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Estimation of electromagnetic compatibility and efficiency of the adjustable load systems of PMSG in wind turbines

***Abstract**. In wind turbine (WT) systems with variable angular speed of permanent-magnet synchronous generator (PMSG), the harmonic components of generator currents in transient and steady state have impact on energy efficiency. This paper investigates the nature of harmonic distortions and analyses some promising basic schemes of adjustable load systems of PMSG in WT. Simulation results are presented to illustrate the performance of the proposed systems.*

Streszczenie.** Generatory synchroniczne z magnesami trwałymi (PSMG), o zmiennej prędkości obrotowej, stosowane w elektrowniach wiatrowych, wytwarzają prądy, których składowe harmoniczne w stanach przejściowych i ustalonych mają wpływ na sprawność energetyczną takich generatorów. W prezentowanym artykule przedstawiono wyniki badań nad właściwościami zniekształceń harmonicznych oraz analizę wybranych podstawowych schematów układów do regulacji obciążenia PSMG. W celu zilustrowania właściwości proponowanych układów w artykule przedstawiono wyniki ich modelowania. **(Ocena kompatybilności elektromagnetycznej i sprawności systemu regulacji obciążenia PSMG w elektrowniach wiatrowych)

Keywords: wind turbine, electromagnetic compatibility, efficiency, transient and steady state.
Słowa kluczowe: elektrownia wiatrowa, kompatybilność elektromagnetyczna, sprawność energetyczna, stany ustalone i przejściowe.

Introduction

Energy and environmental crises in which mankind found itself at the turn of the 21st century necessitate increasing use of renewable energy sources, including wind energy [1, 2]. In low and medium power wind turbines (WT) they are increasingly using permanent-magnet synchronous generators (PMSG), which are simple to operate, quite easy to control, are reliable, and have high power efficiency [3, 4]. To receive the maximum power from WT, PMSG should work with variable speed. Further conversion of generated electrical energy may follow different schemes, depending on system configuration and its purpose – whether it is meant for stand-along work or for the grid. However, in almost all cases the first step in the transformation of the variable speed PMSG is rectification of alternating voltage into direct voltage. It usually occurs in conjunction with power control, for example, maximum power point tracking (MPPT) of WT [3, 4].

Controlled receiving of power from three-phase PMSG is implemented according to two schemes: 1) PMSG – diode bridge (DB) – DC-DC converter, 2) PMSG – active rectifier (AR) [5]. In the first case, PMSG load is non-linear, and the consumed generator currents are characterized by a wide range of odd and non-multiple of three harmonics. In the second case, due to PWM, it is easy to provide the desired form of linear currents.

Assuming that the automatic power control is perfect, the factor that limits energy efficiency of the system is nonobservance of electromagnetic compatibility (EMC) of subsystems – power generation and taking power from PMSG – in both transient and steady state, which is the subject of this study [6].

Description of the research system

To study energy regularity, we apply computer simulation in MatLab/Simulink of the WT generation system with nominal power of 7.5 kW at wind speed V = 10 m/s.

Options of WT [7]: a washing area A = 41.17 m^2, dependency of wind power conversion efficiency factor on the tip speed ratio of WT λ is approximated by polynomial

$$C_P(\lambda) = 0.04698 - 0.1285\lambda + 0.1960\lambda^2 - 0.05705\lambda^3 + 0.00621\lambda^4 - 0.000236\lambda^5, \tag{1}$$

where $\lambda = \omega r / V$, ω is the angular velocity of WT, and r is the radius of WT.

The computer model of WT is based on two well-known equations for its power and torque [1, 3]:

$$P_{\mathrm{WT}} = 0.5\,\rho\, A\, C_P(\lambda) V^3 \tag{2}$$

$$T_{\mathrm{WT}} = 0.5\,\rho\, A\; r \frac{C_P(\lambda)}{\lambda} V^2 \tag{3}$$

For the bearless WT, we used a multi-polar (number of pairs of poles p = 20) sinusoidal surface magnet PMSG with the following parameters: R = 0.3 Ω, $L_d = L_q$ = 3 mH, Φ = 0.4 Wb. Total moment of inertia of WT and PMSG is J = 10 kg·m^2.

