RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Industrial Electronics and Electrical Engineering

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RESEARCH OF THE AUTOMATION TASKS OF THE WIND GENERATORS IN THE LOW-POWER MICROGRIDS

Summary of the Doctoral Thesis

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

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on ____________ ___, 2017 at the Faculty of Power and Electrical Engineering of Riga Technical University, 12/1 Azenes 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 Engineering Sciences is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Genadijs Zaleskis ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction; 5 Chapters; Conclusion; 101 figures; 6 tables; 3 appendices; the total number of pages is 117. The Bibliography contains 175 titles.

SIGNIFICANCE OF THE TOPIC

The European Union Renewable Energy Directive 2009/28/EC mandates levels of renewable energy use within the European Union, such that the EU will reach a 20% share of energy from renewable sources by 2020 and a 10% share of renewable energy specifically in the transport sector. Statistical data on the production of electricity from renewable energy resources in Latvia shows the increase of renewables use within the recent years, which suggests a possible renewable energy development prospects in Latvia.

The Energy Performance of Buildings Directive 2010/31/EU and the Energy Performance of Buildings Law of the Republic of Latvia provide that all new buildings are close to zero energy buildings before 31 December of the year 2020.

From the political point of view, any power dependent country excites possibility of the country-supplier to influence economic and political processes in the dependent country. Development of the renewable energetics systems can improve the state power independence and safety.

Strategical objectives of the use of the renewable energy sources are:

- to reduce the consumption of non-renewable energy resources;
- to reduce the environmental burden from conventional energy complex activities;
- to reduce costs to import fuel;
- to provide energy to the decentralized consumers and regions with remote or seasonal fuel supply.

AIM AND OBJECTIVES OF THE RESEARCH

The main goal of the thesis is to develop technical solutions that can provide effective operation of the wind generators in the low power microgrids, that means stable operation of the consumers and wind energy conversion at as wider generator speed range as possible.

To realize the stated aim the following tasks was defined.

- to define the automation tasks for the wind energy based power systems;
- to create synchronous generator automation system principles operating with DC bus of the microgrid;
- to create synchronous generator automation system principles for the low power DC microgrid collaboration with conventional AC power grid;
- to create methodology for wind turbine economic efficiency evaluation.

METHODS AND MEANS OF THE RESEARCH

- The power quality measurements were used for evaluation of the renewable energy source impact on the conventional power grid.
- Practical experiments were made in the laboratory of the Institute of Industrial Electronics and Electrical Engineering with the purpose to determinate the parameters of the investigated generators.
- The meteorological station of the Faculty of Power and Electrical Engineering was used for getting data about the wind speed.
- Matlab and MS Excel software was used in order to accelerate mathematical calculations and to visualize the obtained functions.
- Power electronics theory was applied in order to analyse the power electronics converters.

- The simulations of power electronic circuits were carried out in PSIM software.
- PCB design was made using Cadence OrCAD software pack.
- Microcontroller programming was made using Microchip MPLAB IDE software.
- The practical check of the developed algorithms was made in the laboratories of the Institute of Industrial Electronics and Electrical Engineering.

SCIENTIFIC NOVELTY

- The capacitor activated synchronous generator self-excitation system is developed. Latvian patent on invention No. LV 14496 B „Synchronous generator self-excitation system” is received.
- The synchronous generator self-excitation system with step-down DC/DC converter is developed. Latvian patent on invention No. LV 14951 B „Synchronous generator self-excitation system with step-down DC/DC converter” is received.
- The methodology of evaluation of the wind turbines economic efficiency is developed.

PRACTICAL APPLICATION OF THE WORK

- The developed methodology of evaluation of the wind turbines economic efficiency can be used for determination of the wind energy price in the specific places.
- The power grid operator rules dependence on the wind turbines economic efficiency is studied.
- The principles of the wind energy based DC microgrid collaboration with the AC conventional grid are defined.
- The developed methodology of evaluation of the wind turbines economic efficiency can be used for determination of the wind turbine suitability to the specific load.

WORK APPROBATION

The approbation of work has been realized participating the following international conferences:

1. 20th International Conference Electronics 2016, Kaunas, KTU, 2016.
2. 56th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, RTU, 2015
3. 14th International Symposium “Topical Problems in the Field of Electrical Engineering * Doctoral School of Energy and Geotechnology II,” 2014
4. 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, 2014
5. 54th International Scientific Conference of Riga Technical University (RTUCON), Riga, 2013.
6. 16th International Conference Electronics 2012, Palanga, June 19, 2012.

AUTHOR’S PUBLICATIONS

1. G. Zaleskis, I. Steiks. Alternative Energetics DC Microgrid with Hydrogen Energy Storage System. The Scientific Journal of Riga Technical University – Electrical, Control and Communication Engineering, Riga, RTU Press, 2016, pp. 21–26.
2. G. Zaleskis, I. Rankis. Problem of an Estimation of the Wind Generators Economic Efficiency in Latvia. Proceedings of the 20th International Conference Electronics 2016, Kaunas, Kaunas University of Technology, 2016, pp. 16–21.
3. G. Zaleskis, I. Steiks, A. Pumpurs, O. Krievs. DC-AC Converter for Load Supply in Autonomous Wind-Hydrogen Power System. 56th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, RTU Press, 2015, pp. 169–173.
4. G. Zaleskis, I. Rankis. An Overview on the Synchronous Generator Self-Excitation Converter Possible Configurations. 14th International Symposium “Topical Problems in the Field of Electrical Engineering * Doctoral School of Energy and Geotechnology II,” Elektriajam, 2014, pp. 78–81.
5. G. Zaleskis, M. Gavrilovs, I. Rankis. Improvement of Self-Excitation Process in Synchronous Generator. 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University, Riga, RTU Press, 2014, pp. 22–25.
6. G. Zaleskis, I. Rankis, M. Prieditis. Self-Excitation System for Synchronous Generator. Electrical, Control and Communication Engineering, Riga, RTU Press, 2013 No. 4, 32–37 pp.
7. G. Zaleskis, I. Rankis. Self-Excitation System of Synchronous Generator with Buck-Converter. Electronic Proceedings of the 54th International Scientific Conference of Riga Technical University, Riga, RTU Press, 2013, p3.1.–p3.4.
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CONTENTS OF THE DOCTORAL THESIS

INTRODUCTION

The energetics problem is one of the fundamental problems of mankind. Obviously, that the main sources of energy, such as oil and gas, are not limitless. Of course, solutions of alternative energetics can be an effective remedy of enrichment, considering their rather high cost, and, respectively, high market price, but it is impossible to challenge environmental pollution by products of fossil fuel burning and because of technogenic accidents.

The strategic objectives of the use of renewable energy sources [1, 2] are to decrease consumption of the non-renewable energy sources, to decrease the environmental load from the energetics complex, to decrease the cost of fuel imports and the power supply of the decentralized consumers and regions with the remote or seasonal fuel supply.

Use of the centralized power supply in some regions can be limited due to technical or economic aspects. In conditions of possible natural disasters, the centralized power supply can be broken. Therefore, on some isolated area, for example, wood, mountain or small island, generation of the electric energy can be realized only by means of the local autonomous system. Many technological processes demand an uninterrupted power supply, and the autonomous system will allow satisfying these requirements in case of network shutdown.

From the political point of view, any energetically dependent country excites possibility of the country-supplier to influence economic and political processes in the dependent country. Utilization of the renewable energy sources can bring the significant contribution to increase of the state power independence [3].

Before installation of the wind turbine, it is necessary to evaluate its economic efficiency. In some cases it is possible that the use of the wind turbine gives the negative economic effect, it means that attempts to fulfil political requirements will lead to financial losses. It is important to create technical solutions for efficient use of wind turbines. The low-power systems are explained in this thesis, and it may be important for households. It is proposed to use microgrids [4]–[8] for the effective utilization of the renewable energy sources. The method for wind turbine economic efficiency evaluation is proposed in this thesis.

1. PRECONDITIONS OF THE WIND TURBINES UTILIZATION

The economical motivation of the wind turbines utilising

The price of the wind energy depends on many factors [18]–[20], but overall, they can be defined as follows:

- installation costs;
- operational costs;
- operational period;
- capacity factor.

The market price of electricity $C_{\mathrm{kWh,market}}$ is accepted equal to 0.065 EUR/kWh, according to [93]. The price of wind energy in various cases is compared only with conventional grid energy price $C_{\mathrm{kWh,grid}}$, which is accepted equal to 0.16 EUR/kWh.

The use of the wind turbine is economically justified in such cases:

- if the use of the conventional grid or another RES is not possible technologically;
- if the use of the conventional grid or another RES is relatively expensive under the conditions of the factors mentioned above.

