Ihor Shchur, Andrzej Rusek, Politechnika Czestochowska, Czestochowa
Volodymyr Klymko, Politechnika Lwowska, Lwów
Andrzej Gastołek, Jarosław Sosnowski
Politechnika Częstochowska, Częstochowa, Revico, Płock

ANALYSIS OF METHODS OF ELECTRICAL LOAD OF PERMANENT MAGNET SYNCHRONOUS GENERATOR FOR SMALL WIND TURBINES

ANALIZA SPOSOBÓW ELEKTRYCZNEGO OBCIĄŻANIA GENERATORA SYNCHRONICZNEGO Z MAGNESAMI TRWAŁYMI W ELEKTROWNIACH WIATROWYCH Z OSIAMI PIONOWYMI

Abstract: The article compares the different ways to create and regulate electrical load of synchronous generator with permanent magnets (PMSG) in the low-power wind turbines with vertical axis (VAWT). Briefly describes the methods that allow you to adjust the electromotive force of PMSG. But focuses on such in which the simplest unregulated three phase PMSG is applied, and control of electric load is carried out by means of semiconductor converters. The methods of adjusting the electrical load were relied to each other in terms of complexity and thus of realize cost and of the value and energy efficiency. As a compromise between these indicators a combined method with a low-power DC-DC-converter, which operate at low winds, and passive control –at high winds is proposed. The research was conducted by computer simulation in Matlab/Simulink.

Streszczenie: W artykule porównano różne sposoby powstawania i regulowania obciążenia elektrycznego generatorów synchronicznych z magnesami trwałymi (PMSG) w elektrowniach wiatrowych małej mocy, o pionowej osi obrotu (VAWT). Krótko opisano metody regulujące siłę elektromotoryczną PMSG. Skupiono się na metodach, w których stosuje się najprostsze trójfazowe PMSG, a regulację ich obciążenia elektrycznego prowadzi się za pomocą przetworników półprzewodnikowych. Sposoby regulowania obciążenia elektrycznego porównano pod względem efektywności energetycznej. Jako kompromis między tymi wskaźnikami zaproponowano mieszany sposób z DC-DC-przekształtnikiem małej mocy, pracującym przy niskich wiatrach i sterowaniem pasywnym – przy dużych wiatrach. Badania prowadzono z użyciem symulacji komputerowej w środowisku Matlab/Simulink.

Keywords: *Wind turbine, PMSG, electric load control, active rectifier, DC-DC converter, energy efficiency*
Słowa kluczowe: *Elektrownia wiatrowa, PMSG, regulowanie obciążenia elektrycznego, prostownik aktywny, DC-DC przekształtnik, sprawność*

1. Introduction

The potential of wind energy in the prevailing territories of Ukraine and Poland is characterized by low average of annual speed of the wind flow at level 4 - 5 m/s [1]. Low-power wind turbines (WT), which are installed nearby consumers, can be operated on such winds with the best efficacy. Using of wind turbines with vertical-axis of rotation (VAWT) is appropriate for this through the next number of their advantages: the independence of work on the direction of wind, simplicity and reliability of construction due to lack of the multiplier (gear), the possibility of mounting directly on the buildings, low noise level [3].

Looking at low-power WT, the main emphasis is placed on the optimal ratio between energy efficiency and low cost, that leads to reduce the period of recoupment of WT [4].

The use in VAWT synchronous generator with the excitation from permanent magnets (PMSG) allows one to generate electricity with maximum energy efficiency [5]. The direct drive between wind rotor (WR) and PMSG is used, in order to increase reliability and reduce the cost of WT. Since the VAWT operate with variable frequency of rotation, output electromotive force (EMF) of variable frequency of the PMSG should be converted into direct voltage with certain value. The latter then is connected to the storage battery (SB) in

a case of autonomous work of the WT or to the voltage inverter (VI), which is connected to the supply grid in the case of parallel work with electricity network. In order to obtain the maximum energy from the wind, it is necessary to provide automatic adjustment of WT work, which in the case of the most reliable passive WR can be carried out only by changing the load torque on the shaft of WR. For this purpose a number of methods are used, which differ in their complexity and, accordingly, cost, on the one hand, and energy efficiency, on the other [6, 7]. These indicators usually are in contradiction with each other. Therefore analysis of the effectiveness and search for optimal technical solutions concerning the implementation of energy efficient simple control of WT work is an actual scientific task.
The purpose of work is analysis of the effectiveness of different methods of adjustment electrical load of VAWT with PMSG, and substantiation solution which will be effective in terms of the fastest recoupment of the WT.