To control the AR output voltage, we applied strategy VOC (orienting the current vector along the voltage vector) with relay currents control. MPPT was provided by the control of angular speed of the generator in proportion to wind speed to ensure maximum value $C_P(\lambda)$ [7].

Steady-state of PMSG loading

Many designers mistakenly think that DB receives and rectifies voltage with high efficiency. However, this is not so, because we cannot consider DB alone without the energy source. In order to study energy regularities in the taking of power from PMSG, we investigated stationary conditions of wind generation plant’s operation in 3 fundamentally different systems of loading PMSG (Fig. 1). All systems were investigated under four different wind speeds, and for each of them we were trying to choose an optimal load – such a value of resistance that would allow us to achieve MPPT. These values are given in Table 1 together with the same (for all surveyed systems) value of power of WT P_{WT} , its angular speed ω, the frequency of PMSG voltage f, as well as the values of angle shift φ between the first harmonics of phase emf and current.

The research results are given in Figure 2 as depending on the wind speed of the generator efficiency $\eta_G = P_{\mathrm{out}} / P_{\mathrm{WT}}$ – ratio of active output power of PMSG to mechanical power of WT.

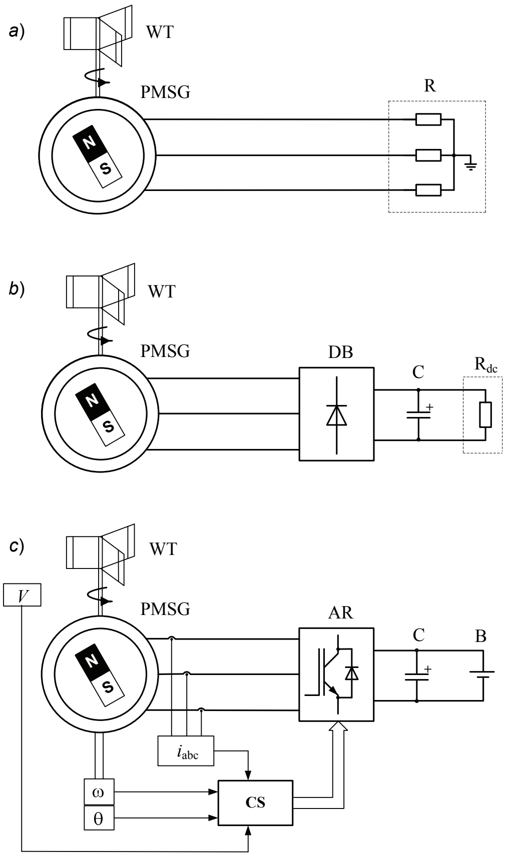

Fig.1. Investigated shemes of wind generation plants: *a*) symmetric loading on three resistors, *b*) loading on the resistor through DB with capacitor filter (C = 10000 μF), and *c*) loading on voltage AR with sinusoidal currents in phase with generator emfs

The difference between values η_G in the cases of loading PMSG on AR and resistors R (vertical shading in Fig. 2) is characterized only by the value of $\cos\varphi$ because the consumption currents have a sinusoidal shape. This difference becomes significant only at high power (wind speeds), when $\varphi > 30^{\circ}$.

Table 1. Parameters of simulations

V, m/s	P_{WT}, W	ω, rad/s	f, Hz	R, Ω	R_{dc}, Ω	φ, deg	$\cos\varphi$
2.5	152	2.71	8.59	4.29	7.20	3.5	0.998
5.0	1217	5.40	17.19	2.00	3.07	13.2	0.974
7.5	4095	8.36	26.61	1.295	1.82	31.8	0.850
10.0	9563	11.77	37.46	0.815	1.10	53.5	0.595

Reduction η_G in the case of the load on DB compared with resistance load (horizontal shading in Fig. 2) is due to only harmonic distortion because in both cases φ is the same. The results of total harmonic distortion factor THD and major harmonic distortion factors HD (5, 7, 11, 13) of output current and voltage of PMSG from wind speed are given in Figure 3. As it shows, at small wind speed (low power), there is a significant distortion of current and low voltage distortion, whereas at high wind speed (high power), there is a significant distortion of voltage and low current distortion, and finally at medium speeds (5 m/s), there is roughly equal average distortion of both current and voltage. With increasing of wind speed V, optimal angular velocity of WT and emfs of PMSG increases directly in proportion to V, the maximum power - in proportion to V^3, and currents - in proportion to V^2. However, the difference between η_G on non-distorted currents (R) and on the distorted ones (DB) increases slightly thanks to reducing of currents harmonic distortion, which is due to the inductance of generator windings.

