

MODELING AND CONTROL OF AN ELECTROMECHANICAL SYSTEM WITH A PERMANENT MAGNET GENERATOR AND A VOLTAGE SOURCE CONVERTER

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Abstract. In the paper simulation dynamic models for the analysis of characteristics and transients of electro-mechanical system using a permanent magnet electric generator (PMG) connected to a variable speed fixed pitch wind turbine (WT) and a voltage source converter (VSC) mathematical models are developed. The system supplies a direct current (dc) resistive load through a controlled switch. The objective of the controlled resistive load connected to the VSC dc circuit of the system is to perform the dc output voltage stabilization for simulating the mode of generating the active power into a grid via a grid inverter. Two algorithm structures of realization of tracking the optimal WT motion trajectory in the coordinates “WT aerodynamical power – rotary speed” have been considered. The tracking algorithms function is to provide the maximization of power extraction from wind flow by WT. Electromechanical processes in the PMG – VSC system for both tracking algorithms have been investigated using developed dynamic simulation models and vector control technique of electromagnetic torque of the generator at variable WT mechanical power. The results of numerical investigations of the electromagnetic processes in the system have been analyzed. The efficiencies of the proposed control algorithms applied to the VSC in the considered electromechanical system have been compared and discussed.

Key words: permanent magnet generator, voltage source converter, wind turbine, MPPT algorithm, simulation.

1. Introduction

Generation of electrical power using synchronous machines with permanent magnets has recently gained scientists' close attention [1, 2, 3]. These machines have high power efficiency and reliability, since they do not need an excitation system outside and do not have a rotor winding. High power density of the permanent magnet generator (PMG) makes it possible to decrease weight and cost of wind energy conversion system (WECS). Combining a PMG and a controlled voltage source converter (VSC) allows creating WECS operating with maximum aerodynamic efficiency at different wind speeds. High aerodynamic efficiency of the WECSs is achieved by regulating the wind turbine (WT) angular speed. In grid-connected WECSs, a

back-to-back AC/DC/AC semiconductor converter realized with connected to the dc link VSC on the generator side (active rectifier) and a VSC on the grid side (grid inverter) is employed.

In autonomous small scale WECSs, as usual, a one-phase DC/AC converter with output 220 V/50 Hz is used instead of the grid inverter. The main function of the VSC on the generator side is the regulation of electromagnetic torque of the generator to maintain WT operation at optimal angular speed according to the maximum WT aerodynamic efficiency operational criteria. In order to perform this function the development of efficient algorithms of controlling the VSC on the PMG side and transient simulation models for testing the developed algorithms, calculation and analysis of dynamic characteristics of the electromechanical systems using a PMG, WT (rotor blades and shaft) and semiconductor VSC is needed.

2. Circuit design

General arrangement of the investigated in the paper electromechanical system is shown on Fig.1. The system is composed with a PMG rotated by the WT rotor blades connected to the shaft with a gearbox (G), electronic VSC and switched load with active resistance R_L . The VSC consumes electrical power of alternating current from the PMG and transforms it into electrical power of direct current. Availability of a VSC in the scheme separates the generator from the load (or a grid), at the same time limiting the value of electromagnetic torque of the PMG. This provides the decrease in mechanical stresses caused by strong gusts of wind on some elements of the WECS (gearbox, yaw drive, tower). Switch S_L and resistor R_L act as a grid inverter and the grid itself and, therefore, ease the system simulation. Grid inverters, as usual, are regulated to keep the dc-link voltage at constant level. Under these conditions, balance between generated and consumed power in the system is maintained. Therefore, for the substitution of the grid inverter and the grid itself, the $S_L - R_L$ branch should perform the same function, that is, provide the stabilization of the dc-link voltage. For simplifying the model, the gearbox can be considered ideal without losses and providing rigid joint without backlash.

