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A CONTROL SYSTEM BASED ON THE DC-DC CONVERTER FOR STAND-ALONE VERTICAL-AXIS WIND TURBINES

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Summary: In this paper the investigation of uncontrollable and adjustable by the boost DC-DC converter systems of autonomous wind turbines are conducted on the basis of computer simulation. To achieve the maximum efficiency of energy transference and conversion at different wind speeds, the optimal combination of regulated and unregulated modes is proposed. The developed control system allows taking off the maximum power from wind without a wind sensor.

Keywords: wind turbine, vertical-axis, wind turbine rotor, PMSG, DC-DC converter, optimal control

1. 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. The experience gained over the last two decades in the development of wind power in the world has allowed us to identify two ways of further development: use of powerful (0.1 ... 5 MW) wind turbines (WT) and power stations in industry, and low and medium power (0.3 ... 50 kW) WT for private homes, rural estates, farms etc. Because the latter are meant to work in close proximity to people, in medium to low wind speeds, they must meet high environmental and energy efficiency standards. These standards are best met by the WT with the vertical-axis rotation (VAR) of the wind turbine rotor, which have recently become popular in the world. Compared with traditional wind wheels with the horizontal axis of rotation, the mechanical part of the vertical-axis WT does not require any control, and the transmission can be bearless. However, in order to ensure the high ratio of useful energy from wind power at variable wind speeds, the electromechanical energy conversion systems of VAR WT and electronic control systems must be more complex and multifunctional.

2. ANALYZING THE PROCESSES OF ELECTRICITY GENERATION AND POWER TAKEOFF FROM THE GENERATOR

One of the main elements of the WT is the wind turbine rotor (WTR) which converts wind energy into mechanical energy. Its main parameters are output power P_{WTR} and torque M_{WTR}, which are determined by the following formula [1]:

$$P_{WTR} = 0.5 \rho A C_P(\lambda) V_w^3, \tag{1}$$

$$T_{WTR} = 0.5 \rho A r \frac{C_P(\lambda)}{\lambda} V_w^2, \tag{2}$$

where:

ρ	–	density of air,
$A = \pi r^2$	–	washing area of WTR,
$C_P(\lambda)$	–	wind power conversion efficiency factor,
$\lambda = \omega r / V_w$	–	tip speed ratio of WT,
ω	–	angular speed of WTR,
r	–	WTR radius,
V_w	–	wind speed.

Wind power conversion efficiency factor of WTR depends nonlinearly on its tip speed ratio, and for different turbines there exist different curves which are determined experimentally: for example, by studying the WTR in a wind tunnel. For instance, Fig. 1 showed the dependence $C_P(\lambda)$ for the WTR [1], at the optimal point of which ($\lambda_{opt} = 3.8$) the maximum of wind power is taken off. Using $C_P(\lambda)$ as expressed in (1) and (2), we can build for a specific WTR the basic dependences that characterize its work, as shown in Fig. 2.

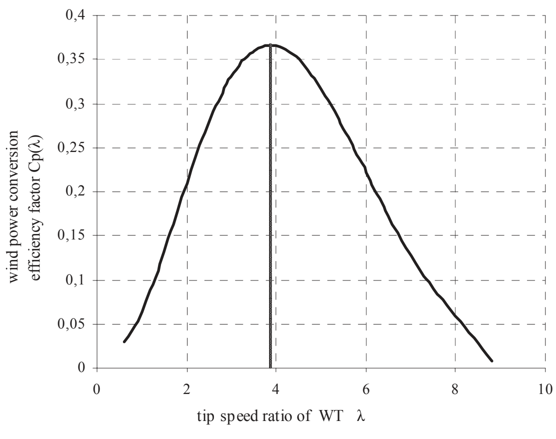

Fig. 1. Wind power conversion efficiency factor of the WTR versus tip speed ratio

