Evaluation of Control Solution for Grid Inverter of Low Power Wind Turbine for Implementation With Inexpensive Hardware

Ilya Galkin, *Member*, *IEEE*, and Janis Zakis, *Member*, *IEEE*

Abstract—**The growing energy demand all over the world and the approaching deficit of traditional energy resources makes the development of renewable energy sources including wind energy necessary. A significant part of any wind turbine is the grid interface converter, operation of which depends a lot on the control system. Although this consideration is valid for all wind turbines, it is especially important for small wing turbines where control system cannot be expensive. This paper evaluates the possibility to split control functions into more simple ones with a goal of their practical implementation in a low cost system. The proposed version of split control is explored using MATLAB-Simulink simulation. It is concluded that the proposed control principle is capable of operation, but further experimental testing is necessary to validate it completely.**

Index Terms—**Wind energy, Permanent magnet machines, Pulse inverters, Phase control, MATLAB.**

I. Introduction

Among different renewable energy sources wind has become most used all over the world and at the same time power harvested from wind generators are steadily growing. The most of wind energy is produced in high power generators but also the power produced in small power generators is growing [1]. For example, according to World Wind Energy Association report [1] there were 46000 small power wind generators produced in 2008, 521000 in 2009, 656000 in 2010 and 730000 in 2011. Similarly it could be admitted that more than120 new small wind manufacturers were established between 2000 and 2010 worldwide [1]. The annual increase of installed capacity of small wind turbines in recent year showed the incremental growth of 35% per year. These numbers clearly show the growing wind energy potential in world.

In European scale the Renewable Directive [2] that is officially known as European Union (EU) directive of renewable energy use requires that until year 2020 20% of energy consumed in EU shall be produced from renewable energy sources (wind, solar, biomass, etc). The Road Map set out the Commission's long-term strategy for renewable energy requires meeting two objectives: increasing security of energy supply and reducing greenhouse gas emissions [3]. Unfortunately there are several difficulties to reach these targets, for instance high cost of renewable energy generation systems that require significant investments. The future of wind energy production expansion mainly depends on the enhancement of supportive policies and economic incentives, fossil-fuel prices, certifications, regulations and permitting processes.

This paper presents elaboration and implementation of simplified control system for small and medium power wind generator interface converters.

II. Review of Wind Turbines Technologies

Research in three main fields should be carried out in order to maximize the efficiency of energy generation from wind: mechanics – study of design and properties of blades, shaft, yaw and gearbox [4], electro-mechanics – study of different types and structures of generators (synchronous, asynchronous and custom constructions [5]) and power electronics – study of interface converter that adjusts generators and grid voltages as well as provides active and reactive power flow [6]–[8].

At the time when wind generation systems started to develop the main structure included heavy mechanical transmission systems to drive induction machines. Nowadays due to simple structure, high reliability and increased efficiency directly driven permanent magnet synchronous generators (PMSG) are widely produced and installed in residential wind generation systems [9]. Accordingly this generator type is selected for the further coupling with interface converter. As the drawback of PMSG the high cost can be mentioned not only because of costly magnetic materials but also because of rather complicated interface converter. The complicity is mainly related to the variable wind speed which in turn affects output voltage of the generator. Despite wind speed variations the interface converter should provide stabilized output voltage and frequency.

There are numerous PMSG based variable speed turbine interface converter topologies suitable for integration with the grid discussed in literature. When talking about interface converters one should understand that generally the interface converter comprises the generator side converter and grid side converter with their control systems together with filters and an isolation transformer. In general there are two European standards that stand for wind generation system connection with grid EN 50160, 50438 [10], [11].

The simplest and cheapest generator side converter topology consists of uncontrolled diode rectifier which has no need for control system. Unfortunately the drawback of this concept is very low flexibility and low wind power utilization [12]. More advanced generator side converters [12] and

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[13] (diode bridge rectifier with intermediate DC/DC converter, single-switch switched-mode rectifier, semi-bridge switched-mode rectifier, and active rectifier) in generator side can stabilize the DC-link voltage, provide higher output power at low wind speed, enable higher power factor and reduced THD of the generator current. If the galvanic isolation is essential then DC/DC converter that is used together with conventional rectifier and performs voltage pre-regulation functions is possible solution. In recent years impedance source DC/DC converters has shown themselves as very promising solutions in this field due to voltage buck-boost operation in single stage, continuous input current and shoot through proof properties [14] and [15].