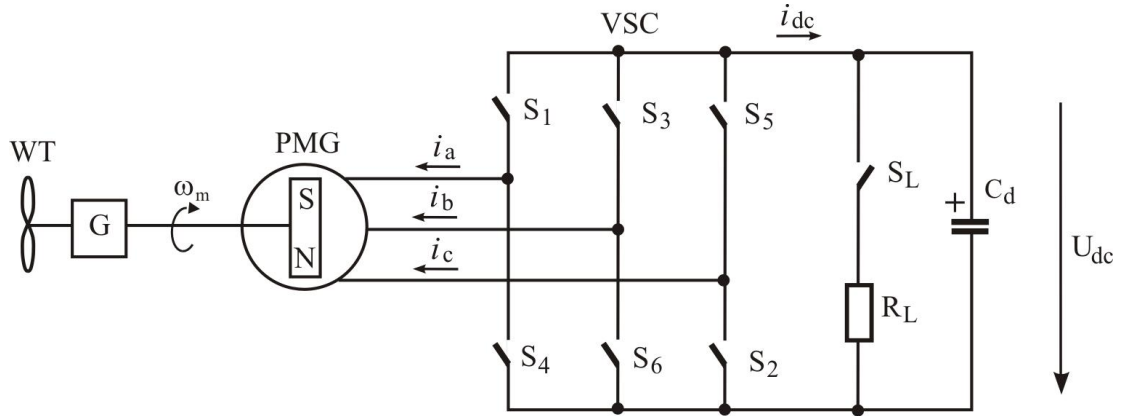


Fig. 1. Configuration of the system.

3. Mathematical models of system elements

The main system elements (Fig. 1), as it was mentioned above, are WT, PMG and VSC. Let's consider the specific features of the WECS's elements simulation.

3.1. WT simulation

For WT rotational mass (rotor blades, hub, gearbox and shaft) simulation in the system, a typical relation between WT mechanical power, WT rotational speed referred to generator side and wind speed (Fig. 2) was used [3]. The power-speed characteristics characteristics show that with varying wind speed the optimal value of WT rotational speed related to WT maximum aerodynamic efficiency point when WT extracts maximum power possible for a given WT design from the wind flow varies as well.

Maximum aerodynamic efficiency of modern WT is in the range 0.44–0.48 and theoretically limited by value 0.593 according to Betz' law. If WT gearbox friction losses are taken into account by the friction losses in the generator, then applied from WT to the high speed PMG shaft mechanical torque will be equal to the ratio of WT aerodynamic power to PMG rotor angular speed ω_m ($\omega_m = \pi n / 30$, ω_m is angular speed in radians per second, n – is rotational speed in rpm). Referred to the PMG mechanical torque of the WT is used as input variable for the PMG model, and input variables for the WT model are angular speed ω_m of the PMG rotor and instantaneous value of the wind speed.

Suppose the back electromotive force in electric machine is sinusoidal. The simulation of dynamical processes in the PMG is carried out often using PMG equivalent circuits in the dq rotor reference frame (Fig. 3, 4) [2, 5, 6]. Accordingly, dynamical equations of PMG electrical circuits in dq rotor reference frame rotating synchronously with rotor are as follows:

$$L_d \frac{di_d}{dt} = v_d - R_S i_d + L_q p_n \omega_m i_q, \quad (1)$$

$$L_q \frac{di_q}{dt} = v_q - R_S i_q - L_d p_n \omega_m i_d - \psi_m p_n \omega_m, \quad (2)$$

where R_S is the stator phase resistance of the PMG winding; L_d, L_q are the stator winding inductances along the axes d and q ; i_d, i_q are the d and q components of the space vector of the stator winding current; v_d, v_q are the d and q components of the space vector of the stator winding voltage; p_n is the number of pole pairs on the rotor; ψ_m is the magnitude of the flux linkage of the stator phases induced by the permanent magnets.