Wind turbine energy price determinants

The discussed renewable power system comprising the wind turbine with rated power $P_{\mathrm{w,r}}$ producing annually averaged power $P_{\mathrm{w,av}}$ which should be partially consumed by load with averaged by year power $P_{\mathrm{load,av}}$ and difference of the both powers $P_{\mathrm{grid,av}}$ should be through the bidirectional DC/AC converter transmitted to the conventional AC grid. The difference $P_{\mathrm{grid,av}}$ should be described as:

$$P_{\mathrm{grid,av}} = P_{\mathrm{w,av}} - P_{\mathrm{load,av}}. \tag{1.1.}$$

Wind turbine producing average power is characterized with the capacity factor α, which is the ratio indicator of wind power utilization per year (or the ratio of averaged generated power to the rated one):

$$\alpha = \frac{P_{\mathrm{w,av}}}{P_{\mathrm{w,r}}} \leq 1.$$

Part of the averaged wind power should pass to the local grid consumers, an averaged consumed power of which can be characterized with the wind turbine power distribution factor:

$$\beta = \frac{P_{\mathrm{load,av}}}{P_{\mathrm{w,av}}} = \frac{P_{\mathrm{load,av}}}{\alpha P_{\mathrm{w,r}}}. \tag{1.3.}$$

The price of the wind energy essentially depends on the installation investments and on the wind power utilization factor:

$$C_{\mathrm{kWh}} = \frac{C_{\mathrm{kW}} k_{\mathrm{a}}}{T_{\mathrm{an}} \alpha}, \text{ EUR,} \tag{1.4.}$$

where T_{an} = 8760 – amount of hours per year;
C_{kW} – installation outcomes of 1kW installed power of plant including power converters costs, EUR;
k_a – reduction factor for cost of installed power.

Accepting normal operation period equal to 20 years and the relative part of annual operation costs equal to 20 %, k_a = 0.06 year^{-1}.

The impact of the renewable energy sources on the power quality of the conventional power grid

In accordance with the contract between Riga Technical University and „Latvenergo" JSC regarding the power quality measurements in the specific, complex power grid nodes, power quality measurements were carried out on the proprietary border at „Sadales tīkls" JSC selected users, to identify the causes of voltage quality problems and offer utilizable technical solutions to the problems. The objects with installed wind turbines, which are connected to the three-phase power grid through inverters and bi-directional electricity meters, were inspected. It was noted that existed connection does not provide an uninterrupted power supply, because the inverters are synchronized with the conventional power grid, so in the case of the grid voltage failure wind energy is not used.

This problem could be resolved if the inverter operates in the autonomous mode, then the object must be disconnected from the conventional grid with the safety purpose, but the inverter operation must be synchronized according to a voltage level, frequency, and phase number.

Conclusions of the chapter

The strategic objectives of the use of renewable energy sources can be reached by integration of the renewable energy sources, e.g. wind turbines. This way, the appropriate laws and regulations on the use of renewable resources and energy efficiency in buildings will be implemented.

Political and ecological factors stimulate the development of the renewable energy. The use of the wind turbine is economically justified if the use of the conventional grid or another RES is not possible technologically or the use of the conventional grid or another RES is relatively expensive under the conditions of the factors affecting the price of wind energy.

Annual wind turbine usage costs and price of the received energy depend on capacity factor, which is the ratio indicator of wind power utilization per year, as well as on the ratio of energy consumed by load to the energy generated by wind turbine. The economic effect of the utilization of the wind turbines depends on the conventional grid operator regulations and electricity payment system, which determine possibilities for the wind turbine owner to get a compensation for energy transferred to the grid.

Power quality research on the objects equipped with renewable energy sources shows, that existing connection does not provide an uninterrupted power supply, because the inverters are synchronized with the conventional power grid, so in the case of the grid voltage failure wind energy is not used.

The automation task of the wind energy based power system is to minimize power consumption of conventional power grid by effective use of the renewable energy sources and providing stable operation of the consumers.

According to the strategical objectives of the use of the renewable energy sources, it was decided to use the microgrid, which can operate synchronously with the conventional network and autonomously, ensuring energy supply to the decentralized consumers or in the emergency case.

2. PRINCIPLES OF THE WIND ENERGY BASED MICROGRID DEVELOPMENT

The technological configurations of the microgrid

The DC based microgrid topology in this thesis is discussed. This choice is determined by the most efficient use of the renewables, which is achieved by reducing the conversion losses, and the ability to provide uninterrupted power supply. Also, the possibility to use the recuperated braking energy of the electrical drives is taken into account. Because of this option, DC microgrid becomes popular in the industry sector [113].

All generating object and energy storages are connected to common DC bus in the DC based microgrid topology (Figure 2.1.). AC generating objects need for AC/DC converters. Energy storage system provides energy for consumers on demand. AC consumers are connected to the DC bus through the inverters.

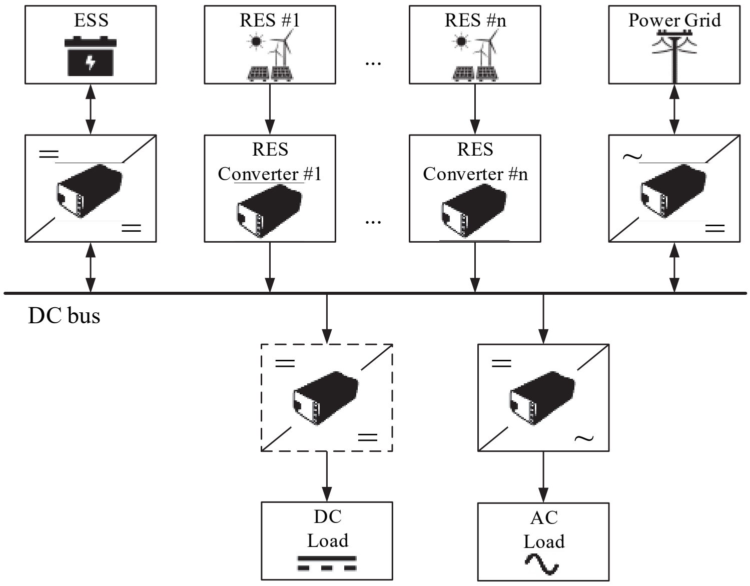


Figure 2.1. The block diagram of the DC based microgrid with the renewable energy sources [38]: ESS – energy storage system; RES – renewable energy source

Wind turbines

It is appropriate to use a variable speed wind turbine with permanent magnet synchronous generator (PMSG) and full power electronics conversion [37] (Figure 2.2.) in the DC based microgrid.

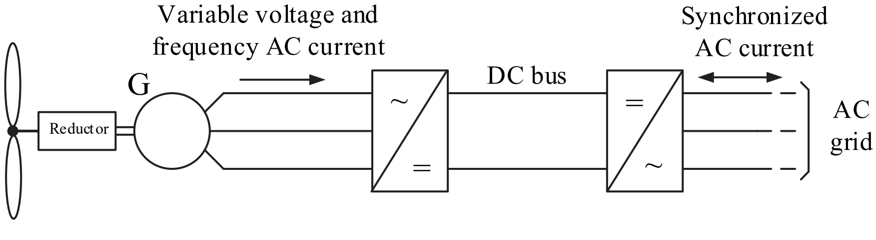


Figure 2.2. Wind turbine with permanent magnet synchronous generator

Instead of PMSG, it is possible to use the synchronous generator with separate excitation, which operates in self-excitation mode [120]–[125]. In this mode, generator output voltage can be changed depending on the generator speed by use of the self-excitation device, which is important at relatively high wind speed when generator voltage can exceed the allowed value.

Choosing of the DC bus voltage level

Taking into account the power grid standard of the Republic of Latvia 230/400 V and household connection types there is a possibility to connect a microgrid to one or three phase AC grid. In this thesis, the connection to three phase power grid is discussed. It can be realized by the use of the active rectifier (active front-end) [65], in this case, DC bus minimum voltage must be equal to rectified AC voltage peak value [103], which is equal to AC line voltage amplitude:

$$V_{\mathrm{d,min}} = V_{\mathrm{l,m}} = V_{\mathrm{l}}\sqrt{2} = 565V, \tag{2.1.}$$

where: $V_{\mathrm{l}} = 400$ V – line voltage r.m.s., V.

According to standard LVS EN 60038 [131], the rated DC bus voltage $U_{\mathrm{d,r}}$ was accepted equal to 600 V.

Conclusions of the chapter

The DC based microgrid topology in this thesis is discussed. Firstly, this choice is determined by the most efficient use of the renewables and the ability to provide uninterrupted power supply. Secondly, the possibility to recuperate the braking energy of the electrical drives and the rest of the generated energy is taken into account.

The synchronous generator with full power electronics conversion as a basic energy source of the microgrid was chosen. It is possible to use the permanent magnet synchronous generator or synchronous generator with separated excitation winding and self-excitation system.

In the autonomous microgrid it is necessary to use the energy storage system with the aim to provide uninterrupted power supply. If the microgrid is connected to conventional power grid the energy storage system may be used to reduce energy consumption from the conventional grid during periods when wind energy is not available or in the emergency cases. Energy storage system must be chosen according to specific task and power range.

In accordance with the national standards and features of the DC bus cooperation with three-phase power grid the microgrid rated voltage value 600 V was selected, but allowed minimum voltage was accepted equal to 565 V. The proposed system is based on the active rectifier.

3. SYNCHRONOUS GENERATORS IN THE LOW-POWER MICROGRIDS

The characterization of the permanent magnet synchronous generator

The model of the synchronous generator with built-in rectifier shows, that PMSG load curve $V_{g,dc} = f(I_{g,dc})$, where $I_{g,dc}$ is rectifier output load current strength (for the sake of simplicity, hereinafter referred to as – current), can be estimated as (3.1.), because of voltage drop and commutation processes:

$$V_{g,dc} = k_{dc} n - I_{g,dc} R_g, \tag{3.1.}$$

where k_{dc} – factor, which depends on generator construction and permanent magnets magnetic flux; in specific case is equal with 3.26;
n – generator rotation speed, rpm;
R_g – factor, characterizing the internal resistance of the generator and the impact of commutation, Ω.