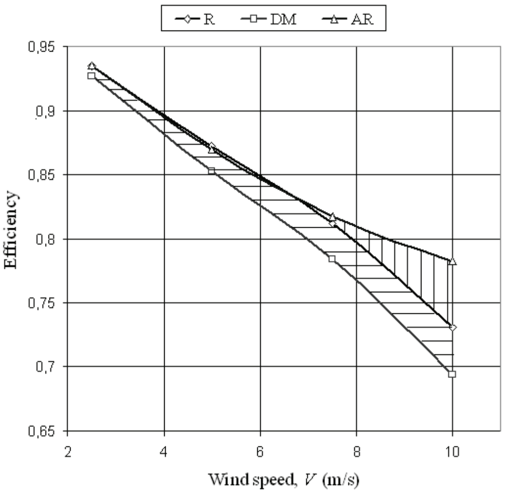

Fig.2. Efficiency of PMSG versus wind speed at different loads

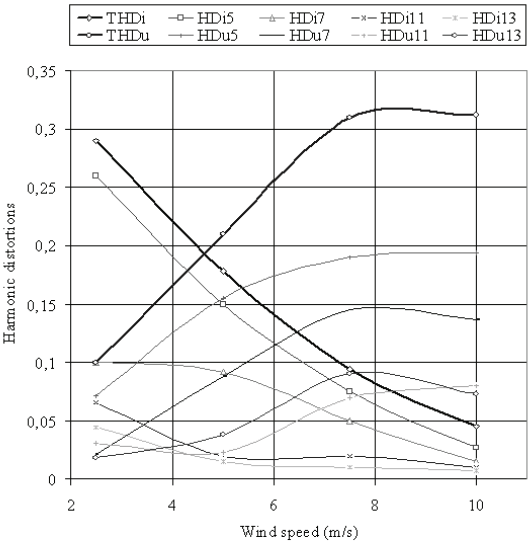

Fig.3. Current and voltage harmonic distortions of PMSG, loading on DB, at different wind speeds

Transient conditions of PMSG loading

Because of stochastic nature of the wind speed and the consumption of generated electricity, WT systems are almost always in a transient condition. That is why, besides the possible harmonics associated with non-linear generator load, there are harmonics due to transient voltage and current of the generator. The purpose of this section is to study the impact of these harmonic distortions on the efficiency of the WT.

A. Theoretical study

To assess the impact of only harmonic distortion caused by transients, we will assume that the generator windings have zero resistance and inductance and load on resistors.

We will model the transient mode by means of the harmonic temporal dependence of PMSG angular speed:

$$\omega(t) = \omega_0\left[1 - \gamma\cos(2\pi f_n t)\right] \tag{4}$$

where $\gamma = \omega_m/\omega_0$ is the relative change of angular speed of the generator, ω_m and ω_0 are amplitude and average values of angular speed of the generator, and $f_n = T_n^{-1}$ is oscillation frequency of PMSG angular speed.

Time dependence of the angle of the generator rotor position is equal

$$\vartheta(t) = \int \omega(t)\,\mathrm{d}\,t = \omega_0\left[t - \frac{\gamma}{2\pi f_n}\sin(2\pi f_n t)\right] \tag{5}$$

Phase emf of PMSG will vary according to the law

$$e_1(t) = E_{1m}(t)\sin[p\,\vartheta(t)] \tag{6}$$

where

$$E_{1m}(t) = p k_\Phi \omega(t) \tag{7}$$

reflects the relationship between the peak value of phase emf of PMSG and its angular speed, and k_Φ is a factor that depends on the pole magnetic flux.

