second approach. 4 node system is tested.

Configuration of 4 node system contains four nodes, four generators with quadratic or piecewise cost functions, 5 branches with maximal permissible power and annual inelastic loads. Configuration and parameters of the considered system are presented in Fig. 19.

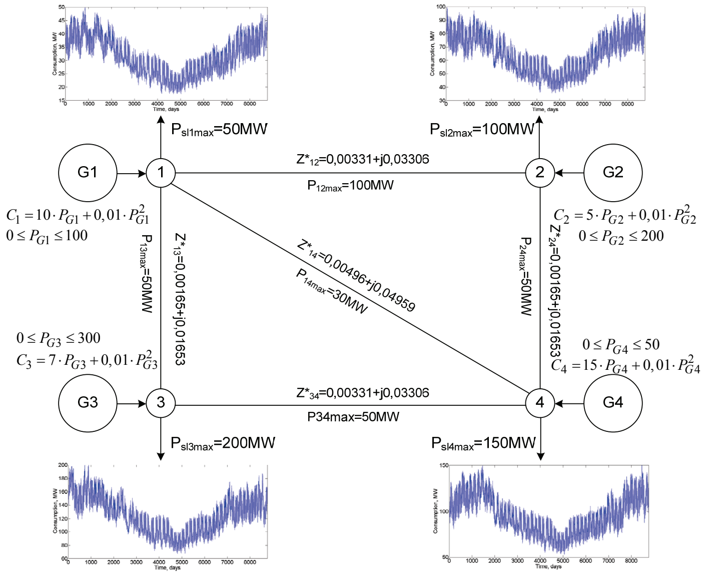

Fig. 19. 4 node system with grid parameters

The results of calculations using the above-described approaches for AC model, taking into account power system constraints, shown in Fig. 20. Application of the approach with typical schedules speeds up calculation process and preserves the main trends of the system, but smoothing of the consumption and production peaks does not give a full technical evaluation of development state.

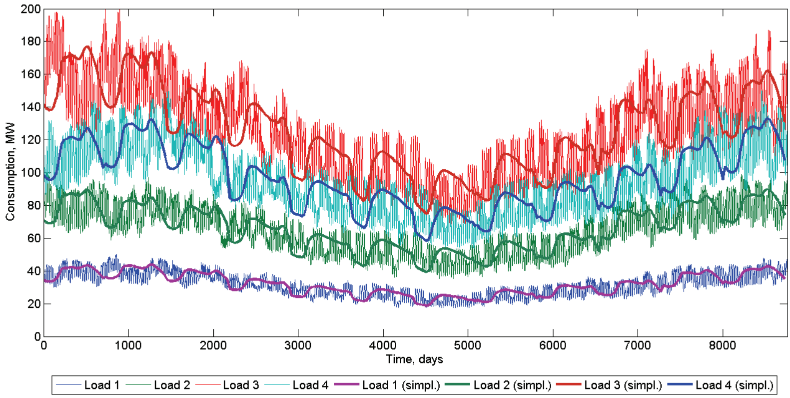

Fig. 20. 4 node system consumption profiles at full and simplified calculations

Calculation results for four nodes system, comparing ACOPF and DCOPF models with different approaches, presented in Tables 6 and 7. Calculations were made for different conditions of the system (with congestions and without them), using polynomials or piecewise costs functions.

Table 6

4 node system case without simplification

Name	Costs of production, €	Total production per year, MWh/year	Total consumption per year, MWh/year	Calculation time, seconds
Without Congestions				
DC without limits (polynomials)	21250166	2805405	2805405	338,06
DC without limits (Piecewise)	21265159	2805405		381,84
AC without limits (polynomials)	21262709	2806701		1066,65
AC without limits (Piecewise)	21277741	2806706		1204,02
With Congestions				
DC with limits (polynomials)	22437402	2805405	2805405	**338,61**
DC with limits (Piecewise)	22455709	2805405		385,10
AC with limits (polynomials)	22447357	2806305		1103,53
AC with limits (Piecewise)	22464853	2806371		1000,14

Table 7

4 node system case with simplification

Name	Costs of production, €	Total production per year, MWh/year	Total consumption per year, MWh/year	Calculation time, seconds
Without Congestions				
DC without limits (polynomials)	21234295	2805424	2805424	11,61
DC without limits (Piecewise)	21249341	2805424		13,01
AC without limits (polynomials)	21246743	2806709		27,66
AC without limits (Piecewise)	21261863	2806716		32,81
With Congestions				
DC with limits (polynomials)	22406685	2805424	2805424	**11,70**
DC with limits (Piecewise)	22424455	2805424		13,22
AC with limits (polynomials)	22415876	2806395		29,62
AC with limits (Piecewise)	22433627	2806397		33,36

Traditionally, when optimizing the operation of a regulated power system, the objective function in (6) takes a simple smooth quadratic form. The electricity market, however, does not use quadratic cost, since it does not cognitively match the manner in which market participants want to trade in the real world [36].