Reference power equation, received by approximation of the generator GL-PMG-5000 power curve:

$$P_{ref} = 0.089n^2 + 8.929n - 357.143. \tag{3.2.}$$

The factor R_g can be calculated from the generator idling voltage and power curves:

$$R_g = \frac{V_{g,dc,0}}{I_{g,dc,max}} - \frac{P_{ref}}{I^2_{g,dc,max}},\ \Omega, \tag{3.3.}$$

where $I_{g,dc,max}$ – the maximum value of the generator output direct current.

Permanent magnet synchronous generator connection to the DC bus

In accordance with the generator parameters use of non-inverting buck-boost DC/DC converter was prompted [138]–[140]. The control system of the converter is based on setting the wind generator optimal power curve and directly adjusting the DC/DC converter duty cycle [135]–[137]. The block diagram of the proposed system and principal scheme of the converter are shown in Figure 3.1. The DC bus voltage is equal to:

$$V_d = V_{g,dc} \frac{D1}{1 - D2},\ \text{V}, \tag{3.4.}$$

where $D1$ – duty cycle of the switch VT1;
$D2$ – duty cycle of the switch VT2.

In buck mode $D1$ = 0…1 and $D2$ = 0, in boost mode $D1$ = 1 and $D2$ = 0…1.

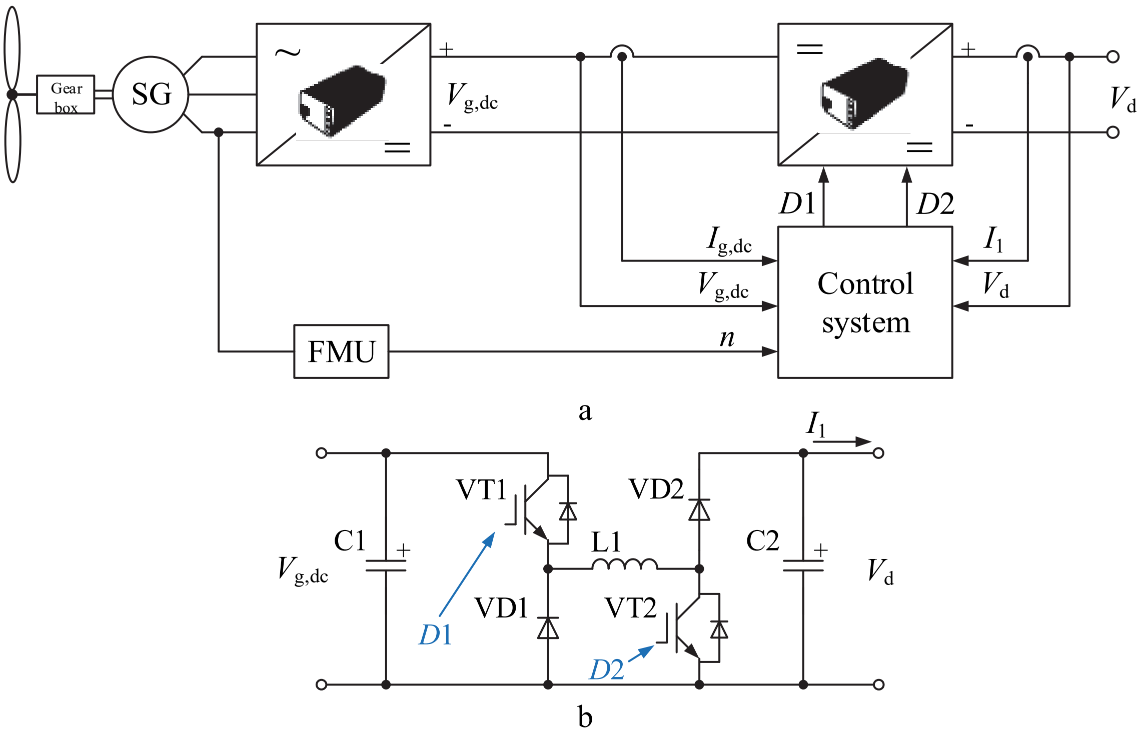


Figure 3.1. The block diagram of the proposed system (a) and the principal scheme of the DC/DC converter (b)

At low generator, speed converter operates in boost mode at $D1 = 1$ and maximum $D2$, which is limited with $D2_{max}$. According to [141], $D2_{max}$ is accepted equal to 0.9. The generator output DC voltage is also low:

$$V_{g,dc}^{1} = 0.1V_{d}, \text{ V.} \tag{3.5.}$$

At this generator voltage, generator output direct current must be:

$$I_{g,dc}^{1} = \frac{k_{dc}n}{R_g} - \frac{0.1V_d}{R_g}, \text{ A.} \tag{3.6.}$$

At low generator speed range, generator converter output current is:

$$I_1^1 = 0.1I_{g,dc}^{1} = \frac{0.1k_{dc}n}{R_g} - \frac{0.01V_d}{R_g}, \text{ A.} \tag{3.7.}$$

At $I_1 = 0$, generator speed is:

$$n_0 = \frac{0.1V_d}{k_{dc}}, \text{ rpm.} \tag{3.8.}$$

Generator current reaches the maximum value $I_{g,dc,max}$ when speed is equal to n_1 (Figure 3.2.), in this case converter current is:

$$I_1^1 = 0.1I_{g,dc,max}, \text{ A.} \tag{3.9.}$$

The maximum current of the discussed generator GL-PMG-5000 is $I_{g,dc,max} = 10$ A. If DC bus rated voltage is 600 V, the speed n_0 is equal to 18.5 rpm, but n_1 is approximately 65 rpm (Figure 3.2.). Between n_0 and n_1 generator DC voltage is equal to 60 V, according to (3.5.). At n_2, converter current I_1 is equal to $I_{g,dc,max}$, and operation mode of the converter changes to step-down. At $n > n_2$ converter operates in step-down mode. Received generator power coincides with the rated one (Figure 3.3.). Initial converter testing at DC bus voltage 60 V and 200 Ω load shows the suitability of the duty cycle adjusting algorithm (Figure 3.4.).

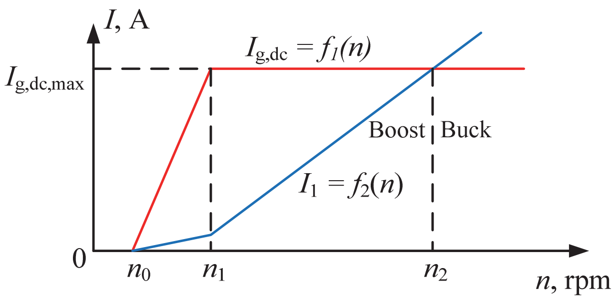


Figure 3.2. Wind turbine circuit current as function of generator speed

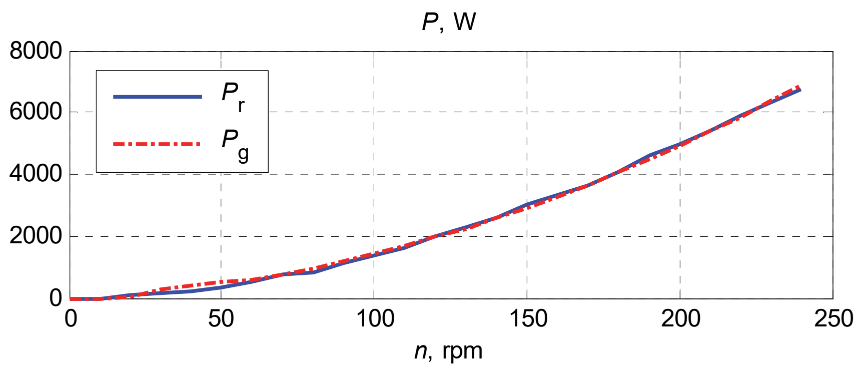


Figure 3.3. Wind generator GL-PMG-5000 rated (P_r) and theoretically received (P_g) power curves

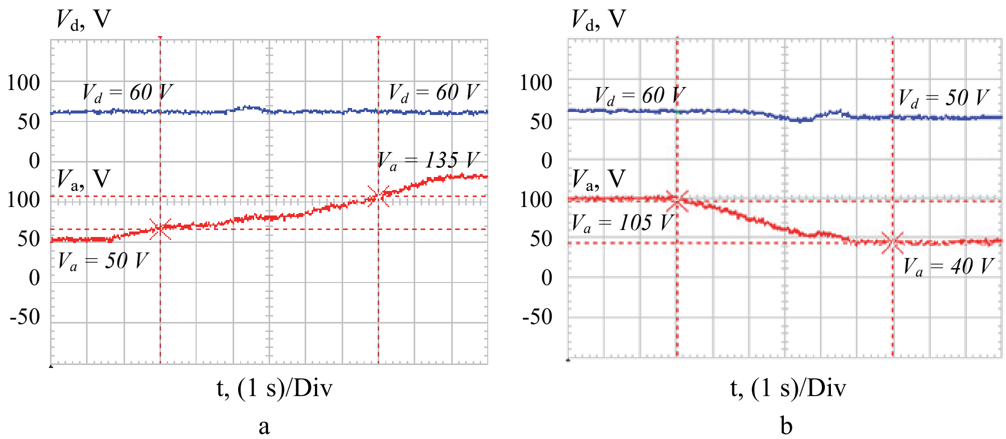
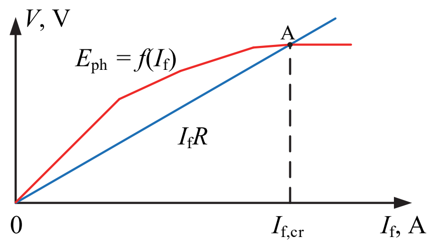


Figure 3.4. Operation of the DC/DC converter with DC load in case of increasing (a) and decreasing (b) of the converter input voltage: V_a – converter input voltage; V_d – DC bus voltage

Improvement of the self-excitation process of the synchronous generator

The course of the self-excitation process in the synchronous generator is caused by the generated EMF and voltage drop $I_f R$ across the generator resistance R, which is caused by the excitation current I_f. If voltage drop $I_f R$ reaches point A (Figure 3.5.) there is not possible use of the generator energy by the consumer since all energy dissipates in the generator windings resistance [123].