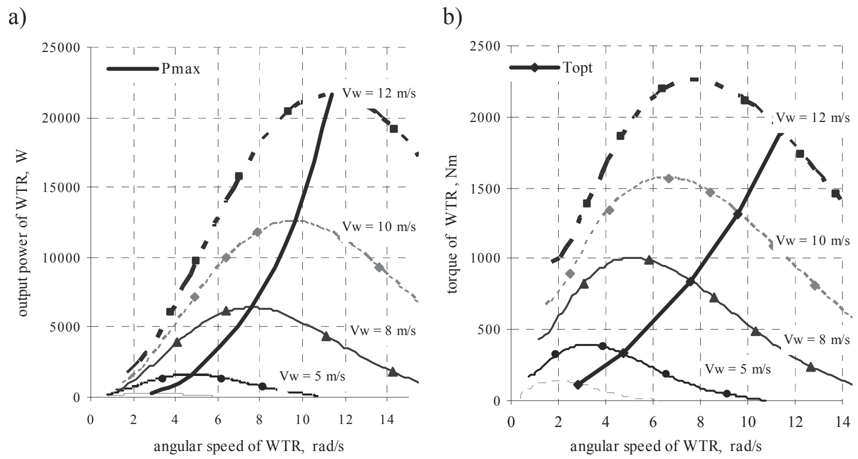

Fig. 2. Dependences of the output parameters of the WTR on its angular speed at different wind speeds: a) power P_{WTR} , b) torque T_{WTR}

To generate electricity, there are various ways of constructing the WT electromechanical systems [2,3]. Asynchronous machines and synchronous machines with electromagnetic excitation are used in the WT that are designed for high wind speeds and operate in parallel to the power networks. Synchronous machines with permanent magnets are more suitable in the WT that are designed for low wind speeds and autonomous load. The use in WT of the multi-pole synchronous generator with permanent magnets (PMSG) allows one to avoid a boost gear (multiplier), which simplifies the design and improves the reliability of WT.

In Eastern Europe, winds of low and medium speed prevail, which makes it a suitable area for the use of low-power WT. In such turbines, especially for turbines with VAR, it is advisable to use the simplest and most reliable system, which is PMSG without a multiplier with a DC link. A number of factors, such as lack of agreement with the electric power companies about connecting the private WT to the power networks, small power of the WT, outages of power and lack of power networks, make it advisable to build autonomous WT that are designed for individual consumers. In such cases, the random character of generation and consumption calls for such element of the WT as the electrochemical battery of accumulators (AB).

There are two main options for taking power from PMSG: uncontrollable – the load of PMSG through passive diode bridge rectifier (DB) directly onto AB, and adjustable – with electronic regulation of the electric load of PMSG (Fig. 3) [4].

The first option (Fig. 3, a) is a simple and more cost-efficient one: for a particular PMSG, one selects the optimum number of AB. However, in this case it is impossible to provide operation in the point of the maximum takeoff of wind power. At low wind speed, the WT hardly generates any electric power, and at large wind speed, it typically overloads AB by charge current, which significantly reduces their life [5].

The second option necessitates the use of a power semiconductor converter: voltage DC-DC converter in the DC link (Fig. 3, b) or an active voltage rectifier (AR) (Fig. 3, c).

In such cases, one can apply a maximum power point tracing (MPPT) system, and one can simultaneously solve other problems of automatic control [5].

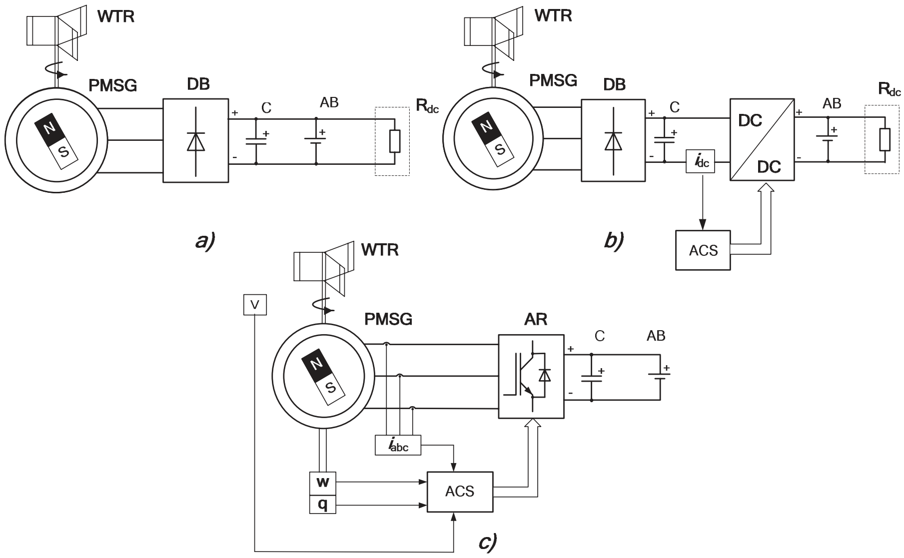

Fig. 3. Functional schemes of taking power from PMSG: a) uncontrollable, b) adjustable with a DC-DC converter; c) adjustable with an active rectifier

In addition to taking into account the peculiarities of low power WT (operation at low wind speeds and for local consumers), one must ensure its highest possible performance at all stages of energy conversion, including taking maximum possible power from the WTR at different wind speeds, transferring the received power to the consumer with minimal losses in all the elements of the power system, and monitoring all the processes. All of these requirements can be best satisfied by the system with AR. However, financial considerations for the low-power WT make it preferable to use a DC-DC converter.