From the above-presented results, a significant acceleration of the calculating process for one development stage using approach with the typical schedule can be seen. From Tables 6 and 7, it can be concluded that DC model calculation without simplification takes 338 s (5,63 min), as opposed to calculation with simplifications taking 11,70 s (0,19 min), meaning, in 29 times faster than usual. Annual values of these calculations do not differ significantly. The proposed approach with typical schedules speeds up calculation process 30 times and preserves the main trends of the system. However, the smoothing of the consumption and production peaks does not give a full technical evaluation of development state.

2.5. Security-Constrained OPF

The SCOPF problem is an extension of the OPF problem and contains important features of reliability in the optimization model. It guarantees the stable work for the whole power system, without changing active power generation, when some predetermined contingencies occur (such as outages of transmission line) [37]. The efficient solution of SCOPF is crucial for system operators, in the context of planning, operational planning and real time operation.

Flowchart of the iterative SCOPF algorithm is provided in Fig. 23, which starts by solving an OPF with (N-0) constraints. Having solved the contingency analysis, it identifies the critical group of lines and selects lines according to these criteria:

$$K^*_{L,re} = \chi_L \cdot Ps_{L,re}, \tag{33}$$

where L transmission line ordinal number; $Ps_{L,re}$ transmission line flow in operational state; χ_L interruption probability of transmission line L;

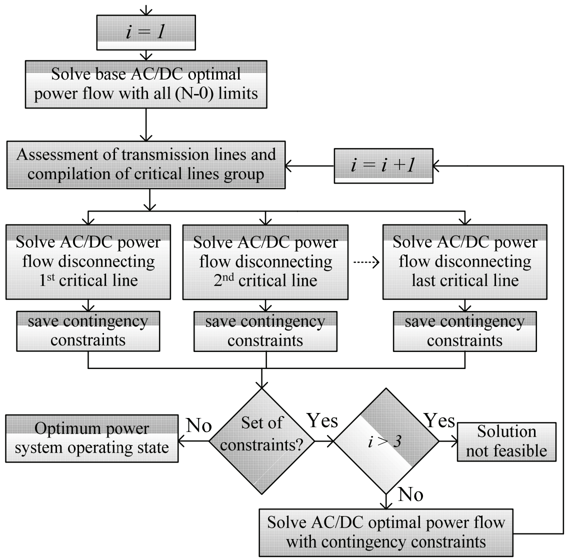

Fig. 23. Security-constrained OPF

In development planning tasks for optimal steady-state operation determination, only 10 % of electric transmission lines should be taken into consideration in which transmission line flow: transmission line interruption probability and therefore criteria K* are the highest values. This criterion is necessary in order to select a critical group of lines, subsequently reducing the size of optimization problem and calculation time.

2.6. Simplified Unit commitment

The unit commitment (UC) problem involves determining the start-up and shut down schedules of thermal units that are to be used to meet the forecasted demand over a future short term period [38, 39]. Due to the fact that the UC problem is a complex mathematical optimization problem and that it significantly increases the development planning tasks complexity, some assumptions have been made to simplify the problem: not to assume start-up and shut-down cost, system reserve requirements and ramp rates (each hourly base steady-state operation is independent from other hours).

Flowchart of the iterative simplified UC-SCOPF algorithm is provided in Fig. 30, which starts by solving a SCOPF without the units' low MW limits. Upon solving (SCOPF without units' low MW limits), the compilation of power plants group starts with a generation less than ε (in calculation ε assumed 10 %) to identify the group of power plants, which should be switched off. Having obtained the steady-state operation, social welfare and nodal prices reflect the network real processes and thereby taken for development modeling.