2. Analysis of the methods of adjustment of the WT load

All the methods of adjusting the load of the WT can be divided into passive and active (Fig. 1).
In passive systems of WT (Fig. 1,a) the adjustment is done automatically under the influence of variable wind speed. To do this, elements of the system of WT (WR, PMSG, SB) must either be specially designed or their parameters need to be optimized [8]. Such systems are marked with the lowest cost, but their energy efficiency can be high only in a narrow range of change of wind speed. Hence – the low energy efficiency and in accordance great payback period of passive WT, that does not lead to their distribution, in spite of the simplicity of their design.
In active systems of WT (Fig. 1,b,c) the optimal adjustment of their work carried out by using special technical solutions and devices, which, of course, complicate the design and increase its cost. Such devices can be divided into the following groups: 1) complication of design of PMSG in order to permit regulation of their EMF (Fig. 1,b) [9]; 2) use of electronic converters of the parameters of electric energy, that are included between PMSG and DC link (Fig. 1,c) [4,7,10].

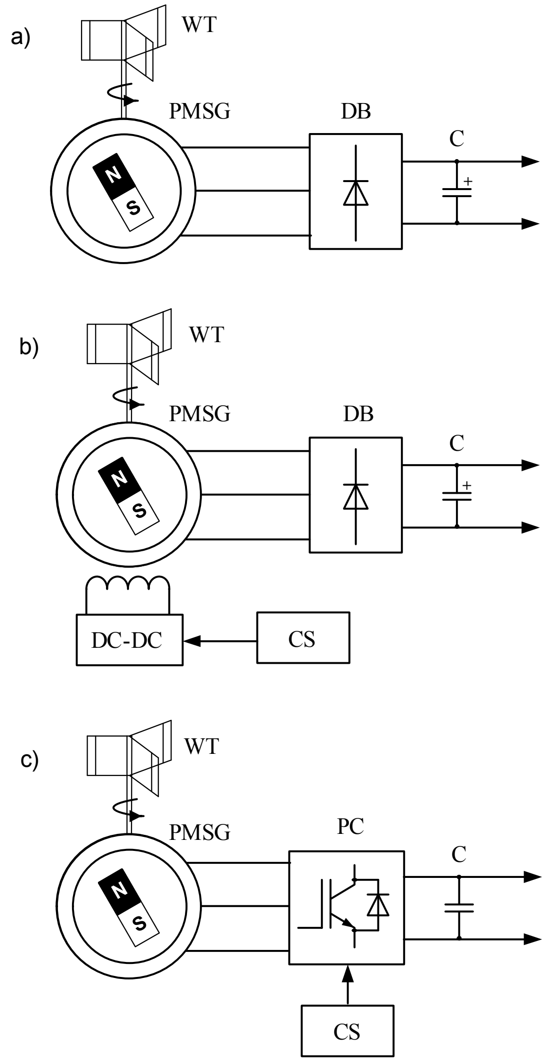


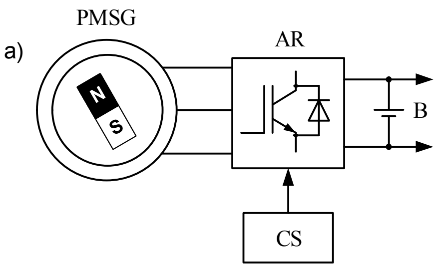
Fig. 1. Configuration of small VAWT with different ways of adjustment of electric load: a) passive, b), c) active

2.1. PMSG with adjustment of the EMF

To adjust the rotation EMF, special hybrid synchronous generators with permanent magnets, which combined magnetoelectric and electromagnetic excitation were developed [11]. Herewith inductor and armature are located on the stator, and the rotor is passive with visibly pronounced teeth. Such dual layer synchronous machines with permanent magnet (DSPM – doubly salient permanent-magnet machine) are marked with high indicators – power density, efficiency and reliability, – and require low-power devices to control excitation. However, designing and manufacturing of hybrid multipolar generators is complicated, which significantly increases their cost in comparison with traditional PMSG.