Using (2), we can express the value of optimum power load of the generator as a functional dependence on its optimal angular speed:

$$P(t) = k_\mathrm{P}[\omega(t)]^r \tag{8}$$

where k_P is the coefficient and r is the index, which for WT is equal to 3.

Amplitude value of power of one phase of PMSG, generating power (8), equals

$$P_{1m}(t) = \frac{2}{3}k_\mathrm{P}[\omega(t)]^r \tag{9}$$

The current that is consumed from one phase of PMSG, equals

$$i_1(t) = I_{1m}(t)\sin[p\,\vartheta(t)] \tag{10}$$

where

$$I_{1m}(t) = P_{1m}(t)/E_{1m}(t) \tag{11}$$

Figure 4a shows time dependences of the angular speed of the generator and phase voltage and current for the concrete parameters of the mathematical model (4) - (11): ω_0 = 6 rad/s, γ = 0.6, T_n = 1 s, p = 20, k_Φ = 0.25 Wb, k_P = 5 W·s^3.

Active power that is consumed from one phase of PMSG over the period T_n of angular speed oscillation is

$$P_n = \frac{1}{T_n}\int_0^{T_n} e_1(t)\,i_1(t)\,\mathrm{d}\,t\,. \tag{12}$$

Effective values of phase voltage and current at the period T_n are equal

$$U_n = \sqrt{\frac{1}{T_n}\int_0^{T_n} e_1^2(t)\,\mathrm{d}\,t}\,;\quad I_n = \sqrt{\frac{1}{T_n}\int_0^{T_n} i_1^2(t)\,\mathrm{d}t} \tag{13}$$

Power factor [8] of the system “PMSG – electricity consumer” is

$$\mathrm{PF} = \frac{P_n}{U_n I_n} \tag{14}$$

Substituting (6) - (13) into (14) finally yields

$$\mathrm{PF} = \frac{\sqrt{\frac{2}{3}k_\mathrm{P}}\int_0^{T_n}\omega^{2r}(t)\sin^2[p\,\vartheta(t)]\,\mathrm{d}\,t}{\sqrt{\int_0^{T_n}\omega^2(t)\sin^2[p\,\vartheta(t)]\,\mathrm{d}\,t\cdot\int_0^{T_n}[\omega(t)]^{2(r-1)}\sin^2[p\,\vartheta(t)]\,\mathrm{d}\,t}} \tag{15}$$

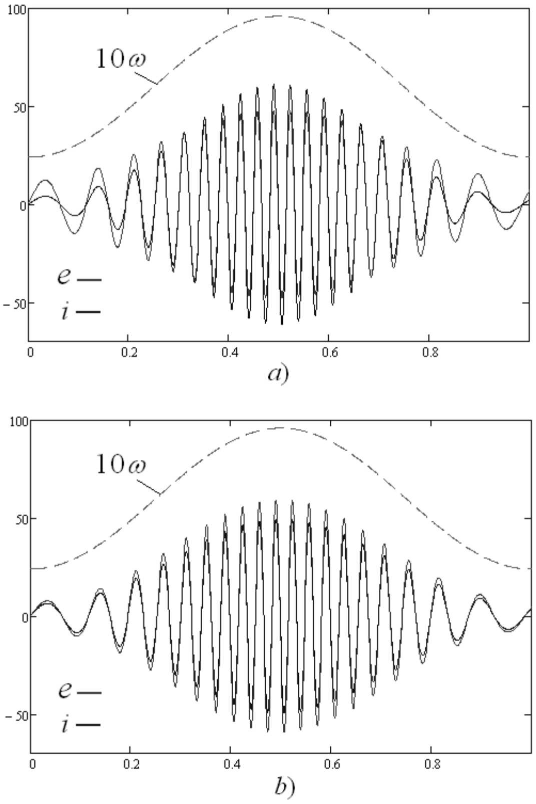

Fig.4. Time dependences of angular speed ω of the generator and it phase emf e and current i: a) traditional approach, b) suggested approach

Numerical study of (15) considering (4) and (5) showed that the value of PF does not depend on the parameters ω_0, p, and T_n, which determine the ratio of oscillation frequencies of angular speed of the generator and emfs at its output. However, PF depends on r and γ. For some integer values of parameter r and the range of valid values γ = 0 ... 1, these dependences are given in Figure 5. Their analysis shows that decreasing the power factor caused by transient mechanical and electrical processes can be significant. Size and character of this decrease are most dependent on the relationship between mechanical and electrical processes, which is defined by the parameter r. For WT the reduction of PF is not high and has roughly 2.5% in the wide enough range of γ =0.4 – 1.