3. COMPUTER SIMULATION OF THE WT: UNCONTROLLABLE AND ADJUSTABLE BY AUTOMATIC CONTROL SYSTEM (ACS) BASED ON THE DC-DC CONVERTER

In order to study the rational parameters of ACS in the first phase of research, it is useful to conduct a computer modeling of the WT with given parameters (see Appendix). It should compare the performance of two configurations of the WT: the conventional one without the automatic control and the one with the DC-DC converter and optimal control (Fig. 3, a, b).

For the simulation of the WT, we used MatLab/Simulink software. The developed computer model (Fig. 4) models the work of the WT and consists of the following subsystems: the WTR, the three-phase PMSG, the diode bridge, the boost DC-DC converter, the AB and the ASC, which allows the MPPT and the charging of the AB at all wind speeds. In this model for the automatic control of the DC-DC converter, we used the optimal linear relationship between wind speed values that were referred in the model, and the angular speed of PMSG. In the case of studying the uncontrollable system, the IGBT transistor in the DC-DC converter did not work.

The control of the IGBT transistor takes place by means of a system that is listed in the subsystem System Control (Fig. 5). It implements the closed system of regulation of the PMSG angular speed with the PID-regulator. Its output voltage is compared with the saw-toothed voltage (carrier frequency 3 kHz), which forms in the subsystem Triangular Generator. The output PWM signal of the comparator controls the gate of the IGBT transistor.

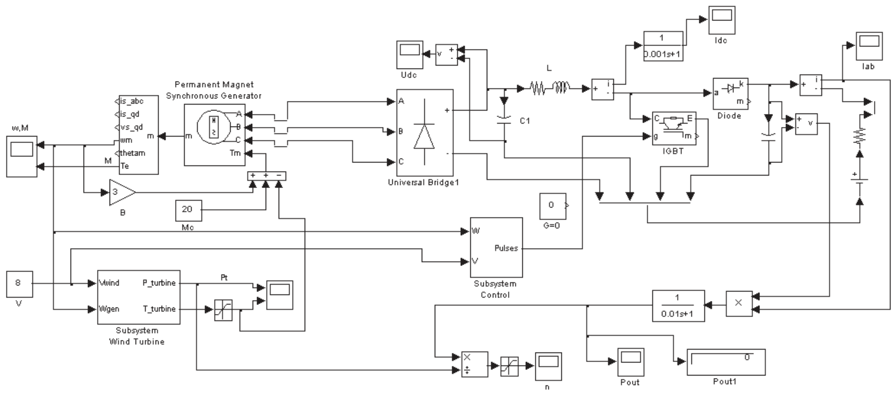

Fig. 4. Basic computer model of the WT with the PMSG and the DC-DC converter

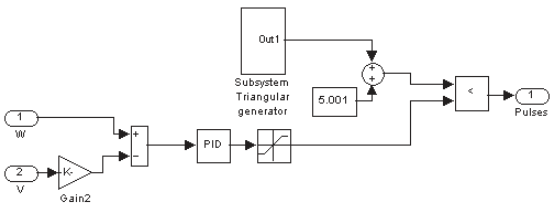

Fig. 5. System Control Subsystem

The energy dependences for both WT systems based on the results of conducted research are given in Fig. 6. Their analysis shows the following:

1. For the uncontrollable WT, the output power value (Fig. 6, a) depends on the number of AB. The nature of the changes in this value with the change of wind speed, and when the amount of AB is constant, does not correspond completely to the character of the maximum power curve shown in Fig. 6, a by the solid line. For the set parameters of the WTR and PMSG, the optimal number of AB is 16, which are connected consistently, when the best match with the maximum power curve is observed. However, electricity generation in this case begins at wind speed of 5 m/s.