2.2. Electronic regulation systems of the PMSG load

Typically, WT with PMSG include power semiconductor converters, which are designed to regulate the power flow taken from the generator, and also simultaneously to adjust the parameters of received electricity. Two systems is most often used in small WT: with transistor active rectifier (AR) (Fig. 2,a) and with DC-DC voltage converter (Fig. 2,b), which may have different properties (buck, boost or buck-boost) [4, 10]. The first system is significantly more expensive than the second, because it requires six power transistors compared with one for the second. In addition, it characterized with much more complicated control. However, AR can perform three functions: regulate consumable by PMSG current or power, provide sinusoidal form of consumption current and cosφ = 1, regulate (stabilize) output voltage [12]. In contrast to AR, DC-DC-converter in the system shown in Fig. 2,b, is not capable of affecting the shape of consumed from PMSG currents, what results in increased energy losses in the generator [13].



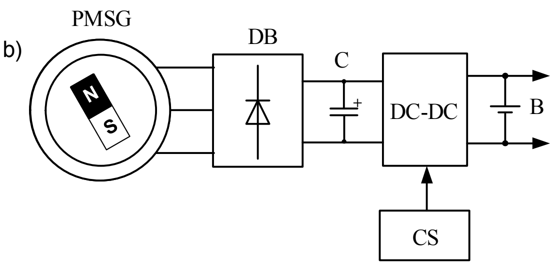
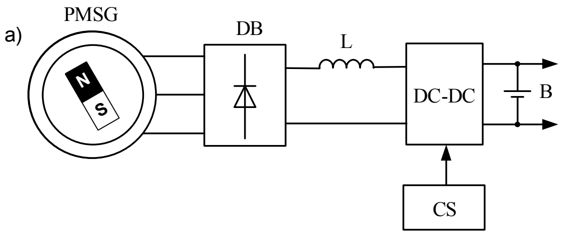


Fig. 2. Electronic regulation systems of load of the PMSG: a) with active rectifier, b) with DC-DC-converter

In order to reduce distortion of the generator currents, a number of methods are used: 1) replacement of direct voltage link on direct current link (Fig. 3,a) [4], 2) the use of three single-phase rectifiers with its DC-DC-converters [14], 3) use of active filters AF of the linear currents of generator (Fig. 3,b) [12]. The first method is marked by simplicity, however it is suitable only for boost type of DC-DC-converter and does not allow to provide sinusoidal form of the generator currents and their in phase with EMF. The second method is characterized by the relative complexity and increased cost, because it includes three control channels. The third method is also complicated, because it has two active converters – DC-DC and active current filter.



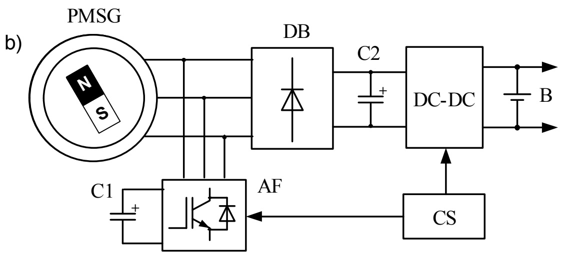


Fig. 3. Regulation systems of load of the PMSG with low distortion of armature currents of the generator: a) with direct current link, b) with usage of active current filter

From these methods favorably differs one more (Fig. 4,a) [15], which is topologically similar to one that is shown in Fig. 3,a, however differs from the latter with operation mode – discontinuous form of the linear currents of generator (Fig. 4,b). Herewith the average values of currents (current curve $i_{A.avg}$ of phase A) have a very close to the sinusoid shape. In order to increase the operating frequency of pulse-width modulation $f_s = 1/T_s$, it is necessary to reduce the inductance of the chokes in the phases of the generator. Therefore as the working inductances, in which discontinuous currents will flow, it is necessary to include small chokes L1-L3 in the linear wires of PMSG and separate them from the generator with capacitors C1-C3, as shown in Fig. 4,a. Then the linear currents of the generator will become continuous.