For a nonsalient-pole rotor, the equation $L_d = L_q$ is valid. The mechanical equation of the PMG can be implemented in the following form:

$$\frac{d\omega_m}{dt} = (T_T - T_e - k_F \omega_m) \frac{1}{J}, \quad (3)$$

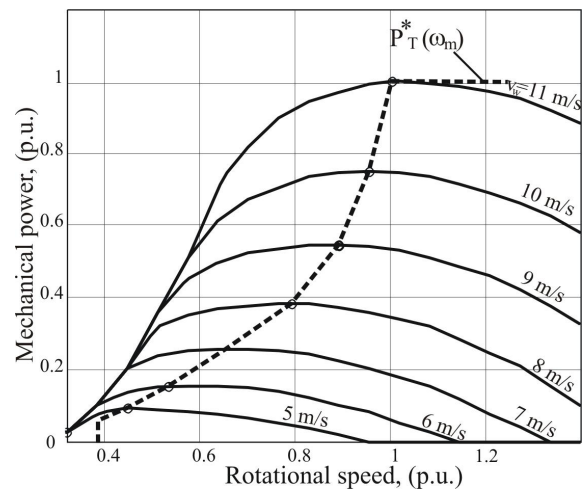


Fig. 2. Fixed pitch WT power-speed characteristics.

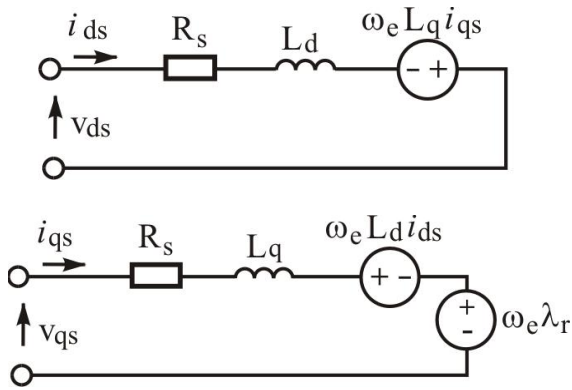


Fig. 3. Equivalent circuits of the PMG without core losses.

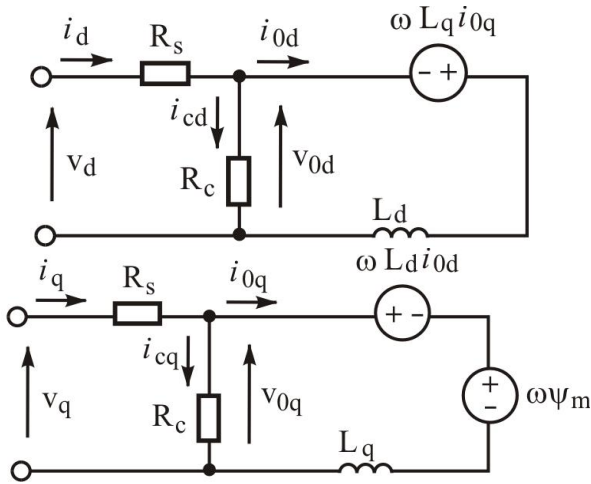


Fig. 4. Equivalent circuits of the PMG taking into account core losses.

where T_T is the WT torque referred to the PMG shaft; T_e is the electromagnetic torque of the generator; k_F is a total friction factor of the PMG rotor, gearbox and the turbine shaft; J is the total moment of inertia of the rotating masses.

The electromagnetic torque of the generator is determined using a well-known equation:

$$T_e = \frac{3}{2} p_n (\psi_m i_q + (L_d - L_q) i_d i_q), \quad (4)$$

If $L_d = L_q$, the equation given above is simplified:

$$T_e = \frac{3}{2} p_n \psi_m i_q, \quad (5)$$

It is necessary to mention that different authors often use different notations and various notation forms describing equivalent circuits and dynamic model of the PMG in their works. Naturally, it can cause certain problems for some readers. However, the model itself is still the same, so it's obvious, that the problem of holding on to uniform terminology and notations during investigations of the

electrogenerating systems with PMG should be taken into account.

3.3. VSC modeling

In VSC dynamic models switches are often represented as ideal ones with zero resistance at on-state and infinite resistance at off-state [5, 7]. For taking into account the static losses in the VSC, resistances of the switches in on-state are considered being different from zero, and resistances in off-state being different from infinity. When such switches are modelled, they are additionally bypassed by RC-snubbers with capacitors of large (or infinite) capacitance for simplifying the calculations of a voltage drop on the switch. Resistance of the RC-snubber determines the resistance of the switch in off-state. Due to the large resistance values of the RC- snubbers, they affect insignificantly the energy performance of the VSC. The switch in the load circuit can be modelled in the same way as the switches of the VSC.