2. For the adjustable WT, the output power value (Fig. 6, b) practically does not depend on the number of AB; that is why their number can be selected according to oth-

er criteria. The nature of the changes in this value with the change of wind speed practically corresponds to the nature of the curve of maximum power. Slight deviations from the maximum power curve are observed only at 16 AB and the wind speed of over 10 m/s, when the output voltage of the diode bridge already exceeds the voltage of AB, and the DC/DC converter does not work. Generation of electricity in the regulated WT starts at wind speed of 3 m/s.

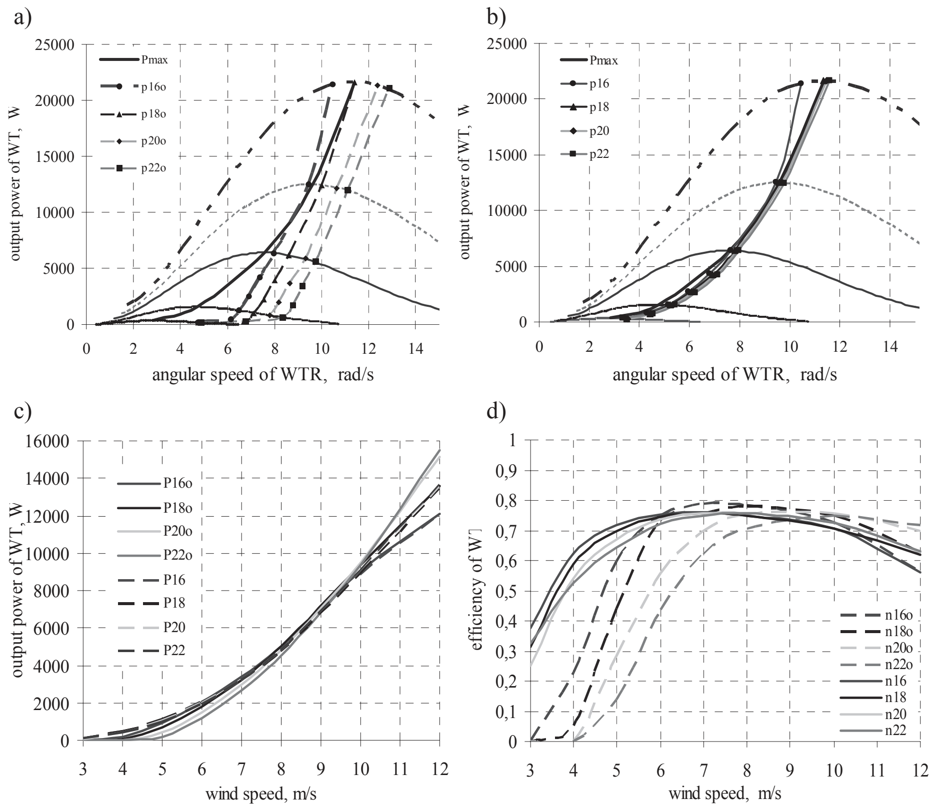

Fig. 6. Energy dependences for uncontrollable and adjustable with the DC-DC converter WT with different numbers of AB (16, 18, 20, 22): a) dependence of the output power of the WT on angular speed at different wind speeds for the unregulated system, b) dependence of the output power of the WT on angular speed at different wind speeds for the adjustable ASC, c) dependence of the output power for unregulated (dotted line) and controlled (solid line) WT systems on wind speed, d) dependence of total efficiency for unregulated (dotted line) and controlled (solid line) WT systems on wind speed

3. Dependences of output power of the WT on wind speed (Fig. 6c) show that for $V_w < 8$ m/s, unregulated electric output power of the WT is significantly lower than the regulated, especially as the number of AB increases. At high wind speeds, $V_w > 8$ m/s, the situation is reversed: the highest electric power output is observed in the unregulated system and at a greater number of the AB. This is because at high output power in the regulated system, switching losses in the DC-DC converter significantly increase. At the

same time, in the unregulated system the output voltage is already high enough to charge AB directly, without significant deviation from the point of maximum power, and at a greater number of AB the same power is transmitted by less current, which helps to reduce resistance losses in the power circuit. This is illustrated well by the dependences of overall efficiency on wind speed, which are defined for all investigated cases and given in Fig. 6d. Total efficiency is defined by

$$\eta_{\Sigma} = \frac{P_{\text{out}}}{P_{\text{WTR.max}}}, \tag{3}$$

where:

P_{out} – output electric power of the WT,

$P_{\text{WTR.max}}$ – maximum power which can be obtained from WTR under a given wind speed (calculated using expression (1) at $C_{\text{P.max}}(\lambda)$ = 0.37).