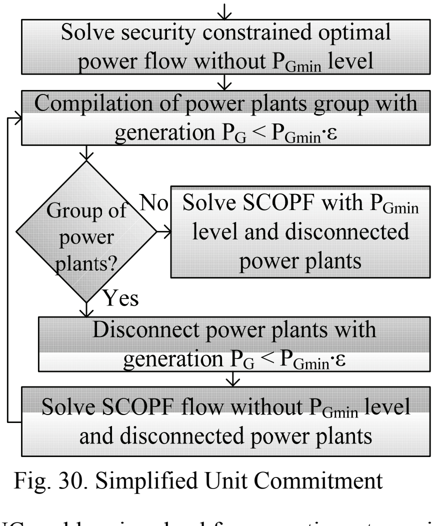

Fig. 30. Simplified Unit Commitment

A Simplified UC problem is solved for a one time step, without regard as to the intertemporal links. These links have to be taken into account when annual hourly availability of generators is formed for whole year.

3. MODELLING TECHNIQUE

3.1. Electrical Network Dynamic Modelling

The main point of this chapter is to demonstrate the new methodology based on the deterministic concept with a dynamic transmission expansion planning in a perfect competitive electricity market with technical and market economic regulation principals. Power system mathematical model is the system, and its development process configuration and network dynamic behaviors introduction in hardware will provide the capability to calculate and assess system criteria for decision making. To provide hardware operation on the given task, data are required and respective software comprising optimization algorithm. Taking into consideration the calculation dimension, the applicable methods must be operable with a relatively high speed and similar requirements are also applied to the data. Development modeling should include network dynamic behaviors and represent the network's real processes as much as possible. Based on the main functioning factors the following functional specifications of proposed model are considered (see Fig. 33.).

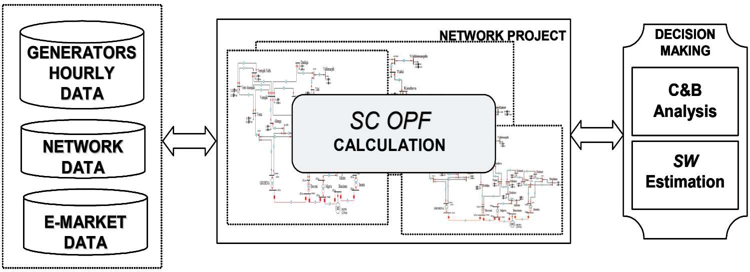

Fig. 33. Functional specification of proposed model

Development model functional specification consists the tree main blocks:

– **First block** contains the necessary input data from generators, consumers, network elements and e-market information.

– The **Second block** is concerned with obtaining the results for scenarios formed by the user, where SCOPF algorithm is implemented. Obtaining of the results by the presented modelling and simulation have to be always motivated by the best effort to achieve valuable results, since those, when applied to the development planning processes, may considerably influence decisions, and thus path of system development and its degree of optimality. Based on the main functioning factors the following development model was created (see Fig. 34.).

This process allows hourly consideration of the RES impacts on the power system and market formation. In [40, 41], the methodology and algorithms are proposed for evaluation of the RES integration effect on the price formation and the level of system penetration.

– **Third block** could be regarded as decision making. Decision making by itself is complex procedure, and in this thesis under the decision making is assumed focus on social welfare and congestion rent estimation, based on the formula (6). Additionally, in order to analyze and compare the future investments in transmission, a set of metrics are defined that show the welfare obtained by the different agents of the market: generators, demands and additional metric that considers the effect of the new lines on the congestion revenue received by TSO.

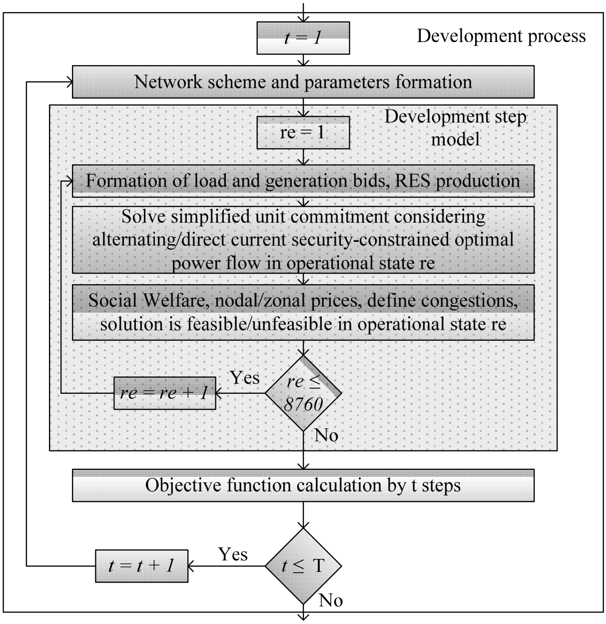

Fig. 34. Mathematical model of development process

3.2. Case study. Application to the modified Garver's 6-bus system

The modified Garver's 6-bus system (Fig. 35) has 14 existing lines, 5 loads and 4 generators.