4. Development of the VSC control algorithms

As it was mentioned, the main function of the VSC on the generator side is regulating its electromagnetic torque to keep WT angular speed close to the optimal angular speed of the WT for operating WT with optimal efficiency. The algorithm of determining the optimal angular speed is called Maximum Power Point Tracking (MPPT) algorithm. For implementation of this algorithm it is advisable to use a vector control system. With vector control technic the independent regulation of active and reactive power of the PNG can be achieved. During the investigations, among other studies, it can be of practical interest, to compare two MPPT algorithms, one of which using controller with a speed feedback and another one without speed feedback. Let us consider block diagrams of the vector control algorithms with speed controllers implemented with speed feedback and no speed feedback (Fig. 5, Fig. 6). The function of the above mentioned controllers is WT angular speed regulation for tracking optimal power-speed characteristic $P_T^*(\omega_m)$ given in Fig. 2.

As it can be seen in Fig. 5 and Fig. 6, block diagrams of the controllers have similar structures with some differences. The d-axis reference current component i_d^* reference is set to zero. The q-axis current component reference i_q^* is calculated from (5)

$$i_q^* = \frac{2T_e^*}{3p_n\psi_m}, \quad (6)$$

де T_e^* – розрахунковий електромагнітний момент, а величина ψ_m вважається відомою або ж вимірюється. where T_e^* is the electromagnetic torque reference; and the ψ_m value is assumed to be known or be measured.

In the control system with speed feedback the speed reference n^* is obtained from WT rotational speed-wind speed reference characteristic $n^*(v_w)$ in the form of a table or a graph. This characteristic, in turn, can be obtained with the use of the power-speed characteristics given in Fig.2. The obtained n^* signal is then limited by a rate limiter (RLT) and compared with the measured and filtered by the low pass filter (LPF) rotational speed n instantaneous value. The rotational speed error is amplified by a proportional-integral controller (PI-controller) and limited by the limiter (LIM) block. As a result, at the output of the LIM block the PMG electromagnetic torque reference T_e^* is obtained. The rotor flux angle θ is determined by integration of the rotor angular speed with subsequent multiplying the integrated signal by the PMG poles number. The obtained d -axes and q -axes current references i_d^* and i_q^* are transformed into the three-axes reference frame and compared with instantaneous values of the PMG phase currents in the hysteresis current controller. The sign of the error between the instantaneous phase current and the current reference determines the state of the VSC switches connected to the phase (upper switch is in on-state and lower switch is in off-state or vice versa).

The control system without speed feedback (Fig.6) can be classified as a parametric program control system. In the system the electromagnetic torque reference T_e^* is not obtained using the rotational speed error, as it is made in Fig.5, but from a given by graph (or table) maximum (reference) aerodynamical (mechanical) power of the WT

as a function the rotational speed $P_T^*(n)$. The optimal power vs rotational speed curve $P_T^*(n)$, as well as optimal rotational speed vs wind speed curve $n^*(v_w)$, is obtained using WT power-speed characteristics plotted in Fig. 2. The PMG electromagnetic torque reference is calculated by dividing the WT power reference by angular speed ω_m . In the Fig. 6 block diagram there is no RLT unit, since the rate of change of PMG angular velocity is limited by the WT and PMG inertia.

And, besides, comparing Fig. 5 with Fig.6, we can also see that the realization of the algorithm of Fig.6, unlike that in Fig. 5, does not need measuring the wind speed.

5. DC-link switch control

A synthesized and tested in [8] voltage controller providing voltage stabilization in the dc-link by regulating the duty ratio of the dc-link switch control signal was used in the developed models. The equation of this regulator is as follows:

$$\delta^* = -R_L C_d (\dot{u}_{dc}^* - K_{1y} \tilde{u}_{dc} - \int K_{2y} \tilde{u}_{dc} dt) / u_{dc}, \quad (7)$$

where $\tilde{u}_{dc} = u_{dc} - u_{dc}^*$ is dc-link error; K_{1y} , K_{2y} are constants; δ^* is duty cycle reference of the S_L control signal.