B. Compensation of losses caused by transient harmonic distortion

For r = 2, power factor (15) equals 1. This is due to proportional relation between emf and current transients, which is equivalent to resistive generator load.

This result suggests a way that can provide PF = 1 for the mover with any value of parameter r – to ensure the changing of the generator emf in transient modes by law

$$E_{1m}(t)=\sqrt{R_{\varepsilon}P_{1m}(t)} \quad (16)$$

where R_{ε} is the equivalent load resistance.

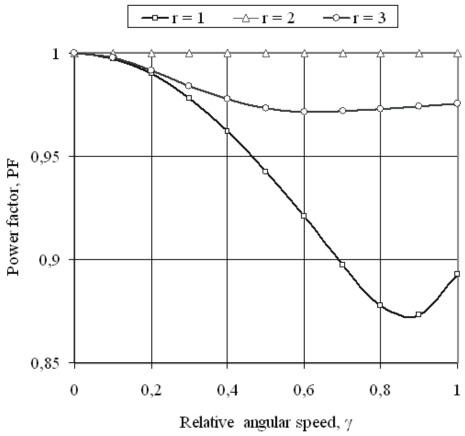

Fig.5. PF at different values of index r versus relative angular speed

According to (11), amplitude value of current will be

$$I_{1m}(t)=\sqrt{P_{1m}(t)/R_{\varepsilon}} \quad (17)$$

Figure 4b shows the time dependences of the angular speed of the generator and phase emf and current for the same parameters of the mathematical model (4) - (11) as in Figure 4a, but according to conditions (16) - (17).

To implement the control law (16), one must be able to control the generator excitation. Recently, a number of effective hybrid synchronous generators (HSG) have been developed. These are generators with permanent-magnet and additional electromagnetic excitation, which is realized by placing on the stator the excitation winding that enables contactless design of the generator and its reliability [9].

Analysis of the promising systems of RMSG adjustable load

Our study shows that the harmonic distortions in the current of the generator, if it is loaded on the DB, lead to the loss of efficiency from 1% at V = 2.5 m/s to 4% at V = 10 m/s (Fig. 2). Thus, for the first compensatory function – providing EMC of the load with sinusoidal generator emf – we have to ensure the sinusoidal form of the load currents. Furthermore, even with sinusoidal currents at high wind speeds efficiency begins to decrease rapidly because of the increase in angle φ. Because of this, it is also advisable to perform the second compensatory function – to provide the linear currents in phase with corresponding emfs. The load control system with such properties may be realized according to the functional schemes shown in Figure 6a-d. In all schemes battery B is used as the load, and to it one may connect electricity consumers or an inverter connected to the grid. The main function of automatic control – the optimal load of the generator – is performed by the control system CS.

In schemes a) and d) the generator is loaded on the DB, which is why the function of providing the EMC is performed by the three-phase current active filter AF. To compensate for the current harmonic distortions, its power may be only 5% of the WT power. However, if we make the AF also responsible for the compensatory function of angle shift φ, then its power must be increased to 10%. In schemes b) and c) the first and the second compensatory functions are performed by the AR.

Schemes a) and b) provide the maximum efficiency of the WT in steady state, but in transient conditions, as investigated above, EMC is slightly worse due to various laws of changes in emfs and currents at optimum load of the PMSG. However, in schemes c) and d), thanks to the use of the HSG this disadvantage can be eliminated in the process of adjusting the generator excitation, that is, one can perform the third compensatory function – proportional change of the emfs and currents in the transient load of the generator.