The second basic and important part of interface converter is grid side converter. Generally grid side converters can be divided in two groups: voltage source inverters (VSI) and current source inverters (CSI). The structure of VSI and CSI can be two-level or multilevel suitable for single phase grid or three-phase grid. Of course it should be mentioned that the more complicated the structure of grid side inverter, the more complicated it control system that in turn increases the price of the overall interface converter. In order to connect the wind generation system to the grid the filters in the output should be used. Conventional VSI is the most widespread grid side converter type which is usually coupled with L, LC and LCL filters [13].

Design of the control system of the interface converter is one of the most complicated tasks for engineers [16]. A successfully functioning system contributes in extraction the maximal amount of wind energy, monitors grid, estimates grid parameters and synchronizes interface converter output parameters with grid, controls islanding or anti-islanding operation etc. The generator side converter should provide maximal power point tracking (MPPT) in order to obtain maximal power from generator. For small wind turbines there are several MPPT algorithms that can be found in literature: tip speed ratio control, power signal feedback control and hill climb search (or perturb and observe control) [17] and [18]. Control systems for grid side converter that are responsible for injection of electrical power harvested from wind turbine into the grid are discussed in numerous papers and books. The three-phase converters are mostly recommended as grid side converter for the grid integration of wind power generation systems. In single phase systems usually problems with low frequency ripple occur that can be solved only using bulky DC-link capacitors. The three-phase VSI is the preferable solution since smaller DC-link capacitors can be used and well established control methods are available. Accordingly two fundamental control methods for three-phase converters could be mentioned: voltage oriented control and direct power control [19].

Voltage oriented control system ensures that the grid currents have only d component in dq synchronous rotation frame that is tied with grid voltages. Its reference value is defined by the outer DC-link voltage control loop. Direct power control system calculates p and q components of total output power of inverter. It ensures that converter generates only the active power. Reference value of the active power is defined by the outer DC-link voltage control loop.

III. General Considerations

The elaboration of cost effective low power wind turbine includes several tasks. One of them is development of simple and cheap control system for the interface converter of the wind turbine. Lower power wind turbines include lower power electrical machines, as well as semiconductor switches and passive components of lower current/voltage ratings. In the same time, functional requirements to the utilized control hardware/software of the turbine and, therefore, their cost remains generally the same. This means, that the reduction of this cost is possible only if the implementation of the requested control functions is simplified, which requires less sophisticated control means of lower price. This paper evaluates one such opportunity of an optimal implementation of control for a wind turbine.

IV. Choice of Configuration of Interface Converter

The configuration of interface converter for a wind turbine has significant impact on its capabilities and, in the same time, may reduce or increase the complexity of the control system. Therefore a trade-off between the functionality and simpler control has to be done. It seems that this trade-off can be achieved at the minimal level of functionality which includes two basic functions of wind turbine interface converter: grid interfacing, as well as maximal power point tracking (MPPT). This forms a topology consisting of two blocks: grid inverter and MPPT block. In the case of three phase grid and DC voltage supply the first block (Fig. 1) can be built as an ordinary voltage source inverter (VSI) which can be controlled by space vector modulation (SVM). In turn, since the generator of a wind turbine is typically a permanent magnet electrical machine which produces wide range of output AC voltage (depending on the wind speed and angular velocity of this generator), the MPPT block must include a rectifier (uncontrollable in the minimal version) and step-up converter (one switch classic boost is minimal). The obtained "minimal" topology is presented in Fig.1.