6. Simulation results

Simulation of dynamic electromechanical processes in the system of Fig. 1 was carried out using Matlab/Simulink software. In the model the following parameters and specifications were set.

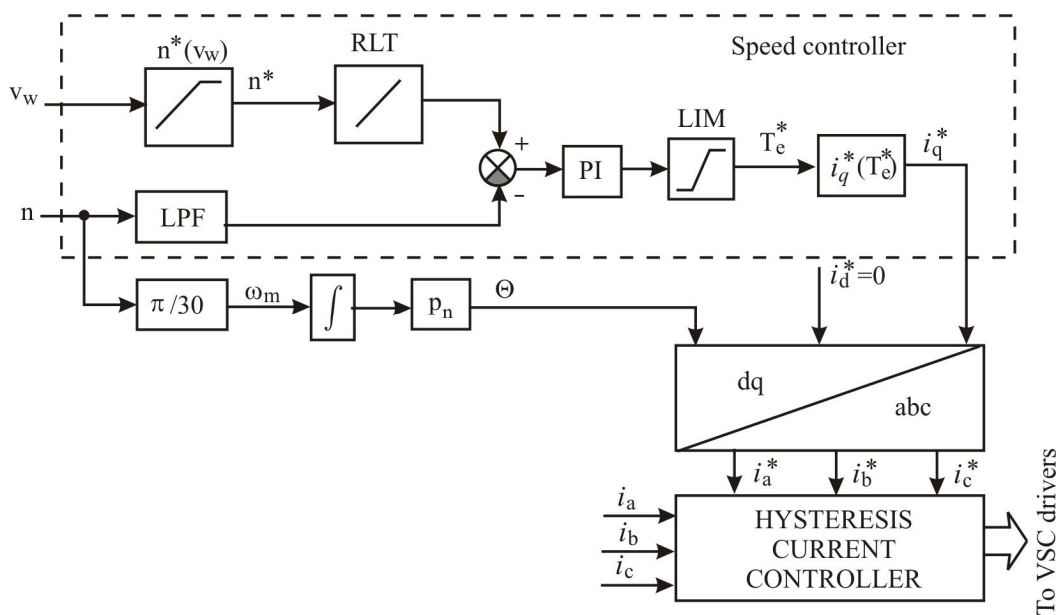


Fig. 5. Block diagram of the VSC control with PMG speed feedback.

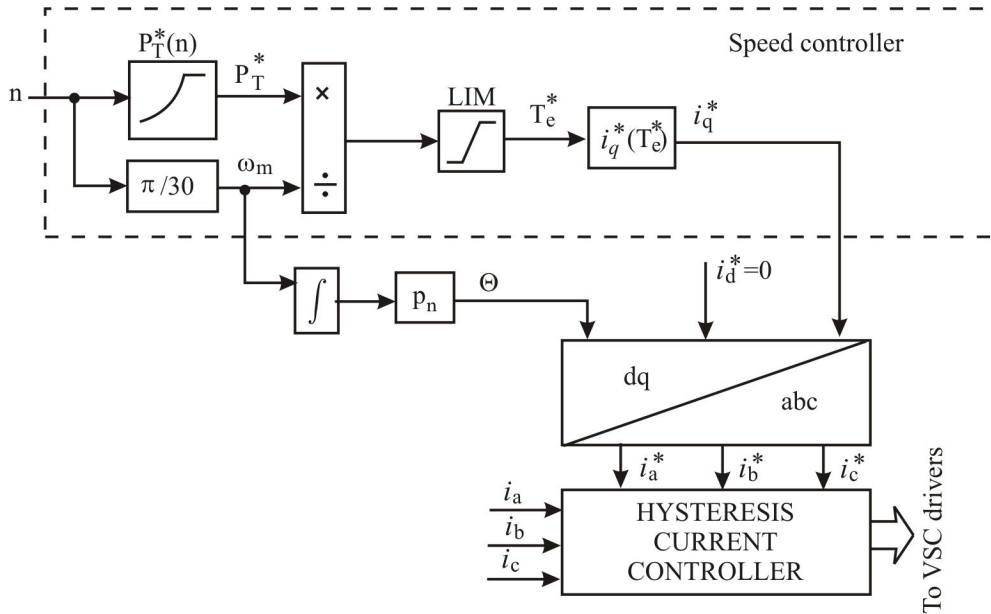


Fig. 6. Block diagram of the VSC control without PMG speed feedback.