3.5. att. Generator phase EMF E_{ph} and voltage drop across the generator resistance:
$I_{f,cr}$ – critical value of the excitation current

The critical value of the excitation current is found from (3.10.):

$$I_f R = kn \frac{I_f}{a + bI_f}. \tag{3.10.}$$

where n – generator speed, rpm;
a, b, k – coefficients.

Calculations show that the generator under discussion can operate in self-excitation mode with the self-excitation system [123] even at speed lower than rated one. In turn, experiments show that self-excitation process does not occur without its improving in discussed generator.

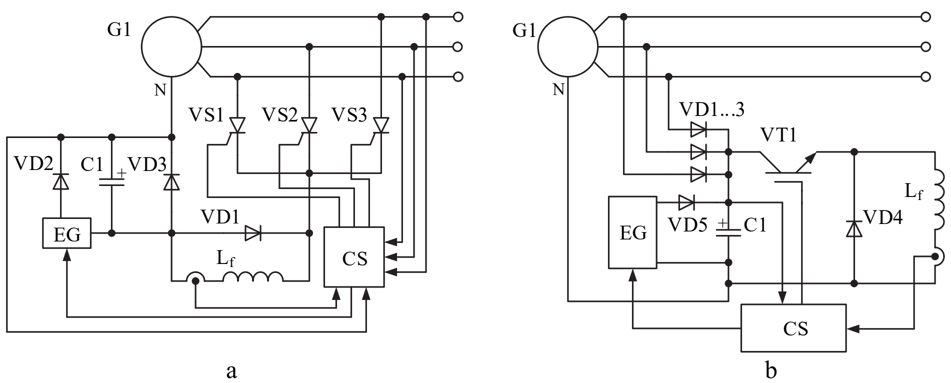


Figure 3.6. SG self-excitation system with the controlled half-bridge rectifier (a) and uncontrolled half-bridge rectifier with the step-down DC/DC converter (b): EG – electronic generator; CS – control system of the self-excitation device; L_f – excitation winding

There are some methods to improve the self-excitation process in synchronous generator [64] with specific advantages and disadvantages. In this work, it is proposed to provide generator self-excitation by the current impulse, which magnetizes excitation winding. No additional power supply for self-excitation starting is necessary. Using proposed method it is possible to control excitation current and, correspondingly, generator voltage [121]–[123], [125], [145]. Current impulse is generated by discharging of the capacitor C1 (Figure 3.6.) in the excitation circuit, but C1 charging occurs through the low-power electronic generator.

Experiments [96] show the progression of the self-excitation process even at generator speed lower than the rated one (Figure 3.7.).

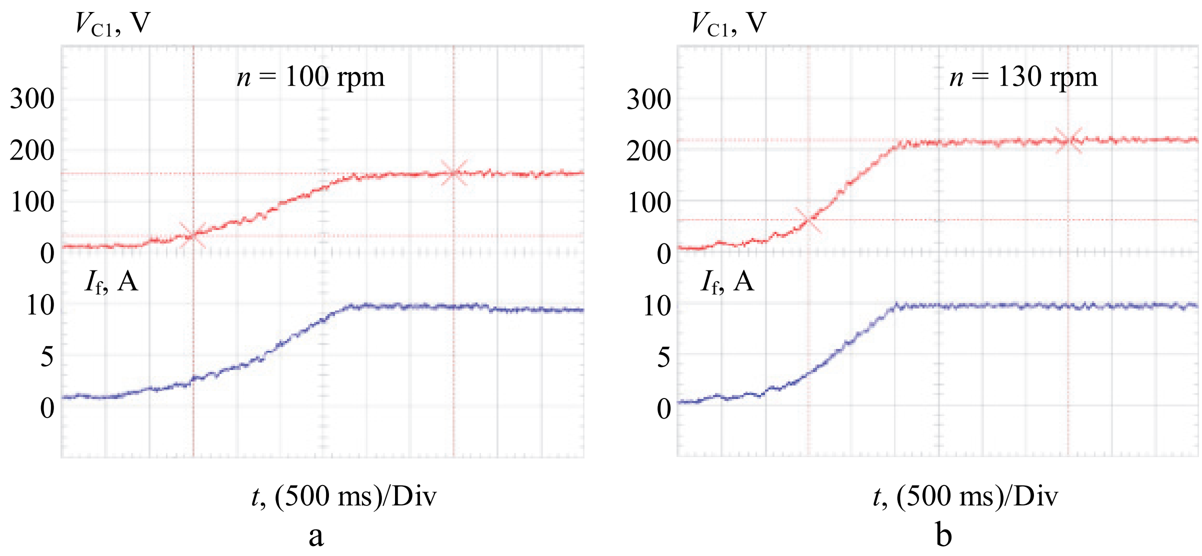


Figure 3.7. Experimental diagrams of the self-excitation process: V_{C1} – capacitor voltage; I_f – excitation current.

Self-excited synchronous generator connection to the DC bus

Self-excited SG connection to DC bus can be made by supplementing block diagram (Figure 3.1.a.) with self-excitation converter DD3 (Figure 3.8.).

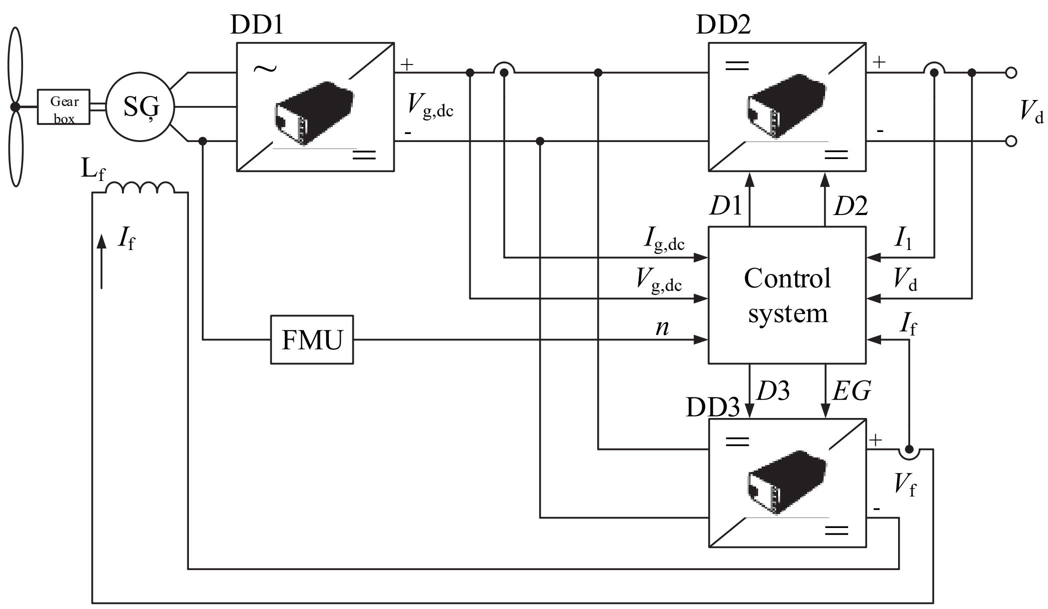


Figure 3.8. Self-excited SG and DC bus interconnection diagram: DD1 – uncontrolled built-in rectifier; DD2 – DC/DC converter; DD3 – SG self-excitation system; FMI – frequency measurement unit; $D1$–$D3$ – PWM outputs; EG – electronic generator control output; V_f – field (excitation voltage); I_f – excitation current; L_f – excitation winding

At rated excitation current and excitation winding resistance 2.85 excitation power is 1140 W, which is 23 % of the generator rated power. At low generator speed necessary excitation power exceeds generator possible power, therefore available power in Figure 3.9. is accepted equal to 0 at low speed.