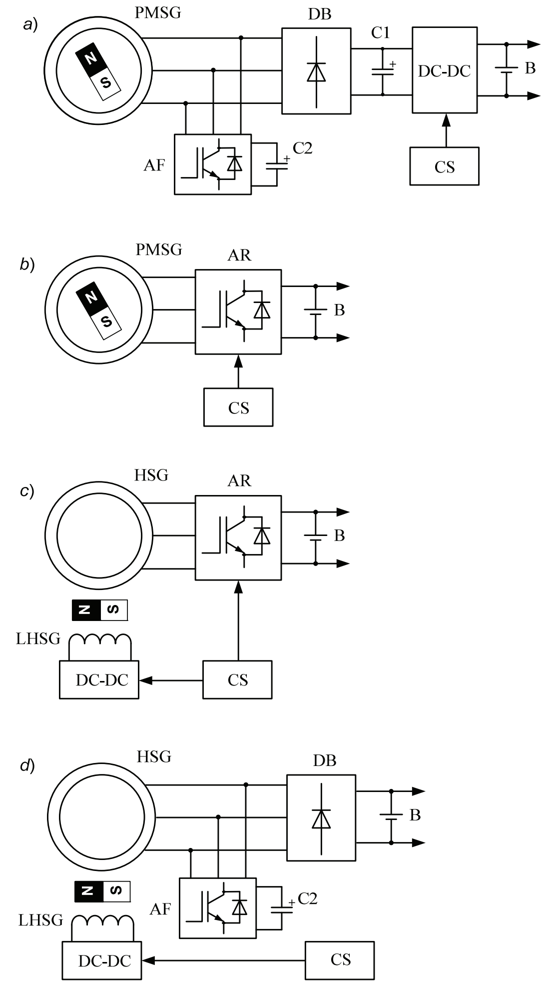

Fig.6. Functional schemes of the promising systems of RMSG adjustable load

To test the effectiveness of the proposed compensation of transient harmonic components, we did a computer simulation of the wind power generation plant described above, with the HSG and voltage AR. For optimal control of the generator load, output voltage of speed regulator $U_{RS}(t)$, which is proportional to the load power, forms a generator excitation according to (16):

$$k_{\Phi}(t)=\frac{\sqrt{R_{\varepsilon}k_{UP}U_{RS}(t)}}{p\omega(t)} \quad (18)$$

where k_{UP} is the coefficient of proportionality between voltage and power.

According to (17), the reference of direct current component I_d in the rotating coordinate system with field angular speed ($p\omega$) is given

$$I_d^*(t)=\sqrt{k_{UP}U_{RS}(t)/R_\varepsilon} \quad (19)$$

Figure 7 shows the waveforms of phase emfs and currents, which illustrate the work of the traditional system with PMSG and of the one suggested in the conditions of variable wind speed (and correspondingly generator angular speed) according to the harmonic law $V=7+3\sin(8\pi t)$. Waveforms show that the proposed system, besides the on phase placing of emfs and currents, ensures their proportionality, thereby compensating for harmonic discoordination between them. The value of equivalent load resistance was chosen R_ε = 2 Ω, which provides the range of changing of generator excitation 0.65 – 1.3. That is why in the traditional system the amplitude of emfs changes from 35 V to 85 V, whereas in the proposed system it changes from 25 V to 115 V. This also allows one to reduce copper losses in the generator because of the reduction of currents at high wind speeds in correspondence to the growth excitation of the HSG as compared to PMSG.