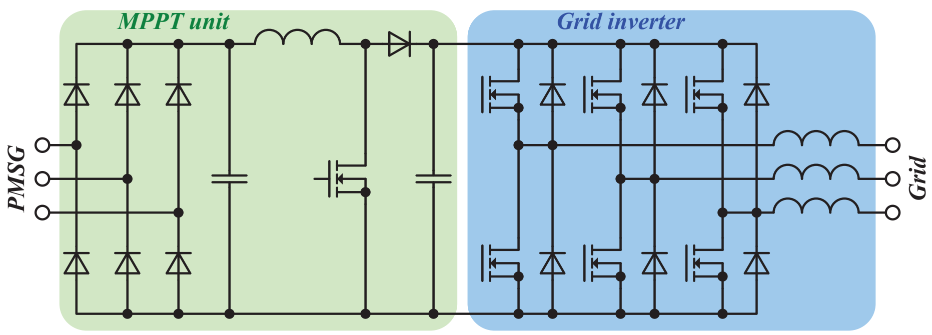


Fig. 1. Topology of wind turbine interface converter with minimal number of controllable electronic switches.

V. Features of Control Hardware/Software

The actual configuration of the inexpensive control system depends a lot on the state of the art in the field of such hardware and the peripheral devices available in this segment. Brief analysis of the currently available low cost MCUs shows that their typical content, besides boundary peripheral hardware, includes significant (x1kB) blocks of volatile and non-volatile memory (0.1% LUT equivalent) and hardware multipliers equipped with accumulate function and automatic data transfer. Something similar can be said about low cost PLDs (high end CPLDs and low end FPGAs) – multipliers and memory blocks are their typical content. The above mentioned leads to the following list of the functions easy implementable with low cost hardware:

- periodic nonlinear (trigonometric) functions with 0.1% accuracy;
- 8–16 bit multiplication operations;
- Arithmetical shifts (divide by 2N, where N is an integer number).

In turn, the following functions are still problematic in low cost devices:

- floating and fixed point operations;
- aperiodic nonlinear functions (first of the all exponentiation and square-root operations);
- divide operation with arbitrary divider.

The possibility to deploy control functions for a wind turbine interface converter utilizing the operation from the first list is discussed in this paper.

VI. Concept of Hardware Saving Control

As it was previously mentioned there are two main parts of interface converters: MPPT block and grid inverter. Amongst various control approaches for these two blocks the simplest one is the split control when the MPPT and inverter are controlled as separate units. Due to the minimal interaction of two control functions this kind of control seems the most suitable for implementation with low cost hardware. Moreover, since the control functions are spit with this approach the control hardware can also be split.

A. Introduction into MPPT Stage

The analysis and implementation of MPPT algorithms is outside of the scope of this paper. However, further analysis of the inverter assumes that higher output power is achieved at higher output voltage of the MPPT. There are several methods of tracking the maximal power, but the most primitive one and the most suitable for implementation with low cost control hardware is the “hill climb” search or incremental control [17] and [18]. It provides a stable maximum power point at all wind velocities, but is rather slow and creates oscillations when close to the maximal point.

B. Operation of Grid Inverter

While the MPPT stage produces the output voltage proportionally to the generated power (or close to that) the inverter has to deliver this power into the grid completely and without distortions and phase shift. If there is no voltage boost stage in the inverter it delivers pure active power into the grid if the amplitude of its voltage is higher, but phase is slightly leading (by α_1) compared with the voltage of the grid (Fig. 2).

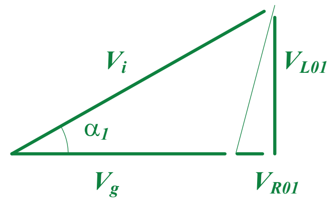


Fig. 2. Vector diagram of balanced operation of grid inverter.