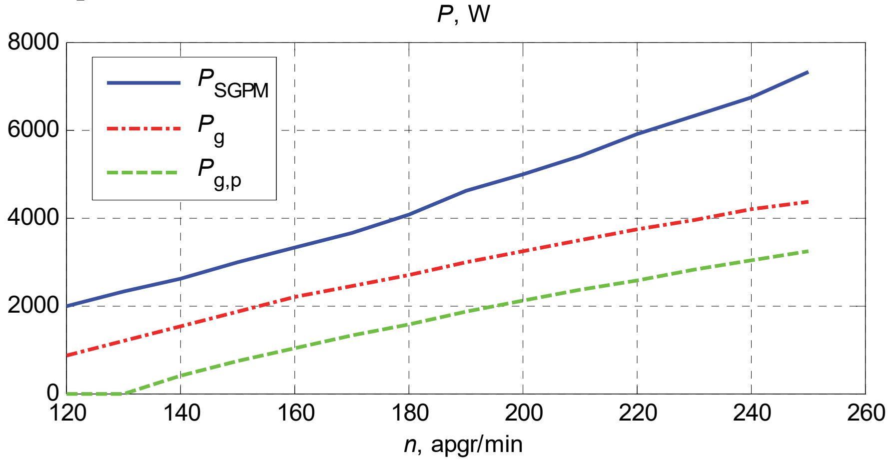


Figure 3.9. The rated power P_g of discussed self-excited generator and the available power $P_{g,p}$ comparing with the PMSG rated power P_{SGPM}

The power curve of PMSG (see Chapter 3.2.) is essentially above power curve of the self-excited SG under discussion (Figure 3.9.), specially taking into account excitation losses. It was concluded, that an excitation power of the self-excited generator is disproportionately high comparing to rated one. Therefore, the use of wind generator with self-excitation system is not profitable, because of the power available to the consumer is much smaller than the rated one which also leads to the reduction in the speed range comparing to PMSG with equal installed power.

Conclusions of the chapter

Synchronous generator interconnection with DC bus is ensured by the use of the buck-boost DC/DC converter, which was chosen because of the generator technical parameters. The converter control system is based on setting the wind generator optimal current and directly adjusting the DC/DC converter duty cycle.

Practical experiments show the suitability of the developed algorithms, therefore the proposed system can be applied to an interconnection of the microgrid and conventional power grid or energy storage system.

The study of the self-excitation process in the synchronous generator shows, that in specific cases there is a need to improve initial self-excitation because of the low level of residual magnetism. The method for initial self-excitation improving was designed. No constructive changes or external power source are necessary. The initial self-excitation is provided by a current impulse from the capacitor, which magnetizes excitation system.

The prototype of the synchronous generator self-excitation system was developed and tested. Generator self-excitation was reached at generator 100 rpm, but at the same speed it is not possible to provide necessary excitation current equal to 20 A. At generator speed below 130 rpm the rated excitation power exceeds the rated generator power.

The minimum speed, when the generator output power is available for loads, is 130 rpm. At rated excitation current the excitation power is equal to 1140 W, that is 23 % of the rated one at 300 rpm or 57 % of the rated one at 160 rpm.

Synchronous generator with self-excitation system can be used in the wind turbines in the case when it excitation power is proportionate to generator rated power. Otherwise, there is a significant decrease in speed comparing to permanent magnet synchronous generator with equal installed power.

4. DEVELOPMENT OF THE SYNCHRONOUS GENERATOR AUTOMATIZATION SYSTEM PRINCIPLES

The control of the active front-end in the DC microgrid

Accepting $I_{g,dc} = I_{g,dc,max} = 10$ A and $V_d = V_{d,r} = 600$ V, generator converter current can be calculated as follows:

$$I_1 = \frac{I_{g,dc}V_{g,dc}}{U_d} = \frac{V_{g,dc}}{60} = \frac{k_{dc}n - R_g I_{g,dc}}{60}. \tag{4.1.}$$

On the other hand, converter current must be equal to:

$$I_1 = \frac{k_{dc}n}{60 + \frac{R_g D1}{(1 - D2)}}, \text{ A.} \tag{4.2.}$$

AC grid current (Figure 4.1.) is:

$$I_2 = I_{load} - I_1, \text{ A,} \tag{4.3.}$$

where I_{load} – load current, A.

For DC microgrid simulation the current-controlled rectifier was chosen [65]. If load current I_{load} is greater than I_1, then current of the active rectifier is with „+” sign (Figure 4.1.), if I_{load} is less than I_1, then it is possible to transfer the current difference into the AC grid. The calculation of the reference current $I_{2,ref}$ of the active rectifier is shown in block diagram (Figure 4.2.). AC grid phase current amplitude:

$$I_{ph,a} = \frac{I_2 2}{\sqrt{3}}, \text{ A.} \tag{4.4.}$$

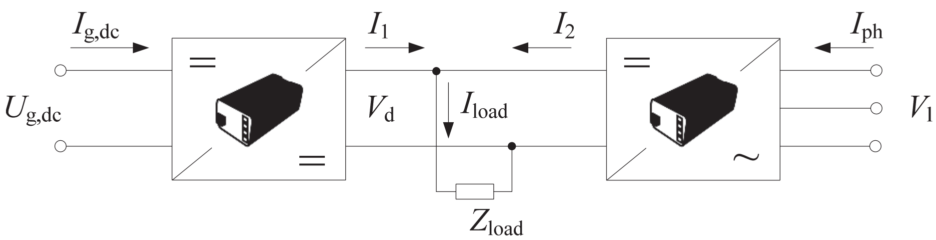


Figure 4.1. DC bus operation with the AC grid: $U_{g,dc}$ – wind generator output DC voltage; V_d – DC bus voltage; V_l – AC grid line voltage; Z_{load} – load impedance; $I_{g,dc}$ – wind generator output DC current; I_l – wind generator converter output current; I_{ph} – AC grid phase current; I_2 – active rectifier output current; I_{load} – load current

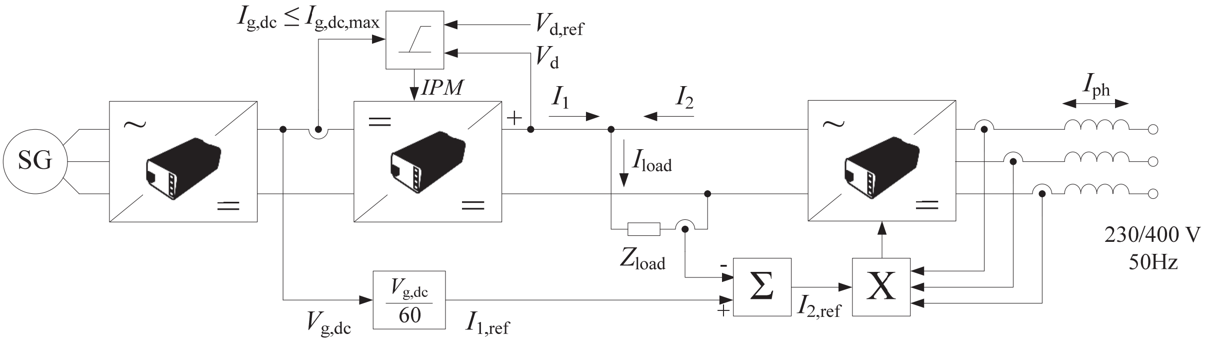


Figure 4.2. The calculation of the reference current of the active rectifier

The current distribution (Figure 4.3.) is presented at the load resistance 200 Ω. Generator output voltage is shown in Figure 4.4. at the DC bus rated voltage 600 V. The speed n_2 of the discussed PMSG is equal to 222 rpm in the case of generator rated current 10 A and rated voltage of the DC bus is 600 V. The received generator power, conventional grid power and load power are presented in Figure 4.5. When $n > 118$ rpm and a load is 200 Ω, the generator starts to transfer produced energy to conventional power grid, therefore P_{grid} values are negative in this speed range.

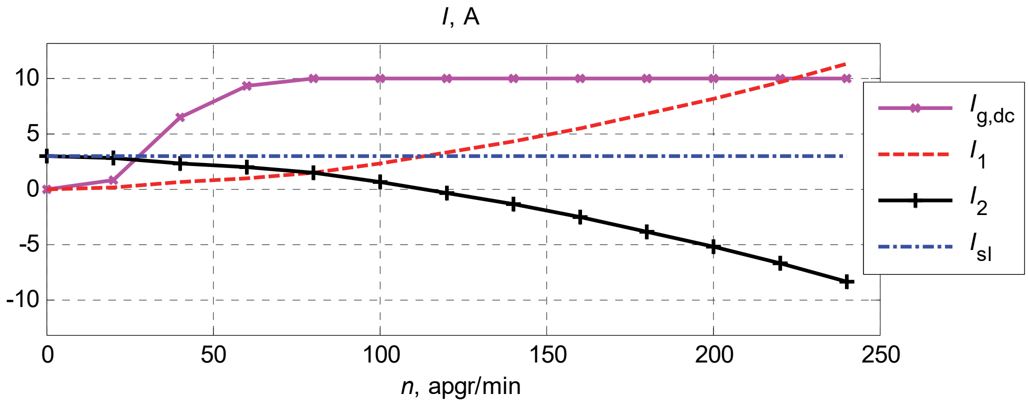


Figure 4.3. Simulation diagrams of the wind energy based DC microgrid connected to the conventional AC power grid: $I_{g,dc}$ – wind generator output direct current; I_1 – wind generator converter output current; I_2 – active rectifier current; I_{sl} – load current