Thus, our study shows that at wind speeds $V_{\text{w}} > 8$ m/s, using the DC/DC converter is impractical. It should work only at low wind speeds, which will always allow operation at the point of maximum power, and the use of low, but lasting wind potential. The power of the DC/DC converter will not exceed one half of the maximum power of the WT. At high wind speeds and high power, the WT system should operate in the unregulated regime, and in order to reduce the total energy losses, one must select the optimum number of AB: in this case, 20, as demonstrated by Fig. 6d.

4. DEVELOPING THE OPTIMAL CONTROL SYSTEM FOR THE TAKEOFF OF WIND ENERGY

In order to provide maximum energy efficiency, the WT should work at the point of maximum output power for each wind speed [1,6]. The key to this is to provide such total electrical and mechanical load of the generator that WTR turns with optimal angular speed at which maximum power is taken from the wind. This corresponds to the optimal points of the tip speed ratio of WTR λ_{opt}, in which the wind power conversion efficiency factor $C_{\text{P}}(\lambda_{\text{opt}})$ reaches a maximum value. Thus, we may formulate the following linear dependence between the optimal value of WTR angular speed ω_{opt} and wind speed V_{w}:

$$\omega_{\text{opt}} = \frac{\lambda_{\text{opt}}}{r} V_{\text{w}}. \tag{4}$$

The condition of WT optimal control (4) is simple and effective, but for its implementation, it is necessary to equip the system with wind speed sensor. In those systems where the wind speed sensor is required in terms of other tasks (for example, in such vertical-axis WT that must be started into operation by preliminary rotation, or in horizontal-axis WT with the electric drive turning of the head to wind orientation), such a simple optimal control system should be used [7,8]. We also used it in previous computer experiments.

Small error in the condition (4) is introduced by a significant increase of power loss in the power part of the WT with the increasing wind speed and the corresponding increase of energy flow. To correct this condition, one should somewhat decrease the generator load, which means to increase slightly the WTR angular speed in comparison with ω_{opt}, defined by (4).

To construct the sensorless optimal control WT systems, a number of ways were developed that differ according to the type of WT (stand-alone, running parallel to the power network), the type of WTR (horizontal or vertical axis, with pitch control of blades), the type of generator (induction or synchronous with modifications), and the principle of their control (scalar or vector), etc. [6-10]. Analysis of different control methods of the WT enabled us to determine the main version of the sensorless optimal control system, which is described in [10] and which works as follows:

As seen from equations (1), (2) and (4), in the optimal point of the WT the following dependences exist between its main parameters:

$$\omega_{opt} = k_{\omega} V_{W} , \quad (5)$$

$$T_{opt} = k_{T} V_{W}^{2} , \quad (6)$$

$$P_{max} = k_{P} V_{W}^{3} , \quad (7)$$

where:

k_{ω}, k_{T}, k_{P} are constant coefficients whose values can be easily obtained through the parameters of the WTR from the equations (4), (1) and (2).

Having determined V from the equation (5) and having substituted it in (6), we find the relationship between the optimal values of angular speed and the torque of WTR:

$$T_{opt} = \frac{k_{T}}{k_{\omega}^{2}} \omega_{opt}^{2} = k_{opt} \omega_{opt}^{2} \quad (8)$$

The analysis of the obtained equation (8) and the dependencies $T(\omega)$ at different wind speeds, shown in Fig. 1, allows us to draw the following conclusion: ACS with the control criterion $T^* = k_{opt}\omega^2$, where T^* is the reference value of static load torque of the WTR, which is realized by means of electric load on the generator, will work is stable areas of characteristics and in steady-state will always be approaching the optimal point with maximum power. Thus, for optimal control it is necessary to provide the angular speed sensor of the WTR and to develop the specified ACS.

The first condition is easy to implement since the angular speed can be clearly determined from the frequency of voltage of PMSG.