DC-link circuit elements. The resistance of the load resistor is 20Ω . The resistance of the switch S_L in ON state is 0.001Ω . The capacitance of a capacitor is 0.05 F .

Voltage source converter. The resistance of the SVR switches in ON state is 0.001Ω .

Wind turbine. Nominal rotational speed referred to generator is 1500 rpm . Nominal power / nominal wind speed is $2.2/11 \text{ (kW/mps)}$. The wind turbine is unregulated.

Generator. Nominal power is 2.2 kVA . The number of pole pairs is 4 . The resistance of stator phases is 0.2Ω . Inductances $L_d = L_q = 0.0085 \text{ H}$. The magnitude of flux linkage induced by magnets in the stator phases ψ_m equals 0.175 Wb . Total inertia moment of rotating masses J is 0.35 kg/m^2 . Friction coefficient k_F is $0.005 \text{ kg}\cdot\text{m}^2/\text{s}$.

During the first numerical experiment the control algorithm of Fig. 5 was applied and during the second one the algorithm of Fig. 6 was used. The same time sequences of wind speed were used in both experiments (Fig. 7a, Fig. 8a). The simulation results of the electromechanical system in Fig. 1 with the VSC control system developed according the block diagram in Fig. 5 are depicted in the a-f graphs of Fig. 7. The simulation results of the system with the VSC control system developed according the block diagram in Fig. 6 are depicted in the a-f graphs of Fig. 8. In oscillograms Fig. 7 b-k the following base quantities were used: the base WT rotational speed=1 p.u. of speed=1500 rpm; the base stator phase currents and base VSC output current=1 p.u. of current=11.55 A (magnitude of nominal phase current); the base VSC output

power=1 p.u. of power=2.2 kW; the base VSC output voltage=1 p.u. of voltage=317 V.

Comparing rotational speed vs time relationships of the driving turbine (Fig. 7b, Fig. 8b) shows that the use of the PMG control system with speed feedback provides considerably less error of rotational speed tracking than while operating without the speed feedback. The q-axis PMG current component i_q (Fig. 7c) changes its sign during the simulation time. This fact indicates that the PMG operates as a motor within some time intervals. If there is no speed feedback, the i_q current of the PNG is negative during the simulation time period (Fig. 7e), and it means that the PMG operates in generator mode permanently. In the VSC output power vs time (Fig. 7d) and output dc-link VSC current vs time (Fig. 7e) relationships the power and current values change sign as opposed to the system without the speed feedback (oscillograms Fig. 8d, e). As the result of the PMG entering to the motoring mode during the time intervals $14\text{-}14.53 \text{ s}$ and $17\text{-}17.62 \text{ s}$, in spite of the high capacity of the dc-link capacitor, significant voltage drops are noticed in the dc-link circuit (Fig. 7f) reaching 17 % and 34 %, correspondingly. The dc-link voltage magnitude in the system without speed feedback (Fig. 7k) was maintained at the preset voltage reference value with insignificant overshoot.

The frequency of phase voltages and currents of the generator changed synchronously with the PMG rotational speed. The q-axes current component i_q was regulated due to changing the value of the first harmonic component of the PMG stator voltages.

