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MATHEMATICAL SIMULATION OF AUTONOMOUS WIND ELECTRIC INSTALLATION WITH MAGNETOELECTRIC GENERATOR

Purpose. Development of a mathematical model of an autonomous wind power plant based on an end-generator with a double stator and combined excitation to evaluate methods for improving the efficiency of conversion of mechanical wind energy into electricity.

Methodology. The research used methods of general theory of wind power plants, methods of mathematical modeling, which are based on the numerical solution of nonlinear differential equations to evaluate methods for correcting the output power in Matlab-Simulink by modifying standard units.

Findings. A numerical simulation mathematical model of an autonomous wind power plant consisting of a magnetoelectric generator with an axial magnetic flux with combined excitation and a double stator has been developed. The model was created to study the parameters and characteristics of the installation, as well as to evaluate methods and means to improve the efficiency of conversion of wind energy into electricity. According to the research, it is established that a more effective method for regulating the output power of the generator in the wind turbine is the use of additional winding for magnetization, compared with the use of additional capacity. The latter provides up to 7–16 % increase in output power, while using the magnetizing winding can increase the output power to 32–35 %. The results obtained by the authors allow further developing a number of methods to increase the efficiency of conversion of mechanical energy of the wind turbine rotor into electrical energy.

Originality. The mathematical model developed for the first time, in contrast to the existing ones, takes into account the presence of a double stator, an additional winding for magnetization of the magnetic system and the axial nature of the circuit of the main and additional magnetic flux. The developed model also takes into account the change in the parameters of the electric generator with axial magnetic flux when changing the parameters of the wind, the rotor of the wind turbine and the load. The model is designed to analyze the possibility of adjusting the output power of the generator when the wind speed changes.

Practical value. The simulation results indicate the prospects of industrial implementation of wind power plant based on magnetoelectric generator for their use as autonomous electrical installations and as part of shunting power systems.

Keywords: *autonomous wind turbine, axial flux generator, double stator, permanent magnets, excitation winding*

Introduction. The axial flux synchronous magnetoelectric generator with combined excitation combines the advantages of permanent magnet generators with the simultaneous possibility of controlling the magnetic flux in the air gap using one or more additional magnetizing windings [1, 2]. This design is promising for use in wind power plants [3, 4], as it allows you to abandon the multiplier and expand the limits of regulation of the autonomous wind power system [5, 6]. A low speed of rotation of the rotor is typical for electric generators working as part of multiplierless installations. This leads to excessive growth of the outer diameter of the rotor, its mass and dimensions. The specific power of such a generator is quite low. The axial flux generator with permanent magnets (AFGPM) does not have this drawback. The use of a double stator allows you to increase the specific power and use the useful volume of the electric machine more efficiently [5]. In combination with an additional magnetizing winding, such a generator has wide opportunities for adjusting the output parameters. This feature makes it possible to use such a system to increase the efficiency of converting wind energy into electrical energy and improve the energy characteristics of an autonomous wind unit [7, 8].

Existing mathematical models of AFGPM [3, 6] are built without taking into account the presence of an additional magnetizing winding. In addition, when changing the parameters of the rotor of a wind turbine or electric generator in existing models [6, 7], it is necessary to reassign the parameters and carry out new series of calculations.

To evaluate the efficiency of the “wind turbine rotor – AFGPM” system, it is necessary to develop a mathematical model in the MATLAB/Simulink environment with further analysis and comparison of the efficiency of various modes of operation of the system: without output voltage control, voltage control using additional capacitors or an additional magnetizing winding.

The subject of the study is the nature of the change in the output power of the generator operating as a part of the wind turbine. At the same time, the traditional aim of regulating the output voltage loses its principle role, because when the voltage drops to the limit (for example, in the absence of wind or at low wind speed), the controller disconnects the generator from the load (for example, charging the battery).

The purpose of the article is to develop a mathematical model of an autonomous wind power plant based on an axial flux generator with a double stator and combined excitation to evaluate methods for increasing the efficiency of converting wind mechanical energy into electrical energy.

Basic material. An axial flux synchronous magnetoelectric machine with permanent magnets is an electromechanical energy converter in which the main magnetic flux is generated by permanent magnets. The change in the magnitude of the main magnetic flux is ensured by the magnetomotive force of the additional magnetizing winding. This design of the machine is also known as an axial magnetic flux generator, since the main magnetic flux is closed through the shaft. The design of the generator studied in this work is shown in Fig. 1.