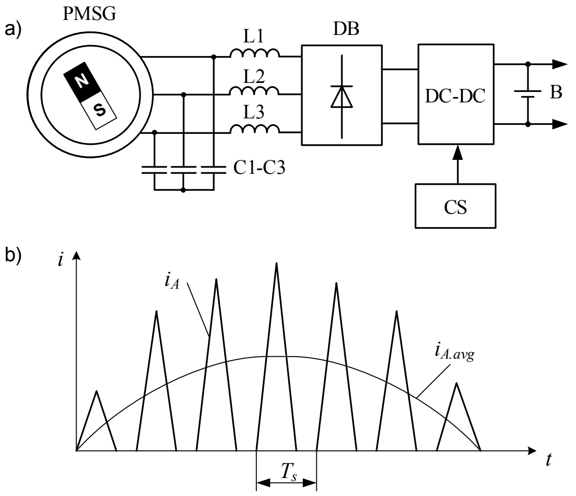


Fig. 4. Discontinuous mode of linear currents of the PMSG (a) and load regulation system of the WT (b), which realize it

3. Comparison of energy efficiency of the alternative systems of electric load of the PMSG

For comparison purposes, were chosen three alternative systems of WT: passive (Fig. 1,a) with different numbers of SB, active with AR (Fig. 2,a) and the last one described in section 3 – with DC-DC-converter and the formation of discontinuous linear currents (Fig. 4,a). Each of these three systems was investigated by computer simulating in Matlab/Simulink of steady-state mode of VAWT with rated output power of 1 kW at constant wind speeds from 3 to 10 m/s. The calculated values of parameters of the main elements of such WT are as follows.

WR: three blade H type, radius r = 1,4 m, washing area A = 5,258 m^2, aerodynamic characteristic of WR is described by the following expression of the wind power conversion efficiency factor [16]:

$$C_{\mathrm{P}}(\lambda) = 1{,}14 \cdot \left(\frac{9{,}47}{\lambda} - 1\right) \cdot e^{\frac{-6}{\lambda}},$$

where $\lambda = \omega r / V_{\mathrm{w}}$ is the tip speed ratio of WR, ω is its angular speed, and V_{w} is the wind speed.

PMSG: rated power $P_{\mathrm{G.n}}$ = 1000 W, rated angular speed $\omega_{\mathrm{G.n}}$ = 27 rad/s, number of pole pairs p = 20, flux linkage of a armature winding with a pair of poles of magnets Φ_{m} = 0.13 Wb, active resistance and inductance of the armature phase winding R = 0.35 Om and L = 4 mH.

The mechanical part of WT: aggregated moment of inertia of WR with generator rotor J = 19 kg·m^2, moment of dry friction M_{st} = 2 N·m.

AB: in the DC link is used SBs with the voltage of 12 V, which are connected in series. For regular work it is necessary to load AR on 8 SBs, boost type DC-DC-converter is enough to load on 7 SBs. The passive system was investigated with the number of SBs 4, 5 and 6. The results of computer investigation are presented in Fig. 5-9. As shown in Fig. 5, both active systems, with AR and DC-DC-converter, through the optimal load adjustment of the PMSG, provide the maximum power extraction from wind at any its rate.