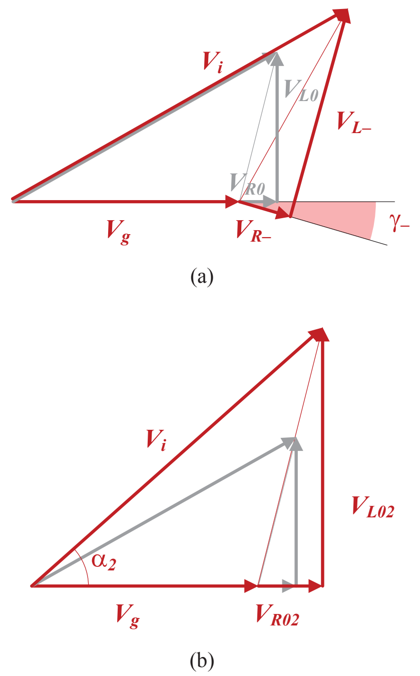


Fig. 3. Operation of grid inverter at voltage over-generation: (a) phase shift between grid current and voltage, (b) compensation of the phase shift between grid current and voltage by control angle.

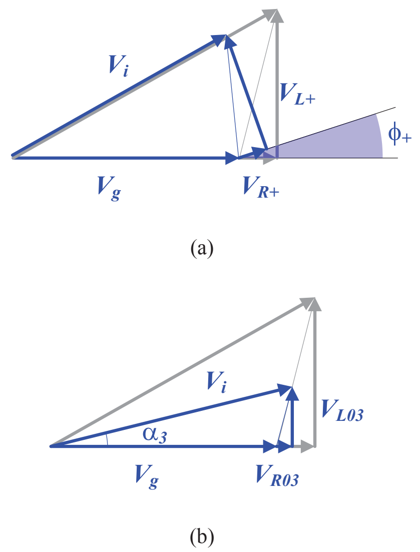


Fig. 4. Operation of grid inverter at voltage under-generation: (a) phase shift between grid current and voltage, (b) compensation of the phase shift between grid current and voltage by control angle.

Then the inverter can be described by a vector diagram composed for rotating reference frame (after Clarke and Park transformations). If the above conditions are fulfilled the amount of the active power injected into the grid depends on the difference of the voltage coming from MPPT stage and magnitude of the grid voltage, i.e. by MPPT stage. In this case the main function of the inverter is to maintain a zero phase between grid's voltage and its current, which requires correct leading angle of inverter voltage. Keeping the modulation index of the grid inverter at maximum level during this operation provides maximal injection of the generated power into the grid. In the same time the constant maximal value of inverter's modulation index requires significantly simplify the control of the inverter which is the goal o this research.

There are two more power balance situations. The first one occurs if the voltage is over-generated. Then the voltage drop in the input inductor and grid current is lagging (inductive) and the inverter produce some inductive reactive power, while the active is reduced, Fig. 3(a). Fixing of this problem requires increase of the control leading angle to the value α_2, Fig. 3(b).

Another situation takes place if the voltage is under-generated. In this case inductors voltage and grid current is leading (capacitive) and the inverter produces some capacitive reactive power, Fig. 4(a). The active power injected into grid is also reduced in this case. The correct reaction of the control system would be to reduce the control leading angle to the value α_3, Fig. 4(b).