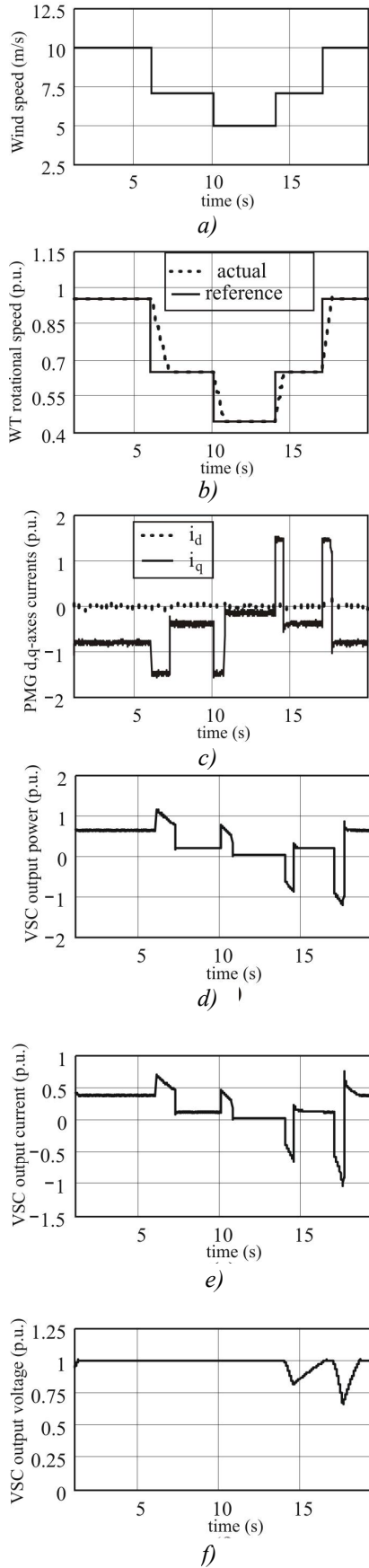


Fig. 7. Transient response of the WECS with speed feedback due to change in wind speed.

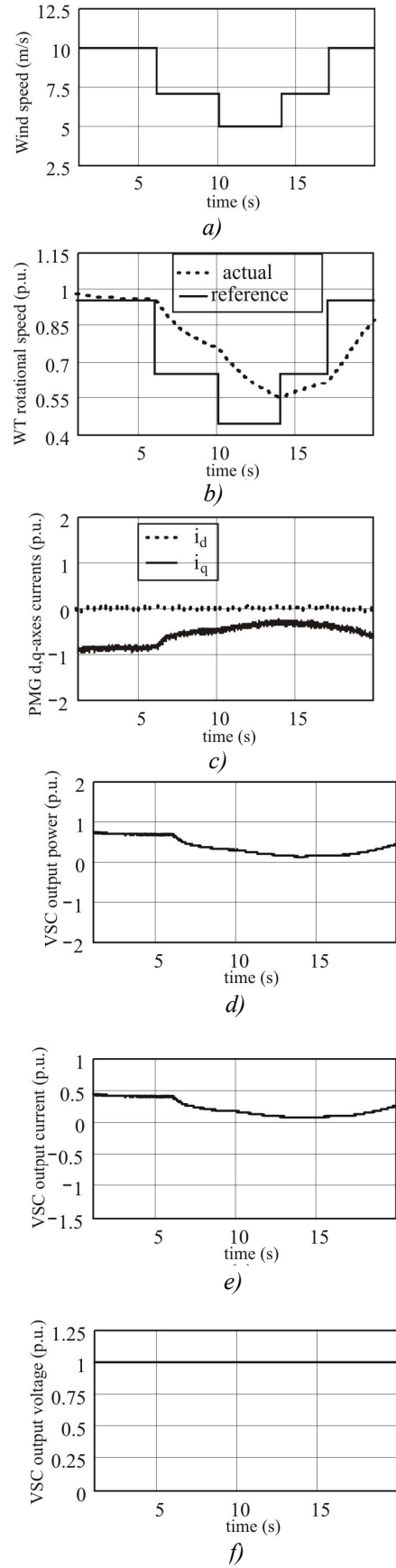


Fig. 8. Transient response of the WECS without speed feedback due to change in wind speed