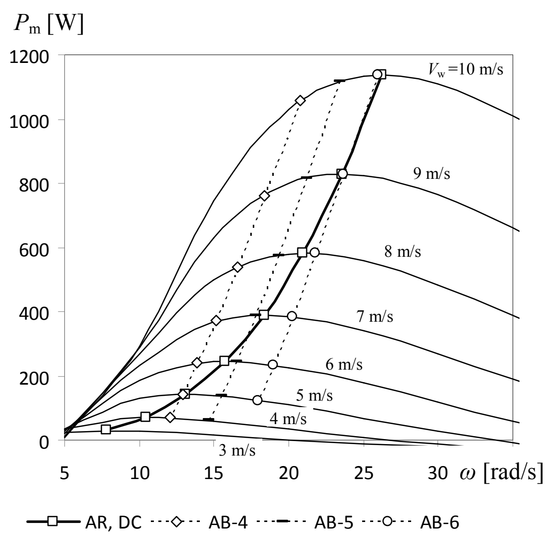


Fig. 5. Variations of the mechanical shaft power of WT with its angular velocity and wind speed for compared methods of adjustment of electric load of the PMSG

The passive system can only work satisfactorily with 4-5 SBs and then starting only at wind speed of 4 m/s and with 6 SBs –at wind speed of 5 m/s. Over the 4 SBs maximum wind power takeoff will occur for the speed of 5 m/s, and at 5 SBs – at 6.5 m/s. At high wind speeds the efficiency of passive WT is reduced.

However, the wind power conversion efficiency factor C_{P} is not a sufficient indicator of the efficiency of WT, because at its various configurations is observed different values of electromechanical system efficiency, which is calculated by the expression:

$$\eta_{EM} = \eta_m \, \eta_G \, \eta_{PC},$$

where $\eta_m, \eta_G, \eta_{PC}$ are respectively efficiency of mechanical system of the WT, PMSG and power converter.
The dependence of the total efficiency of WT as the ratio of electrical power output to a wind stream power that washes WR, is calculated by the expression

$$\eta_\Sigma = C_P(\lambda)\,\eta_{EM}$$

and is presented for the all compared systems of WT in Fig. 6.

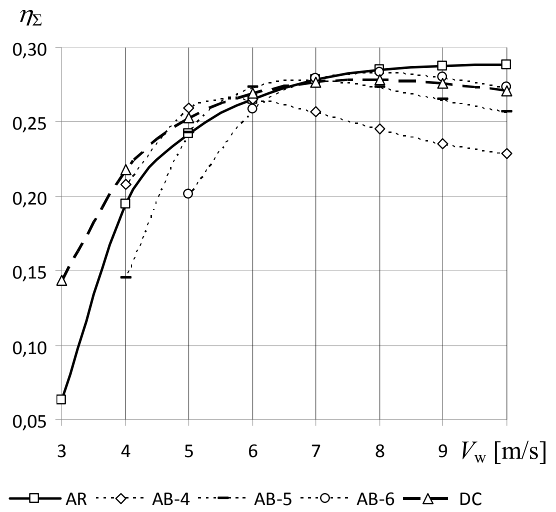


Fig. 6. Total efficiency of WT versus wind speed for compared methods of adjustment of electric load of the PMSG

As seen of the obtained results, differences in the character of dependencies $\eta_\Sigma(V_w)$ for investigated systems caused by the difference in the efficiency of the generator η_G (Fig. 7) and power converter η_{PC} (Fig. 8), because the mechanical part efficiency dependencies η_m are practically the same. AR has significant advantages in high powers (wind speeds), and at low one the efficiencies of the generator and power converter are reduced by increasing relative impact of PWM. At the same time, appropriate efficiencies when using DC-DC-converter is higher, than at AR, at small powers, but on large powers they are lower. In the passive system of WT the efficiency of power converter is always high, but the efficiency of the PMSG is high only at small powers and at large one it is rapidly falling down, because of the distortion of currents. Only under 6 SBs the efficiency of the generator always exceeds the efficiency of the system with DC-DC-converter.