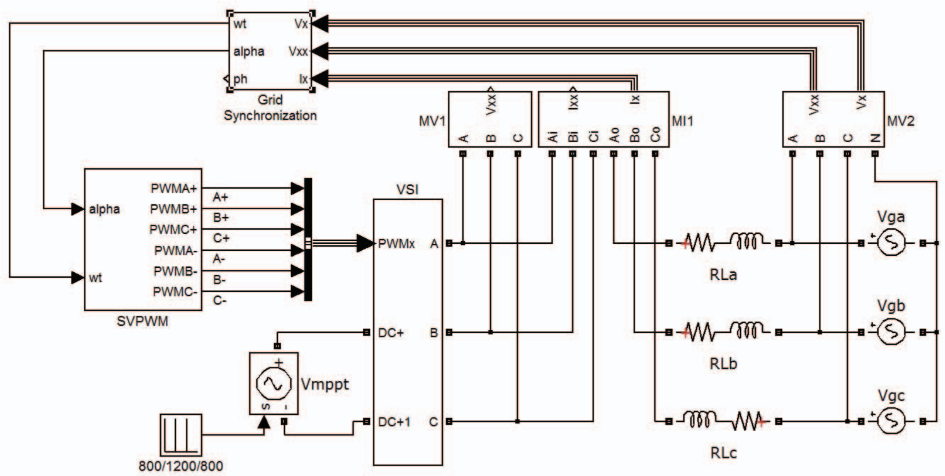
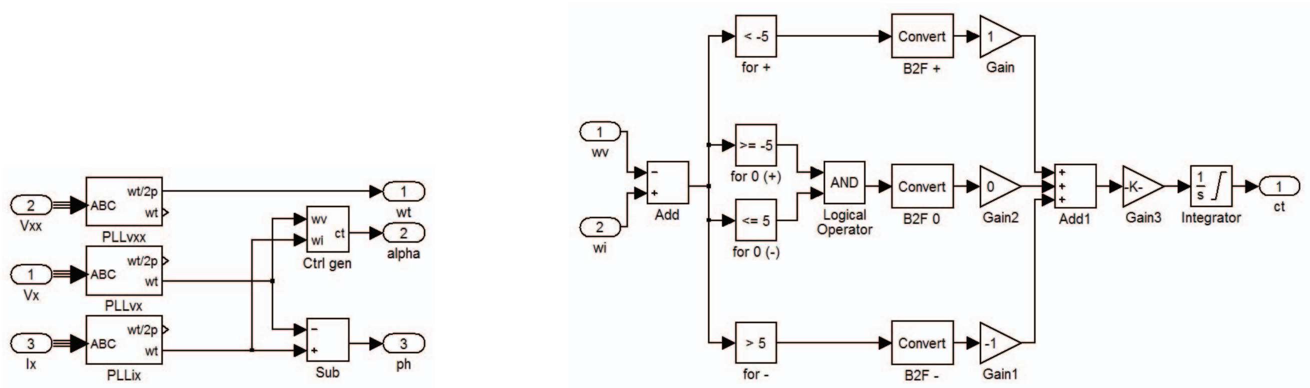


Fig. 5. Overall structure of the model of the proposed simplified control unit of grid inverter for wind turbine.



(a) (b)

Fig. 6. Grid synchronization module (a) of the model of the proposed simplified control unit and its synthesizer of control angle.

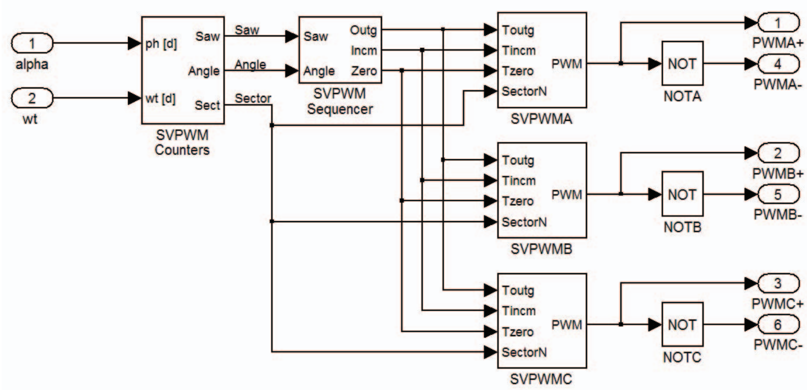
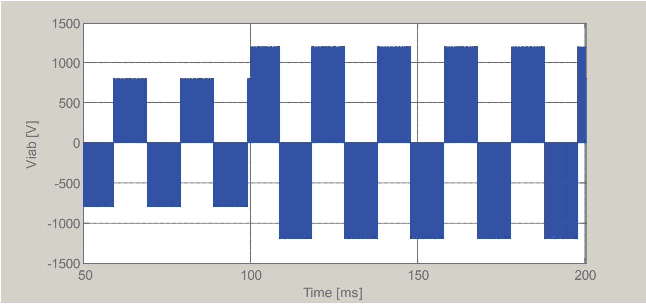
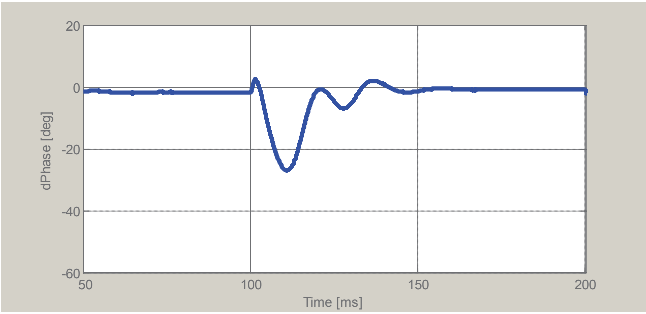