7. Conclusions

In the paper the approaches to mathematical modeling and control of the electromechanical systems using a variable speed PMG and a VSC have been considered. The numerical investigations of the efficiency of the vector current control of the PMG with two speed controllers were carried out. The first controller has the rotational speed feedback and the second one is a parametrical program WT power regulator with rotational speed as input variable. The conducted research confirmed that both considered controllers provide maximum power point tracking in the coordinates “mechanical power of the wind turbine – rotational speed”. It has been found that the first of these controllers provides a smaller speed error in transient modes. However, its disadvantage is that, in transient modes with a rapid increase in the mechanical torque of the turbine in the system with such a controller, the PMG can pass into the motoring mode. As a result, electrical power is consumed from the dc-link circuit to the electric machine and the voltage drop on the capacitor occurs. In practice, it means that, in grid-connected mode of the WECS, the ripple level of power generated into the grid will increase, and, in islanded mode of operation of the WECS with accumulator battery (AB) in dc-link circuit, the AB losses will be increased and its operating life will be reduced.

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МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ І АЛГОРИТМИ КЕРУВАННЯ ЕЛЕКТРОМЕХАНІЧНОЇ СИСТЕМИ З ГЕНЕРАТОРОМ НА ПОСТІЙНИХ МАГНІТАХ І НАПІВПРОВІДНИКОВИМ РЕГУЛЯТОРОМ НАПРУГИ

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Олександр Джура, Максим Шихненко**

На основі математичних моделей структурних елементів розроблено імітаційні моделі для аналізу характеристик і перехідних процесів електромеханічних систем побудованих на основі електричного генератора на постійних магнітах (ГПМ) змінної частоти обертання і напівпровідникового регулятора (НР) напруги, що виконаний за схемою трифазного автономного інвертора напруги. На підключене до кола постійного струму кероване резистивне навантаження покладено функцію стабілізації напруги в колі постійного струму системи для моделювання режиму генерації активної потужності в мережу через мережевий інвертор. Розглянуто два варіанти реалізації алгоритму відпрацювання оптимальної траєкторії руху в координатах аеродинамічна потужність – частота обертання приводної вітротурбіни ГПМ, які повинні забезпечувати максимізацію відбору потужності від турбіни. З використанням розроблених імітаційних моделей досліджено

електромеханічні процеси в системі ГПМ-НР при змінній потужності приводної турбіни за векторного керування електромагнітним моментом генератора. За результатами чисельних досліджень проведено аналіз електромеханічних процесів в системі і порівняння ефективності застосування запропонованих алгоритмів.



Leonid Mazurenko – D.Sc. in Technical Sciences, Full Professor, Head of Department of Electromechanical Systems of the Institute of Electrodynamics of the National Academy of Sciences of Ukraine.

Main research interests: increase in efficiency of electrical mechatronic power converters, autonomous electricity generating plants and power

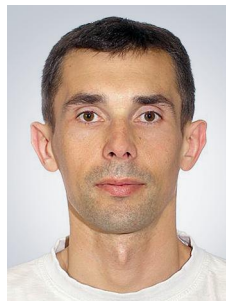
systems of direct and alternating current with power converters for general and special industrial purposes due to the use of new types of generators and generating complexes with electric machines and static converters.



Viktor Grebenikov – D.Sc. in Technical Sciences, Leading Researcher of the Department of Electromechanical Systems of the Institute of Electrodynamics of the National Academy of Sciences of Ukraine.

Main research interests: scientific justification of the optimal structures of magnetic systems of electrical machines with permanent magnets;

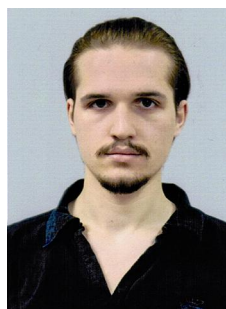
development of mathematical models, analytical calculation method, engineering solutions providing the creation of new electrical machines with permanent magnets with improved power characteristics for applying them to power engineering, automation, transport and technical equipment of special purpose.



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generating sets with power electronic converters and systems for autonomous power supply and the development of distributed generation.



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of mathematical and simulation models for calculating their steady state and transient processes.

Received: 18.08.2020. Accepted: 24.10.2020.