To implement the second condition, in equation (8) we propose to replace the torque on the proportional to it (nonlinear) value of the load current at DC voltage link I_{DC}, which can be easily measured. To find the monotonous nonlinear dependence $I_{DC.opt} = f(\omega_{opt})$, one can use computer modeling or determine it experimentally in multiple points. For theoretical research, we used the first option and obtained as the results of computer simulation the curve shown in Fig. 7. It is approximated by the following polynomial that is the optimal control law:

$$I^*_{\mathrm{DC.opt}} = 16.816 - 10.143 \cdot \omega + 1.909 \cdot \omega^2 - 0.067 \cdot \omega^3 \tag{9}$$

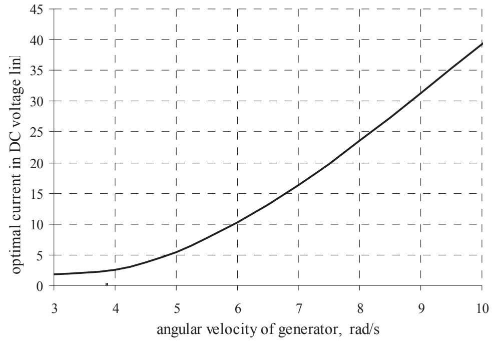

Fig. 7. Relationship between the angular speed of WTR and the current in the DC voltage link at points of optimal work

5. COMPUTER RESEARCH OF THE WORK OF THE WT SENSORLESS ACS

For proposed ACS of the WT, we also developed the computer model on the basis of which we conducted research. This model, unlike previous ones, does not contain a wind sensor, and implements the sensorless optimal control system proposed by us. The reference control signal is the value of current I^*_{DC} in the circuit of generator rectified voltage according to the equation (9). The main model subsystems remained the same as in the case of the model that used the wind sensor (Fig. 4). In this model only subsystem System Control is replaced, the computer model of which is shown in Fig. 8.

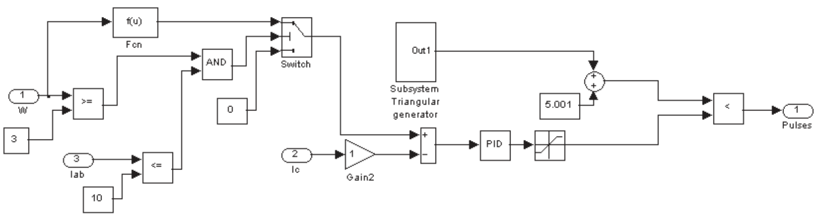

Fig. 8. System Control Subsystem

The value of angular speed ω of PMSG is taken at input of this subsystem, so the block Fcn, which carried dependence (9), forms the reference of current in the DC voltage link. This task may be allowed at input of the current ACS on two conditions: 1) exceeding the minimum angular speed (taken as 3 rad/s) and 2) not exceeding by the rectified generator current of a certain value (for the study done in 10 A), which limits the work range of the DC-DC converter. If both conditions are met, the reference I^*_{DC} is given at the ACS input, where it is compared with the real value of the current in the DC voltage link that comes from a current sensor. The error of current, enhanced by the PID-regulator, comes to the comparator which compares it to the saw-toothed voltage. Output PWM signal makes it possible to control the opening of the IGBT transistor on a specified range of wind speed.

The received dependences of output electrical power on the angular speed of WTR (Fig. 9a) show how the transition from the regulated mode to the uncontrollable one occurs at the wind speed of 7 m/s. Fig. 9, b shows a similar dependence for the torque of the WTR. These dependences show that the points of best performance for the adopted optimal number (20) of AB appear somewhat to the left of the maximum power curve of the WTR, which, as has been shown above, allows us to take into account the losses in the electrical part of the WT.

a) b)

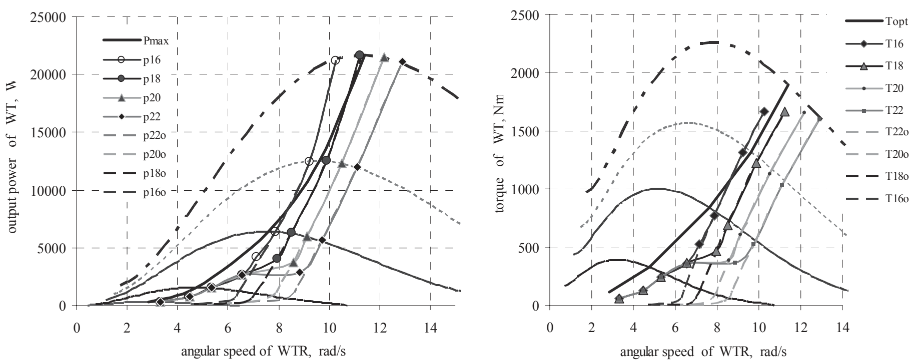

Fig. 9. Energy dependences of the sensorless ACS of the WT for varying numbers (16, 18, 20, 22) of AB: a) output power depends on the angular speed of WTR at different wind speeds; b) torque dependences on the angular speed of WTR at different wind speeds