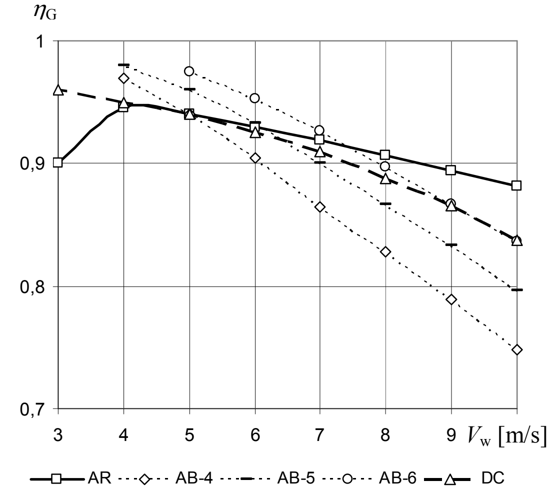


Fig. 7. Efficiency of PMSG versus wind speed for compared methods of adjustment of electric load of the PMSG

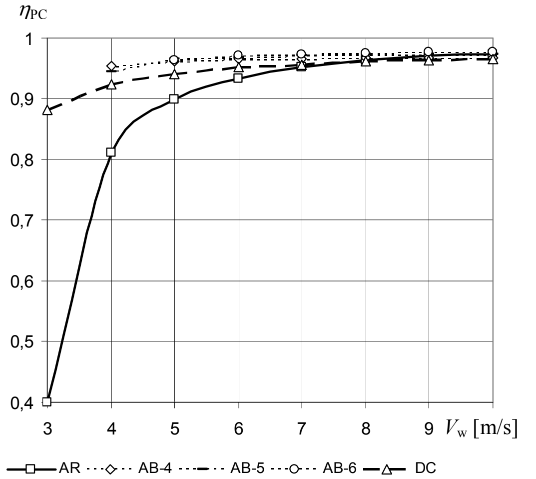
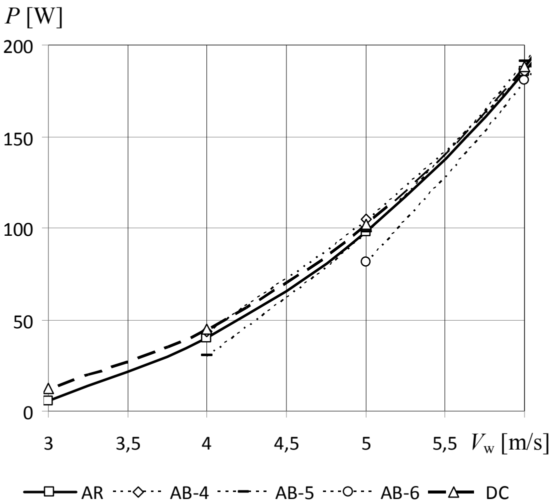


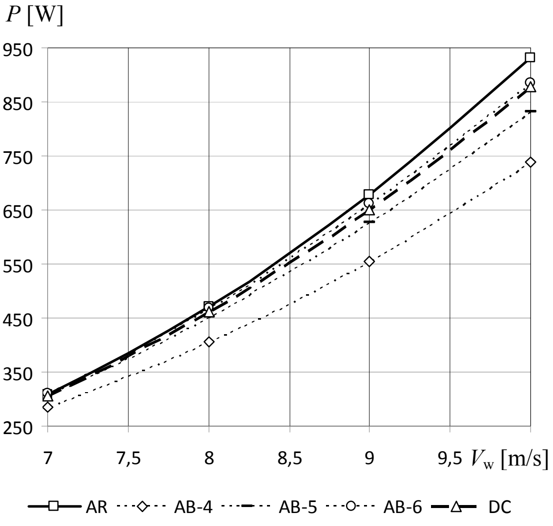
Fig. 8. Efficiency of power semiconductor converters versus wind speed for compared methods of adjustment of electric load of the PMSG

These results confirm the rationality of proposed by us in [17] the combined method of controlling the load of WT, when at low and medium wind speeds adjustment occurs through DC-DC-converter, but at high – with passive way. For investigated VAWT for this is best to pick 6 SBs, and the transition from active to passive control to carry out at wind speed of 7 m/s. At higher than this threshold wind speeds the generator EMF becoming sufficient, order to charge the SBs directly through the diode bridge and the diode of DC-DC-converter VD2

(Fig. 2,b). At small winds we get at the output of WT greater electrical power, than when using AR (Fig. 9,a), and on rather large – by 9% more, than using the DC-DC-converter, and only 7% less, than with the AR (Fig. 9,b). Herewith, the installed power of the DC-DC-converter will be not high (35% of the rated power of generator), that significantly will affect on the total cost of WT.