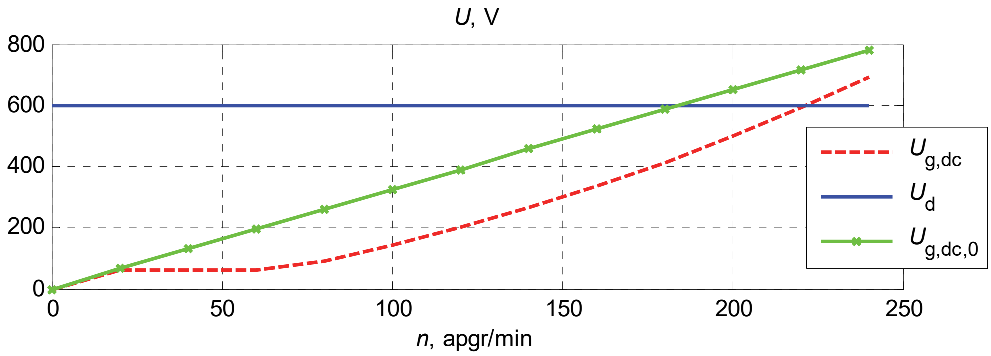


Figure 4.4. Simulation diagrams of the wind energy based DC microgrid connected to the conventional AC power grid: $U_{g,dc}$ – wind generator output direct voltage; U_d – DC bus voltage; $U_{g,dc,0}$ – wind generator output voltage in the idle

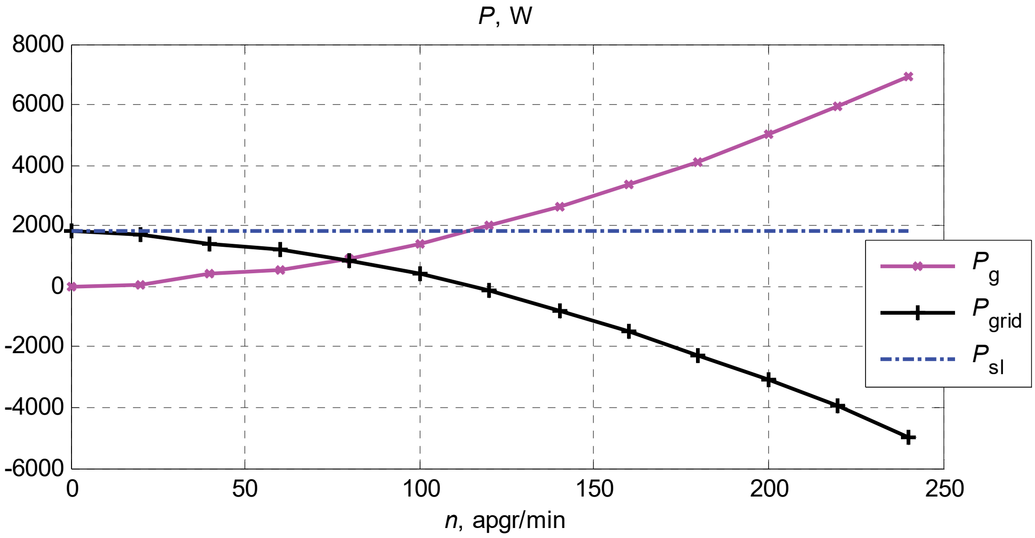


Figure 4.5. Simulation diagrams of the wind energy based DC microgrid connected to the conventional AC power grid: P_g – wind generator power; $P_{s.t.}$ – conventional grid power; P_{sl} – load power

The problem of the uninterrupted power supply

In the case of an accident on the conventional power grid or in the autonomous microgrid the uninterrupted supply can be provided by energy storage system [126], [147]–[149]. Each system has its own characteristics and therefore has its own advantages and disadvantages. Batteries have a limited specific power (W/kg) regarding absorbing and delivering energy compared to supercapacitors. On the other hand, supercapacitors have a more limited specific energy (Wh/kg) compared to batteries. The choice of the energy storage system depends on the specific task and the used power range. Hydrogen based energy storage system is one of many possible solutions to this problem.

The main components of the hydrogen energy storage system [106], [149] are shown in Figure 4.6. The electrolyser [83] and the fuel cell are connected to the DC bus through the corresponding converters, but the electrolyser can be excluded from the system. The experiments for microgrid without the electrolyser were made in this thesis, and the tank is discussed as limited hydrogen source [149]. The pressure regulator is used for ensuring necessary hydrogen pressure for the fuel cell.

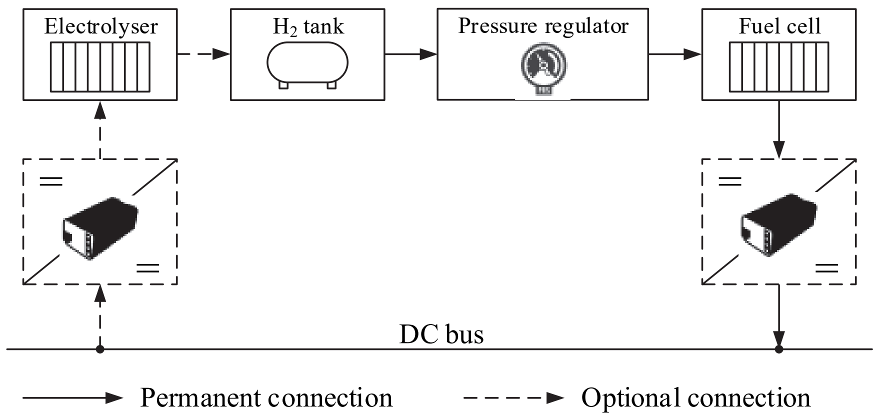


Figure 4.6. Connection of the hydrogen energy storage to the DC bus

For automatic switching to hydrogen energy when the wind power is not sufficient the wind generator converter output voltage is stabilized to constant voltage $V_{dc,r}$ V (Figure 4.7., interval „1”), and in the case of overload it starts to decrease (interval “2”). The fuel cell output is stabilized to lower voltage level ($V_{dc,nom} - \Delta V$ V). The surplus power is possible in interval “1”. The power P_{H2} available for hydrogen production is equal to:

$$P_{\mathrm{H2}} = P_{\mathrm{w}} - P_{\mathrm{load}}, \tag{4.5.}$$

where P_{w} – wind generator power, W;
P_{load} – load power, W.

The power source with higher voltage provides the power in intervals „1” and „2”, and both power sources are providing power in interval „3”. The intervals mentioned above are continuously changing in accordance with the speed of wind.

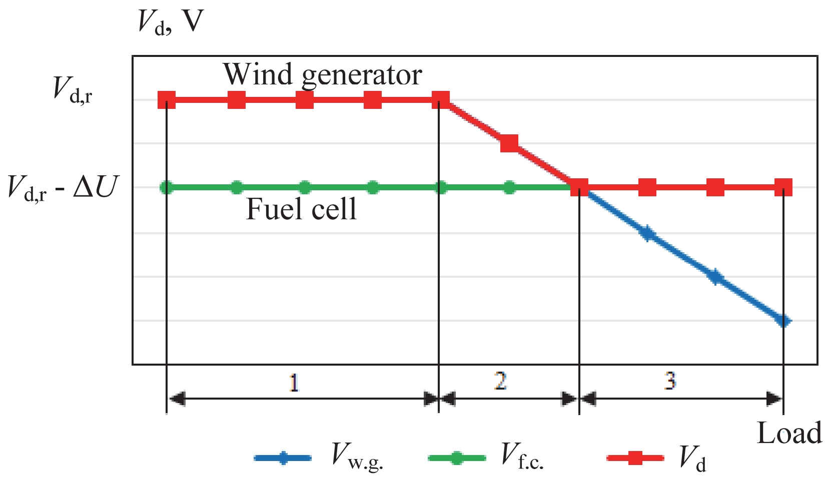


Figure 4.7. The voltage/load characteristics: $V_{\mathrm{w.t.}}$ – wind generator voltage; $V_{\mathrm{d.el.}}$ – fuel cell voltage; V_{d} – DC bus voltage

In the interval “3” the load current is:

$$I_{\mathrm{load}} = I_1 + I_{\mathrm{d.e.}},\ \mathrm{A}, \tag{4.6.}$$

where I_{load} – load current, A;
I_1 – wind generator converter current, A;
$I_{\mathrm{d.e.}}$ – fuel cell current.

The aim of small scale experiments [149] was to test whether it is possible to achieve the required power distribution between the basic source of energy and fuel cell according to (4.6.) the rated voltage 40 V of the DC bus was accepted. The experimental results confirm, that necessary power distribution is possible directly adjusting the duty cycle of the DC/DC converter (Figure 4.8.).