To study the dynamic modes of the designed WT, the simulation of its work during more than 4 s at variable wind speeds was carried out. To simulation time saving, the total inertia of WTR and PMSG was decreased. The simulated waveform of V_W is given in Fig. 10, a. It also shows how the angular speed w of the WTR with PMSG changes as a result of the WT operation. At the time interval 0-0.4 c V_W is growing to 5 m/s and is kept at this level during 1.5 s. ACS is working this increase of V_W in 0.7 s, changing angular speed w from 0 to steady-state value 5.4 rad/s (optimum value of ω of PMSG for the takeoff of maximum wind power). Then (t = 1.5 s) the second increase of V_W to the value of 10 m/s occurs. At this time interval (0.5 s), one can observe the work of power part of the WT both through the DC-DC convertor (up to $\omega = 8$ rad/s) and directly through the bypass diode ($\omega > 8$ rad/s). When V_W is reduced ($t = 2.5$ s), the angular speed of the generator decreases, and at ω = 8 rad/s the DC-DC converter turns on (we observe the increase of the falling rate of the generator angular speed). When the steady-state value of wind speed (V_W = 4 m/s) is reached, the ACS ensures the PMSG work in the optimal mode for the maximum takeoff of wind power. Fig. 10, b shows the simulated waveforms of torques on the shaft of WTR T_{WTR} and PMSG T_{G}, which demonstrate the equality of the latter in the steady state and their differences in the transition. Ripples on the shaft of PMSG arise as a result of non-sinusoidal armature current of the generator, which is caused by its load on the diode bridge with the capacitive output filter. Fig. 10, c shows the simulated waveforms of the output power of the WTR and the WT system and makes it clear that during the growth of the angular speed of the generator, some part of the WT power goes to the accumulation of the kinetic energy. During the braking in the WT, this kinetic energy is transferred to the output of the WT, which ensures the ratio $\eta = P_{\mathrm{WT}} / P_{\mathrm{WTR}} > 1$ as seen in Fig. 10, d. The simulated waveform of the output voltage of the diode bridge Uc (Fig. 10, e) clearly shows the work intervals of the DC-DC converter, when Us = 150-230 V and the output voltage is transmitted to AB at 280 V. At the time interval 1.8 - 3 s, the DC-DC converter does not work because the output power is transmitted to the WT output through the bypass diode, which is also evident from the simulated waveforms of the currents, given in Fig. 10, f.