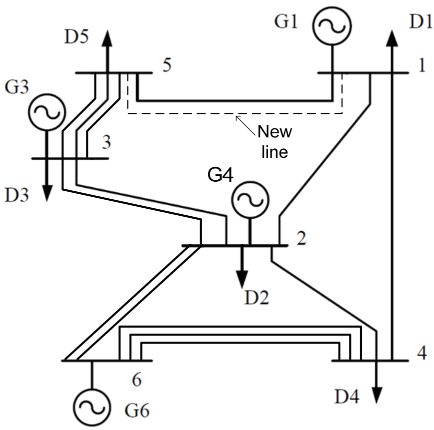

Fig. 35. Modified Garver's 6-bus system with 100MW wind PP

For the present structure of the network the following four case strategies of development are considered:

- Without wind PP and investments;
- Without wind PP and with investments for construction of a new line 1-5;
- With wind PP and without investments;
- With wind PP and investments for construction of a new line 1-5.

For development modeling calculation the following assumptions were made:

1. Consideration of a time horizon of ten years. For this time scale, we estimate the demand, the generation offers, and the demand bids. Therefore, the model represents a "Dynamic Transmission Expansion Planning" problem, for which the net social welfare is maximized;
2. Each development step is calculated in accordance with the present algorithm in Fig. 34. (AC and DC models of the network are used);
3. The generator costs were changed for all the periods of study, so that the gas price would grow each year by 1 % and coal price by 2 %. I'm considering a perfect competition strategy, generators offer at their marginal costs;
4. Each load was defined by an individual demand pattern and grew up each year by 0,5 %;
5. The annual wind production curve for 100MW power plant, obtained from the wind production curve simulation algorithm provided in [40, 41]. The production curve is fixed for each development step and does not participate in the automatic generation control.

The results of one year social welfare are provided in Tables 22 and 23 represent the changes of the annual social welfare values of OPF and SCOPF problems for different development strategies:

Table 22

SW values for the case study without wind PP

Step	Without investment		With investment	
	SW OPF, MEUR	SW SCOPF, MEUR	SW OPF, MEUR	SW SCOPF, MEUR
1	578.664	574.939	578.664	575.525
2	576.030	572.247	576.030	572.847
3	573.241	569.405	573.241	570.021
4	570.292	566.408	570.293	567.042
5	567.180	563.252	567.180	563.905
6	563.899	559.932	563.899	560.605
7	560.445	556.444	560.445	557.137
8	556.812	552.782	556.812	553.496
9	552.996	548.943	552.996	549.678
10	548.992	544.922	548.992	545.678
Total	**5648.551**	**5609.274**	**5648.553**	**5615.934**

Table 23

SW values for the case study with wind PP

Step	Without investment		With investment	
	SW OPF, MEUR	SW SCOPF, MEUR	SW OPF, MEUR	SW SCOPF, MEUR
1	649.103	644.525	649.175	645.317
2	646.845	642.193	646.919	643.000
3	644.440	639.715	644.514	640.538
4	641.884	637.087	641.958	637.927
5	639.171	634.303	639.247	635.162
6	636.299	631.360	636.375	632.238
7	633.261	628.252	633.338	629.151
8	630.054	624.977	630.131	625.896
9	626.672	621.528	626.750	622.469
10	623.110	617.902	623.189	618.865
Total	**6370.839**	**6321.842**	**6371.596**	**6330.563**

The presented results clearly illustrate the behavior and changes in the power system, which should be subsequently considered together with the decision making theory for the future sustainable development of transmission networks [42]. The effect of investments in the construction of the new line is justified in the case of the integration of the renewable energy sources into generating portfolio and could be evaluated as positive, regarding the improved generation and transmission adequacy, as well as the system's reliability.