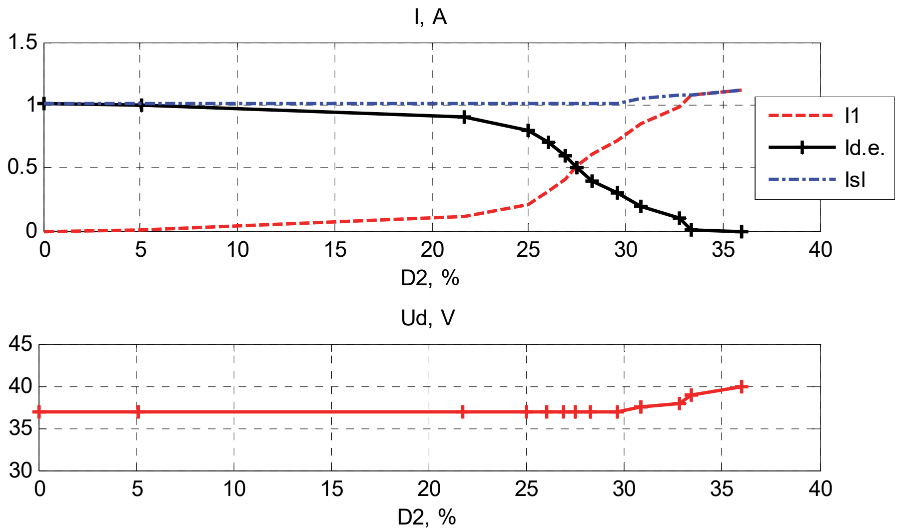


Figure 4.8. Currents and DC bus voltage U_d depending on the DC-DC converter duty ratio D2

Conclusions of the chapter

The proposed system is based on the active rectifier, which is controlled by difference between wind generator converter current and load current. According to proposed control principle, the optimum current curve of the discussed permanent magnet synchronous generator was calculated and recognized by the computer model.

There is a need for energy storage system in the autonomous alternative energetics microgrid. The hydrogen based energy storage system is possible solution to provide uninterrupted power supply in the DC microgrid. The fuel cell must be in the “run” mode all the time, because the transition from standby mode to run (power ready) mode can require up to 5 seconds. The experiments were made in small scale, and the rated DC bus voltage equal to 40 V was accepted. The output voltage of the fuel cell was equal to 37 V. The load power can be split between two sources, including fuel cell.

Theoretical analysis and computer modelling show the correct operation of the control principles. The proposed method allows using all wind turbine generated energy in a wide range of speeds. Surplus wind energy can be transmitted to the conventional power grid and, if necessary, energy flow from the conventional grid can support the needs of consumers. Thus, the performance of the nearly zero energy buildings concept is ensured.

5. EVALUATION OF THE WIND TURBINE ECONOMIC EFFICIENCY

Cover of expenditure and revenue opportunities

The economic efficiency of the wind power plant must be evaluated using the specific annual generation financial efficiency factor C^*_{w}:

$$\begin{cases} C^*_{\mathrm{w}} = \alpha(1-\beta)T_{\mathrm{an}}C_{\mathrm{kWh,market}} - k_{\mathrm{a}}C_{\mathrm{kW}}, \beta \le 1, \\ C^*_{\mathrm{w}} = \alpha(1-\beta)T_{\mathrm{an}}C_{\mathrm{kWh,grid.}} - k_{\mathrm{a}}C_{\mathrm{kW}}, \beta > 1, \end{cases} \tag{5.1.}$$

If $C^*_{\mathrm{w}} = 0$, investments in wind turbine installation during the year, including operating costs are equal to the income from the sale of energy distribution network, so if $C^*_{\mathrm{w}} > 0$, the return on investment is detected. There are three cases, when $C^*_{\mathrm{w}} < 0$:

- the income from the sale of energy to power grid are less than the annual cost of the wind turbines ($P_{\mathrm{grid,av}} > 0$ W);
- energy is not sold to the power grid ($P_{\mathrm{grid,av}} = 0$ W);
- produced wind energy is not enough to ensure the load demand and energy is bought from the power grid ($P_{\mathrm{grid,av}} < 0$ W).

The specific annual equivalent cost factor depends on the load energy costs at the power grid price:

$$C^*_{\mathrm{eq}} = -\alpha\beta T_{\mathrm{an}}C_{\mathrm{kWh,grid}}, \text{ EUR}, \tag{5.2.}$$

where αβ is average load power $P_{\mathrm{load,av}}$, reduced to the rated power of the wind turbine, and sign „–” specifies to expenditure.

The energy produced by a wind turbine will be cheaper than that from a conventional grid in the case, when $C^*_{\mathrm{w}} > C^*_{\mathrm{eq}}$, and this condition depends on α and C_{kW} (Figure 5.1.). The points on which the surface C^*_{w} is above the surface C^*_{eq}, the annual installation costs are less than the equivalent amount of energy, bought from the conventional grid.

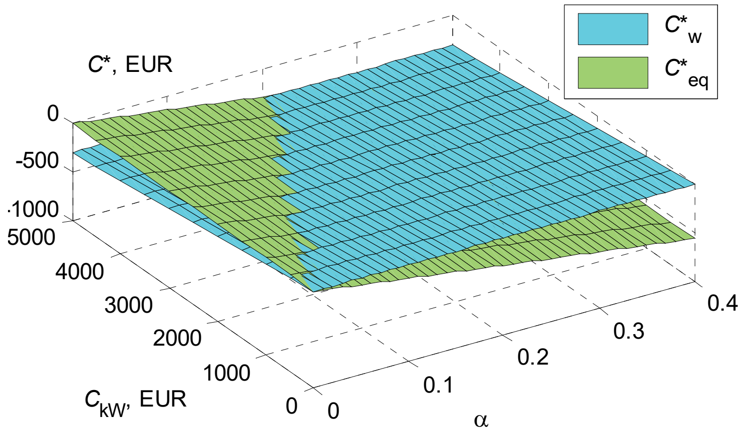


Figure 5.1. The specific annual generation financial efficiency factor comparing with the specific annual equivalent cost factor at β = 1

The minimum capacity factor α_{min} shows, when energy generated by the wind turbine is less than conventional grid energy. If consumption is more than wind turbine can produce ($\beta > 1$), the energy deficit is offset by the energy of the conventional network, in this case:

$$\alpha_{\mathrm{min}} = \frac{k_{\mathrm{a}} C_{\mathrm{kW}}}{T_{\mathrm{an}} C_{\mathrm{kWh,grid}}}. \tag{5.3.}$$

If the consumption is less than energy amount produced by wind turbine ($\beta < 1$), and the surplus energy is not transmitted to the conventional grid, the minimum load $(\alpha \cdot \beta)_{min}$, below which the use of wind turbine is not cost-effective, is defined:

$$(\alpha\beta)_{\mathrm{min}} = \frac{k_{\mathrm{a}} C_{\mathrm{kW}}}{T_{\mathrm{an}} C_{\mathrm{kWh,grid.}}}. \tag{5.4.}$$

If the consumption is less than energy amount produced by wind turbine ($\beta < 1$), and the surplus energy is transmitted to the conventional grid, use of the wind turbine can serve purposes such as cheaper energy acquisition, compared with the acquisition of the distribution network, or investment payback and profit.

The minimum capacity factor α_{min} required in order to achieve economic effect is equal to:

$$\alpha_{\mathrm{min}} = \frac{k_{\mathrm{a}} C_{\mathrm{kW}}}{(1-\beta) T_{\mathrm{an}} C_{\mathrm{kWh,market}} + \beta T_{\mathrm{an}} C_{\mathrm{kWh,grid.}}}. \tag{5.5.}$$

If $C^{*}_{\mathrm{W}} \geq 0$, there is a return on investment into wind turbine installation. In this case the maximum value β_{max} of the wind turbine power distribution factor is determined:

$$\beta_{\mathrm{max}} = 1 - \frac{k_{\mathrm{a}} C_{\mathrm{kW}}}{\alpha T_{\mathrm{an}} C_{\mathrm{kWh,tirgus}}}. \tag{5.6.}$$

The return on investment is possible when $\beta \leq \beta_{max}$.

Estimation of the price of the produced energy

The average theoretical generated power of the wind turbine can be calculated using the power curve (Figure 5.2.) and actual wind speed diagram for the specific period (Figure 5.3.).

Using the theoretical average power of the turbines and the turbine prices the actual and minimum capacity factors are calculated (Figure 5.4.). Figure 5.5. shows the difference between wind turbine produced energy price and price of the conventional grid energy.