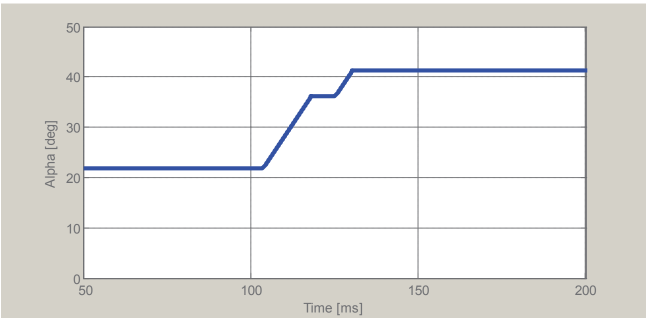
Fig. 7. PWM generator of the model of the proposed simplified control unit.



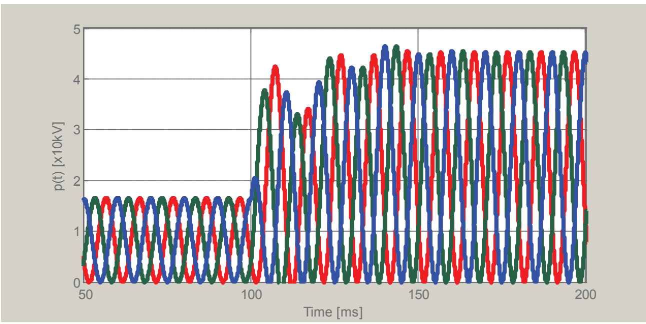
(a)



(b)



(c)

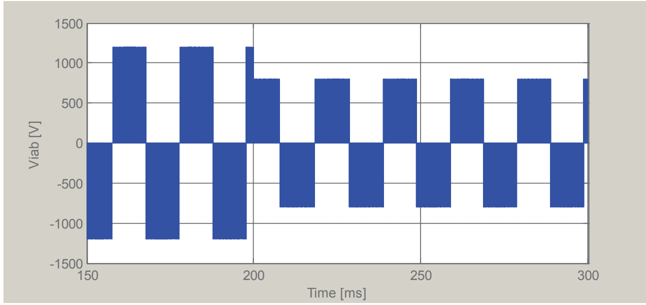


(d)

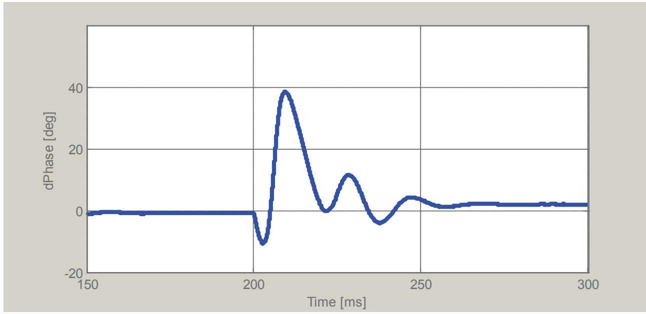
Fig. 8. Operation of grid inverter at voltage over-generation: (a) PWM voltage generated by the inverter, (b) phase shift between grid current and voltage, (c) control angle, (d) instantaneous grid power.

VII. Model and Simulation of Proposed Control Solution

One can conclude from the mentioned above that the main function of the discussed control approach is adjusting the angle of the voltage generated by the inverter and maintaining its maximal value. The corresponding control hardware could be simple. This hypothesis is verified below by means of simulation in MATLAB-Simulink environment.