3.3. Case study. Application to the Baltic Power System

The extensive Baltic power simulation model, presented in Fig. 39, is initially based on the BRELL power system model data. The developed model features a full georeferencing of the buses and the transmission lines, an interconnection to Finland Estlink 1&2, and an update of the recently commissioned /decommissioned wind farms and power plants [43].

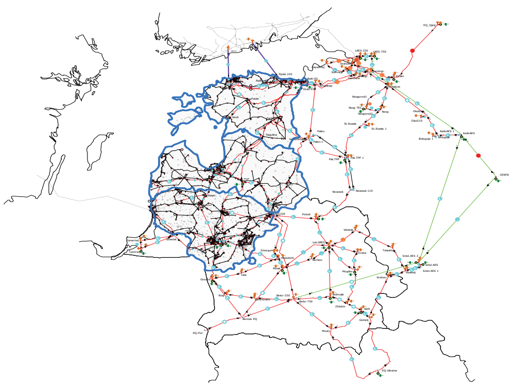

Fig. 39. BRELL power system developed simulation model

The baseline load demand data for the model is based on the peak and off-peak load profiles, registered in 2012. To ensure a continuous assessment of the model, an actual real time data retrieved from the Nord pool spot were scaled up using the initial 2012 load distribution and assuming an average power factor and a similar load distribution within the existing BRELL nodes. The developed model is aimed to simulate the projected transfer allocations of power flows and assess their possible impact on normal and contingency operations.

Based on the methods and algorithms created in this thesis, the Baltic transmission system planning has become possible, and the following results estimation can be done:

- The structure of the Baltic transmission system network has significant drawbacks that reduce the reliability of certain regions' power supply, as well as limit the further development of power system. The existing 110 kV network does not provide a sufficiently reliable power supply in regions. The main cause of power lines tripping of is wind loads (III and IV of the zone). As a result, the complete cessation of energy supply that occurred in 2005 might repeat at some point in time. With the implementation of priority projects in the Baltic region, the existing 330 kV network will be strengthened and the reliability of power supply for the consumers will increase. Simultaneously, priority projects provides the possibility of a widespread use of wind power, as well as – of increasing transit flows between the Nordic countries and Central Europe. The new transmission lines will be able to provide the currently necessary demand and the future demand of electricity in the developing regions, in the case of repairs without special restrictions.

This case study proves that a concept aimed at demonstrating an elaborated methodology's capability and application that would cover all stages – from the data input and analysis till the development scenarios estimation and decision making is indeed plausible.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The increasing penetration of renewable energy sources and development of Internal Electricity Market in EU countries is a driver of fundamental changes in transmission planning and its operation. The variable nature of wind and solar power, the potential for offshore grids and the particularities of optimal utilisation of hydro and retained nuclear capacity reveal a need for changes to the way in which power system planning is currently conducted. However, enhanced system monitoring and online analysis of stability limits along with the potential for growth in demand side measures to address system limits suggest that, for given patterns of available generation and demand, the margins afforded by the underlying capacity of the network can be squeezed with the prospect of lower levels of network reinforcement than would otherwise have been the case. The afore-mentioned implies that attention should be given to the new ways of analysing the system, including advanced methods, algorithms, tools and methodologies to facilitate those analyses along with the new decision making processes.

The main point of this work was to demonstrate the new methodology based on the deterministic concept with a dynamic transmission expansion planning in a perfect competitive electricity market with technical and market economic regulation principals. The proposed methodology for transmission network development planning will facilitate intelligent operation and control of the modern power system, including the concrete task purposes. It will provide the possibility to incorporate smart solutions to technical (secure, stable, and good power quality), economic and environmental goals. They would also incorporate distributed generations and demand response, penetration of new renewable energy sources, forecasting of the load and price.

Further research identification can be facilitated by the EU energy policy perspectives and challenges. The optimal expansion of the power system and transmission system in particular, under conditions of the liberalized market environment calls for forward-looking approaches that are able to reflect and find balance between requirements while these are often contrary.

Forward-looking research is identified in the following areas:

- Extension of existing OPF techniques with operational congestion management by coordinated control of Flexible Alternating Current Technology Systems and High Voltage Direct Current technologies;
- Implementation of Dynamic Optimal Power Flow to cover multiple time periods for network management with high penetrations of renewable generation, including energy storage and flexible demand;
- Development of multi-criteria decision-making methodology for transmission system sustainable development with preservation of the network security and reliability;
- Complex cost-benefit analysis for transmission network reinforcements based on assessments of economic levels of residual congestions;

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