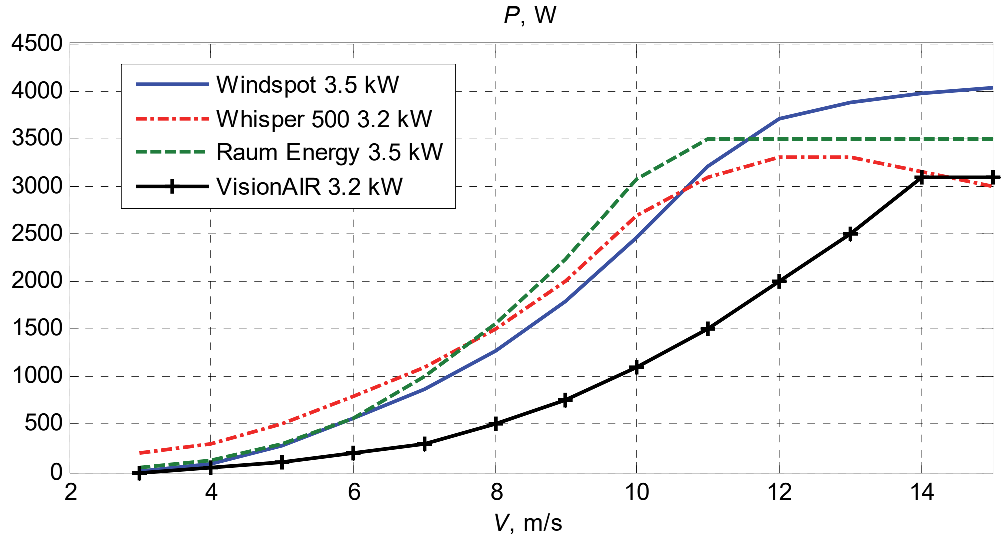


Figure 5.2. Power curves of some 3.2 kW and 3.5 kW wind turbines

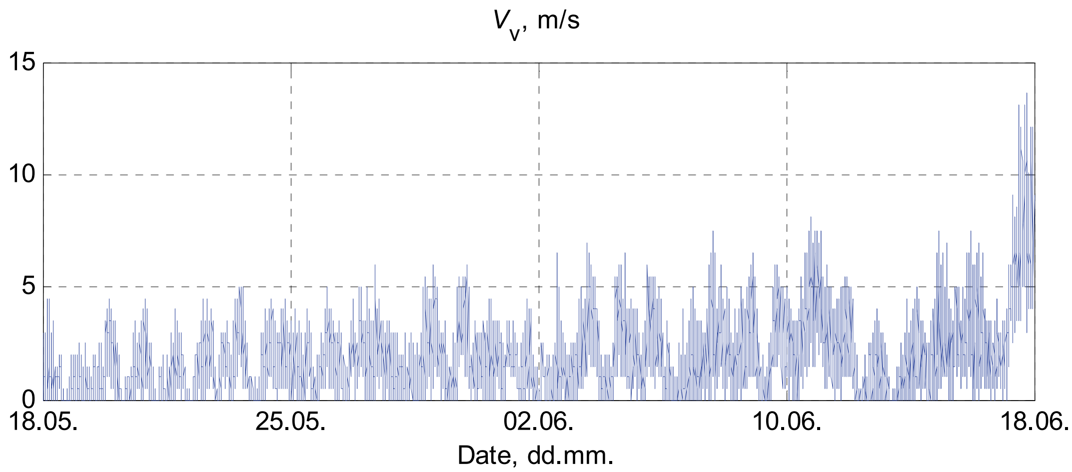


Figure 5.3. Wind speed above the building of the RTU Faculty of Power and Electrical Engineering over the time period from 18.05.2016 till 18.06.2016

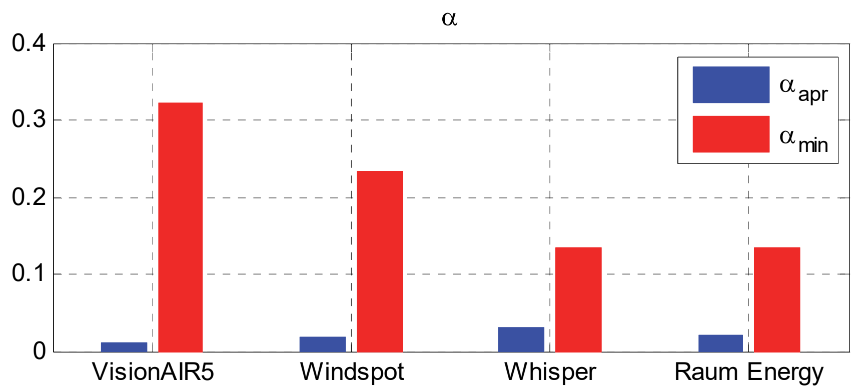


Figure 5.4. Capacity factors of the various wind turbine in discussed conditions: α_{apr} – actual capacity factor α_{min} – minimum necessary capacity factor

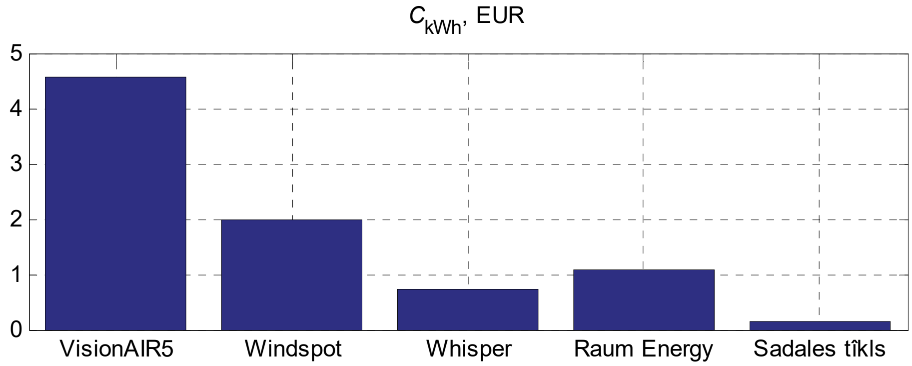


Figure 5.5. The difference between wind turbine produced energy price and price of the conventional grid (Sadales tīkls) energy

Analysis of the electricity NET payment system in the Republic of Latvia

The electricity cost for 1 kWh of each Latvian household consists of three main components: the distribution operator service, the mandatory procurement component (MPC) and the payment for electricity. Each household must paid for operator services and MPC (60% of the total cost for kWh). Payment for the electricity is calculated by the net principle. Total equivalent amount of electrical energy for which household must pay is:

$$E_{\mathrm{eq}} = 0.6E_{\mathrm{grid,cons}} + 0.4E_{\mathrm{neto}} = E_{\mathrm{grid,cons}} - 0.4E_{\mathrm{grid,trans}}, \tag{5.7.}$$

where E_{neto} – the amount of electrical energy for which household must pay, kWh;
$E_{\mathrm{grid,cons}}$ – energy consumed from the conventional grid, kWh;
$E_{\mathrm{grid,trans}}$ – energy transferred to the conventional grid, kWh.

Conclusions of the chapter

The efficiency of the wind turbine is evaluated by use of the generation financial efficiency indicator, which indicates the return of investments (positive values), losses (negative value) or the investment and income equality (equal to 0).

The estimation of the wind turbine economic efficiency for the specific object shows that produced energy of the discussed 3.2–3.5 kW turbines will be 4.4–28.4 times more expensive than conventional grid energy.

The economic effect of the utilization of the wind turbines depends on the conventional grid operator regulations and electricity payment system, which determine possibilities for wind turbine owner to get a compensation for energy transferred to the grid. The analysis of the electricity NET payment system in Latvia was made. To describe the financial efficiency of the wind turbine the indicator E_{eq} (total equivalent amount of electrical energy for which household must pay) was used. The payment for electricity depends on the wind energy amount, which was directly consumed by the load without transfer to the conventional grid. The smallest value of the equivalent energy can be reached at the maximum possible energy amount generated by wind turbine and energy amount directly consumed by load.

CONCLUSIONS

1. The scheme of the microgrid with 600 VDC bus and synchronous generator with full power conversion is proposed with the aim to reach the strategical objective of the use of the renewable energy sources. This way, the appropriate laws and regulations on the use of renewable resources and energy efficiency in buildings will be implemented.

2. The control system of the synchronous generator DC-DC converter is based on setting the wind generator optimal current and directly adjusting the DC/DC converter duty cycle.

3. Taking into account the properties of the permanent magnet synchronous generators, they are considered to be better in use in the low power microgrids comparing to synchronous generators with separate excitation. If the rated voltage of the DC bus is 600 V, the minimum necessary speed of the discussed generator is 18.5 rpm.

4. In case of discussed synchronous generators with separate excitation, at generator speed below 130 rpm the rated excitation power exceeds the rated generator power. At rated excitation current the excitation power is equal to 1140 W that is 23 % of the rated one at 300 rpm or 57 % of the rated one at 160 rpm. Synchronous generator with self-excitation system can be used in the wind turbines in case when it excitation power is proportionate to generator rated power.

5. The automation task of the wind energy based power system is executed by use of the active rectifier for the DC based microgrid connection to the conventional AC power grid. The active rectifier control is realized by determination of the difference between maximum allowed wind generator DC-DC converter current and load current. This method provides bidirectional energy transmission between DC microgrid and conventional power grid. Thus, the conception of the nearly zero energy building is realized.

6. Computer modelling of the created microgrid scheme shows positive results in a wide range of the generator shaft speed. Generator operation with constant rated current is provided, therefore the adequacy of the control principle is affirming. Such system can be recommended to customers.

7. Economic efficiency of the wind turbine can be evaluated by the use of the annual generation financial efficiency factor and power curves of the specific turbines. The estimation of the wind turbine economic efficiency for the specific object shows that produced energy of the discussed 3.2–3.5 kW turbines will be 4.4–28.4 times more expensive than conventional grid energy.

8. Economic efficiency of the wind turbine depends on the conventional grid operator regulations and electricity payment system. The economic effect of the utilization of the wind turbines depends on the conventional grid operator regulations and electricity payment system, which determine possibilities for wind turbine owner to get a compensation for energy transferred to the grid. The analysis of the electricity NET payment system in Latvia was made. To describe the financial efficiency of the wind turbine the indicator E_{eq} (total equivalent amount of electrical energy for which household must pay) was used. The payment for electricity depends on the wind

energy amount, which was directly consumed by the load without transfer to the conventional grid. The smallest value of the equivalent energy can be reached at the maximum possible energy amount generated by wind turbine and energy amount directly consumed by the load.

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