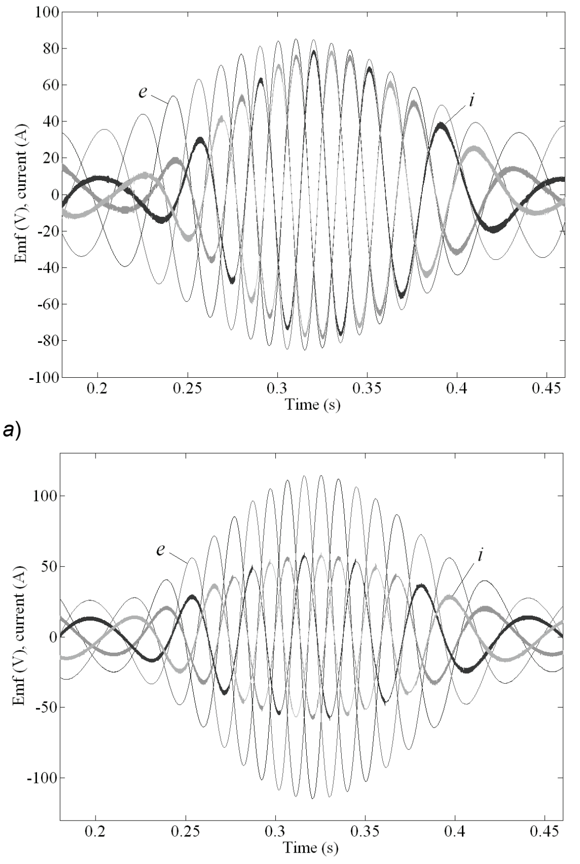

Fig.7. Simulated waveforms of phase emfs *e* and currents *i* of the generator under variable wind speed: a) traditional approach with PMSG, b) suggested approach with HSG

Furthermore, in the traditional system the amplitude of emfs changes according to the generator angular speed, while the amplitude of currents is moved in time according to the power of electrical load (Fig. 7a). The displacement of the latter against WT power is associated with the accumulation of kinetic energy during the changes of WT angular speed (Fig. 8). In the proposed system, thanks to the regulation of generator excitation, amplitudes of emfs and currents form simultaneously and proportionally according to the power of electrical load (Fig. 7b).

Figure 8 shows the waveforms of wind turbine power and output power of the wind generation system in traditional and suggested systems. Total losses in the generator for a period of changes of angular speed decreased in the proposed system by 12.4%, as compared with the traditional.

Unlike scheme c) (see Fig. 6), which through two channels of regulation – AR and DC-DC – makes it possible to provide all three compensatory functions, in scheme d) the regulation of generator excitation performs the basic function of optimal generator load. Thus, the third compensatory function is not realized here. However, scheme d) has advantages over others in its simplicity and the smallest installed power of the semiconductor converter for the main function of controlling the generator load.

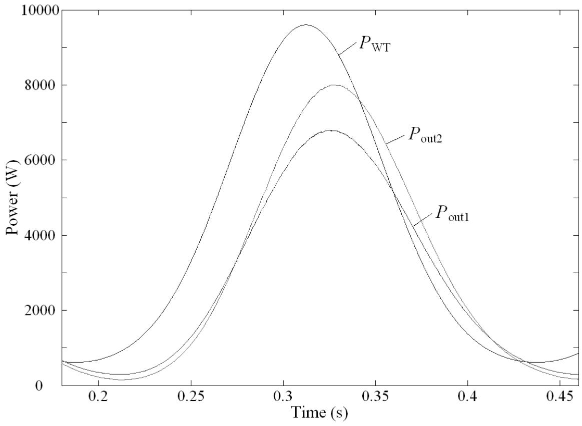

Fig.8. Simulated waveforms of wind turbine power P_{WT}, and output power of wind generation system in the traditional approach with PMSG P_{out1} and suggested approach with HSG P_{out2} under variable wind speed

Conclusions

In wind systems the way in which the power is taken from the PMSG has a significant impact on the energy efficiency of the system. Because of the limited power of the generator and its great internal resistance in the nonlinear load such as a DB with a capacitor, the loss of energy in the generator through harmonic distortion can reach 5% of the nominal losses. The best way to avoid these distortions is to use PWM power electronic converters for taking power from the PMSG, for example, AR, which enable sinusoidal currents and their optimal phase shift in relation to phase emfs with minimal losses in the generator.

In transient conditions of WT systems, for instance when there is variable angular speed or change of the power load in the system, even when AR is used, there appear additional harmonic distortions of the instantaneous power, which have to do with the different characters of change of the emf and current amplitudes. To improve the energy efficiency of electricity generation, this study suggests a method of compensation for the energy losses associated with the transitional modes because of the variable in time flow of wind energy. The method consists in the regulation of both the amplitudes of the generated emf and the load current according to the optimal power of the WT. The goal is to ensure that the load of the generator is equivalent to the resistive one. The results of simulation showed that using the proposed control method makes it possible to reduce energy loss in the system HSG–AR of the wind plant by more than 12% for the test period of harmonic change of the wind speed.

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