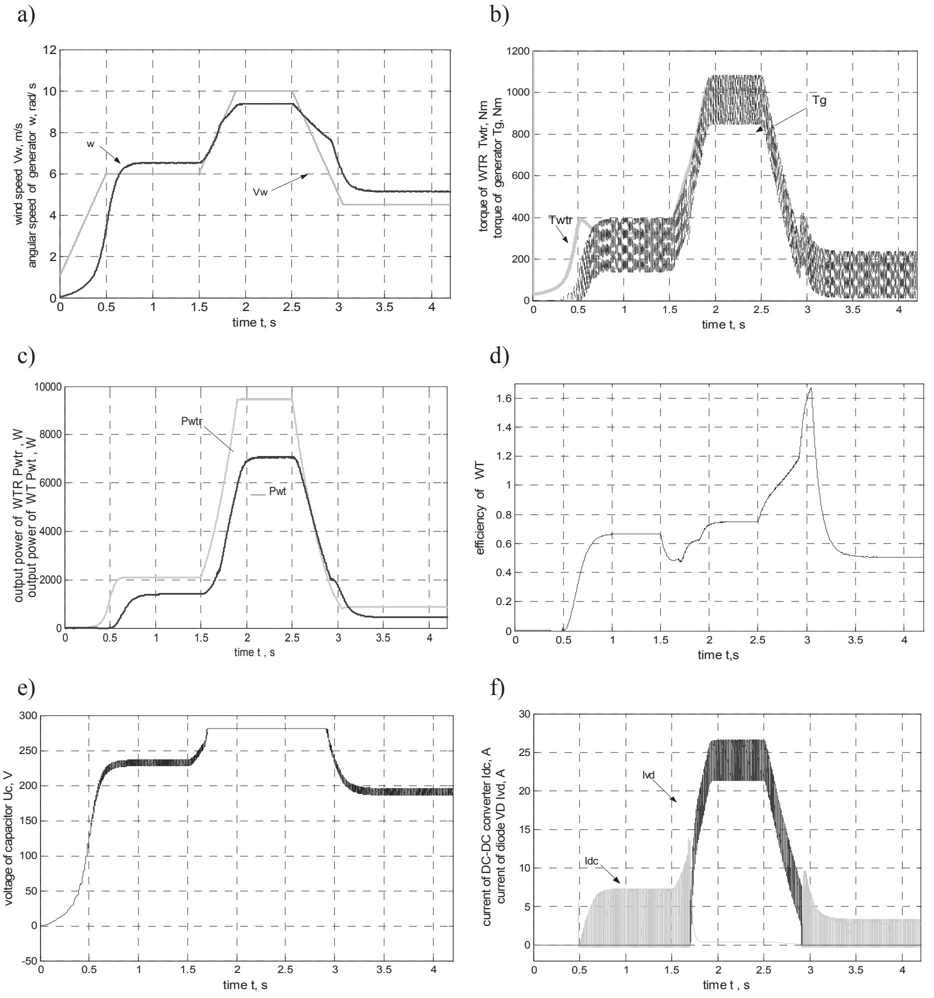

Fig.10. Simulated waveforms of the electrical and mechanical parameters of the sensorless ACS of the WT: a) changes of the wind speed and the generator angular speed during the WT operation; b) torques WTR and PMSG; c) the output power of the WTR and the WT system; d) the ratio of output powers of the WT and the WTR during operation on the test profile of wind speed changes; e) output DC voltage of PMSG; f) the currents of the DC-DC converter Idc and the bypass diode Ivd

6. REALIZATION OF CONTROL SYSTEM

The investigated control system of WT is made as the separate block. It consists of a power part and a microcontroller board. The DC-DC converter is made on the IGBT transistor G4PC50W. The developed control algorithm is implemented in microcontroller ATMEGA 853516PU.

7. CONCLUSIONS

Unregulated takeoff of power from the PMSG is based on the compromise between the capacity of the WT operation at low wind speeds and the prevention of the overload of the AB by charging current at high wind speeds. Using the DC-DC converter for the automatic control of the working point of the WT is advisable only at low power, and later it should work in the unregulated mode with the optimal number of AB. The designed system of optimal control of the WT by changing the parameters of the power part can be adapted to different power of the WT and its type, including both the vertical-axes and the horizontal-axes. The control algorithm incorporated in the microcontroller provides the specific procedure of adjustment for the optimum performance of the WT with unknown parameters. This control system ensures the maximum power of the WT at small and medium wind speeds and the possibility of its operation at great wind speeds without damage to the batteries.

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APPENDIX

Nominal parameters of WTR:

$A = 52.96\ \text{m}^2$; $r = 4.104$ m; $P_{\text{WTR}} = 12500$ W for $V_{\text{w}} = 10$ m/s.

Expression $C_{\text{P}}(\lambda)$ for WTR approximated by the following polynomial:

$$C_{\text{P}}(\lambda) = 0.04698 - 0.1285\lambda + 0.196\lambda^2 - 0.05705\lambda^3 + 0.00621\lambda^4 - 0.000236\lambda^5 .$$

Nominal parameters of PMSG:

$P = 10000$ W; $p = 32$ – pair of poles;
armature windings: $R = 1\ \Omega$ – resistance; $L = 0.005$ H – inductance;
$\Phi = 0.7$ Wb – magnitude of pole flux;
$J = 10\ \text{kg}\cdot\text{m}^2$ – total inertia of WTR and PMSG.

Nominal parameters of each AB:

$U = 12$ V; $C = 200$ Ah.

UKŁAD STEROWANIA DZIAŁAJĄCY W OPARCIU O PRZEKSZTAŁTNIK DC-DC DLA AUTONOMICZNYCH ELEKTROWNI WIATROWYCH Z OSIĄ PIONOWĄ

Streszczenie

W niniejszej pracy są przedstawione wyniki badań układu sterowania autonomicznej elektrowni wiatrowej z osią pionową, który wykorzystuje przekształtnik DC-DC. Badania przeprowadzono za pomocą symulacji komputerowej. Aby osiągnąć maksymalną skuteczność przesyłania i konwersji energii przy różnych prędkościach wiatru zaproponowano optymalną kombinację regulowanych i nieregulowanych trybów pracy. Opracowane sterowanie umożliwia maksymalne wykorzystanie mocy wiatru bez stosowania czujnika prędkości wiatru.

Słowa kluczowe: turbina wiatrowa, pionowa oś, wirnik turbiny wiatrowej, PMSG, DC-DC przekształtnik, sterowanie optymalne