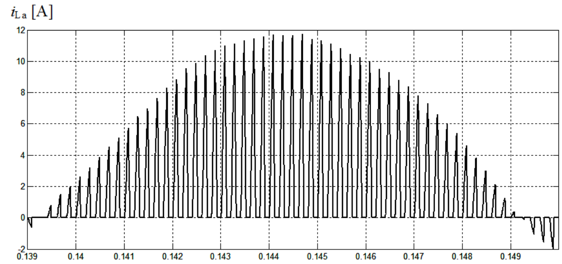
a)



b)

Fig. 9. Electrical power at the WT output versus wind speed at low (a) and high (b) winds for compared methods of adjustment of electric load of the PMSG

Simulated waveforms of phase EMF and linear currents of PMSG at its loading by using DC-DC-converter shown in Fig. 10. As seen from the waveforms, the applicable method of discontinuous shape of armature currents of PMSG provides close to the sinusoidal currents form and close to unique cos*φ*.



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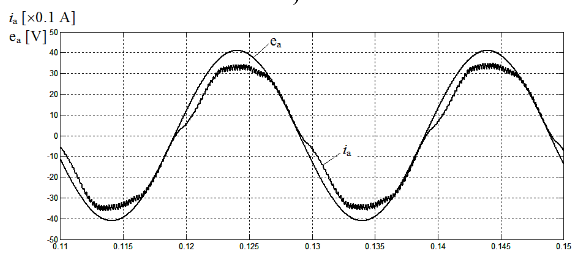

b)

Fig. 10. Simulated waveforms of the basic electrical variables in the armature circle of the PMSG: a) current in the choke L1 (Fig. 4,b), b) EMF e and current i in phase armature winding

4. Conclusions

In order to provide simplicity and reliability of work of small VAWT, in their design is the best to use the passive WR, directly connected with PMSG. For optimal adjustment of electrical load of the WT, the most efficient appeared the combined control system with low-power DC-DC-converter, which runs on small and medium wind speeds, but rather on large – WT is adjusted automatically with passive way, when the generator is loaded directly through the diode bridge on SB with optimum voltage. Such system are inherent next advantages: practically maximum power extraction from wind throughout the full operating range of changes of its speed, high values of efficiency of electromechanical part throughout the full power range, low cost. All this together ensures a minimum payback period of WT.

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Autorzy

Ihor SHCHUR, prof. dr hab. inż., Zakład Maszyn i Napędów Elektrycznych Instytutu Elektrotechniki Przemysłowej Wydziału Elektrycznego Politechniki Częstochowskiej
Tel. +38 0502989963
e-mail: i_shchur@meta.ua

Andrzej RUSEK, prof. dr hab. inż., Zakład Maszyn i Napędów Elektrycznych Instytutu Elektrotechniki Przemysłowej Wydziału Elektrycznego Politechniki Częstochowskiej
Tel. +48 34 3250821
e-mail: rusek@el.pcz.czest.pl

Volodymyr KLYMKO, mgr inż., doktorant, Zakład Napędu Elektrycznego Instytutu Energetyki i Systemów Sterowania Politechniki Lwowskiej
Tel. +38 067 3838789
e-mail: vklymko@gmail.com

Andrzej GASTOŁEK, mgr inż. doktorant, Instytut Elektrotechniki Przemysłowej Wydziału Elektrycznego Politechniki Częstochowskiej
Tel.+48 34 3250821
e-mail: iess@el.pcz.czest.pl

Jarosław SOSNOWSKI, mgr inż., doktorant, Instytut Elektrotechniki Przemysłowej Wydziału Elektrycznego Politechniki Częstochowskiej
Tel.+48 34 3250821
e-mail: iess@el.pcz.czest.pl