(a)



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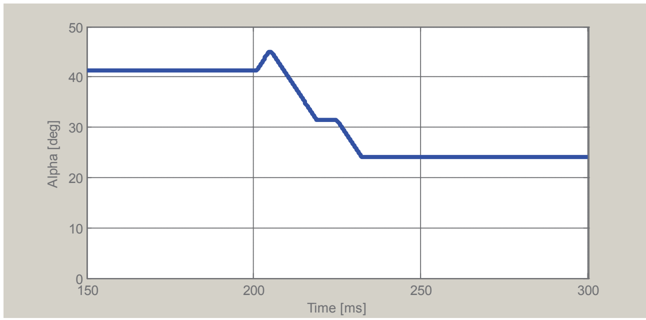
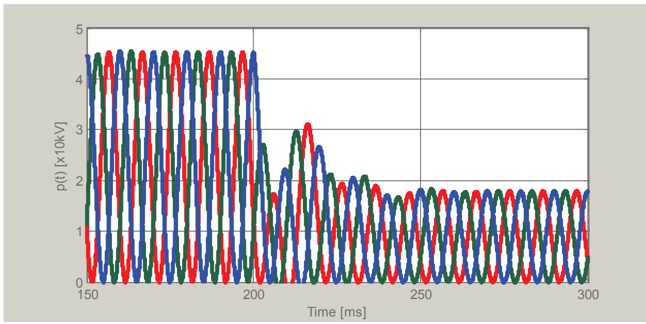


(c)



(d)

Fig. 9. Operation of grid inverter at voltage under-generation: (a) PWM voltage generated by the inverter, (b) phase shift between grid current and voltage, (c) control angle, (d) instantaneous grid power.

A. Description of Model

The proposed model (Fig. 5) consists of the power model developed from SimPower Systems blocks and control model made of Simulink blocks. The power model is a model of VSI with DC input voltage changing in time domain. The control model consists of a SVPWM generator and phase shift detector with attached regulator.

The phase shift detector (Fig. 6) is based on three PLLs which find the instant phase of the grid voltage and current. The difference of these values is the phase shift between current and voltage. This difference is passed to the regulator, where it is converted to the control angle (leading angle between grid and inverter voltages). The phase shift is identified as positive or negative constant which could simplify its practical realization. Also a zero constant is added for stability reasons.

The second significant block is a voltage space vector based generator of pulse-width modulated control signals (Fig. 7). This block operates with maximal modulation index and its realization could be based on table functions which makes it potentially simple. The inputs of this block are the voltage phase produced by the voltage PLL and control angle taken from regulator. Additional elements make this unit discrete and based on simple logic.

B. Explanation and Analysis of Experiments

The simulation results of the model presented above are shown in Fig. 8 and Fig. 9. The results show that the proposed simplified control approach provides inverter's operation at which the phase shift between grid's current and voltage is minimal (defined mostly by the width of band for zero constant). The reaction of the control system depends mostly on the parameters of PLL blocks and may require several grid period. Simulation is not a proper research method for this feature because the impact of non-idealities of real PLL may be significant and depend a lot on PLL realization.

VIII. CONCLUSION

In the given paper it is proposed to reduce the cost of low power wing turbines by making its control system simpler and cheaper. The main hypothesis of this approach says that all necessary functions could be implemented utilizing only simple operations of inexpensive control hardware (multiplications, divisions by 2, LUTs etc.). This requires that the control functions are split into reasonably simple parts. The idea of such control is verified through MATLAB-Simulink simulations. Generally the simulation results confirm the hypothesis, nevertheless further practical verification is necessary for some blocks like PLL. Accordingly, the future plans include practical realization of the proposed control and its further optimization. Cost analysis will play significant role during this planned part of the research.

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BIOGRAPHIES

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Ilya Galkin is IEEE member since 2006 in societies of Power Electronics, Industrial Electronics, Automatic control and Education.

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He has over 30 publications and is the holder of one Utility Model in power converter design. His research interests include flexible ac transmission systems (FACTS), simulation of power systems, switching mode power converters, applied design of power converters and energy storage systems.