Synchronous magnetoelectric generators of this type have high technical and economic parameters. The main disadvantage of these generators is the lack of effective methods for

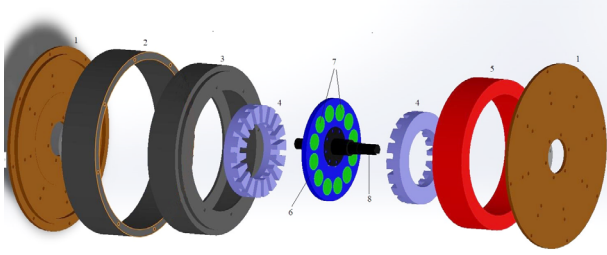


Fig. 1. Design of the studied generator:

1 – bearing shields; 2 – generator body; 3 – ferromagnetic core of the auxiliary winding; 4 – ferromagnetic core of the generator armature winding, made of sheet electrotechnical steel, in the grooves of which the stator windings are placed (it is not shown on the figure); 5 – additional magnetization winding; 6 – rotor core made of non-magnetic steel; 7 – permanent magnets; 8 – generator shaft made of ferromagnetic steel

controlling the magnetic flux, which limits the optimization of the energy balance of the wind turbine [9]. The power supply system based on an autonomous wind turbine consists of an electric generator, a battery pack, a battery charge controller and an inverter, which provides the necessary amplitude and frequency of the consumer's voltage.

In addition, it is advisable to use end generators in wind power plants without multiplexers [10]. This is possible due to the fact that generators of this type are manufactured for a large number of pole pairs, due to a small axial length and a larger outer diameter of the stator compared to traditional cylindrical generators.

In real conditions, the wind speed is constantly changing. At the same time, the wind turbine is operating in the most efficient way only at one, specifically determined value of the wind speed. When the wind speed changes, the efficiency of converting the wind's mechanical energy into electrical energy decreases. Controlling the power of the generator when the wind speed changes is an urgent scientific and technical problem.

Table 1

Main parameters and characteristics of AFGPM

No	Parameter	Size	UOM
1	Full nominal power	400	V · A
2	Nominal phase generator voltage	50	V
3	The number of phases	3	–
4	Synchronous rotation frequency	500	rpm
5	The number of pole pairs	12	–
6	Permanent magnets	NdFeBN38H: Br = 1.21 T, Hc = 939 kA	–
7	Power factor	0.9	–
8	Outer/inner diameters of the stator ferromagnetic core	135/85	mm
9	Axial length of the ferromagnetic core of the stator	23.0	mm
10	Axial length of the rotor disk	8.0	mm
11	The outer diameter of the generator	270.0	mm
12	Thickness of permanent magnets	7.0	mm
13	The value of the axial air gap	0.5	mm
14	Efficiency	92	%
15	The average value of the magnetic induction in the air gap	0.29	T

Table 1 shows the main parameters and characteristics of the AFGPM that was used to develop the mathematical model.

MATLAB/Simulink software package was used to develop a simulation model of the wind turbine rotor – AFGPM system. This package contains mathematical models of the wind turbine rotor, load, measuring devices, etc. However, there are no AFGPM models to study their parameters and characteristics. Therefore, in this paper, a modified model of a synchronous machine with permanent magnets is used to develop a simulation model of this magnetolectric electric generator. The block of the magnetolectric electric generator allows you to simulate the generator and motor operation modes. The electrical and mechanical parts of the generator are represented by algebraic and differential equations. When developing a mathematical model of an axial flux synchronous magneto-electric machine with permanent magnets with a bilateral stator, the following assumptions were made: the air gap is uniform; the stator winding is distributed evenly.

The general system of equations describes the operation of a synchronous machine with permanent magnets and an additional magnetizing winding in the d - q coordinate system.

$$\begin{cases} \frac{di_d}{dt} = \frac{1}{L_s} \left(u_d - R_s i_d - L_m(i_f) \frac{di_f}{dt} + \omega Z_p L_s i_q \right) \\ \frac{di_q}{dt} = \frac{1}{L_s} \left(u_q - R_s i_q - \omega Z_p L_s i_d - \omega Z_p L_m(i_f) i_f - \omega Z_p \Psi_0 \right) \\ \frac{di_f}{dt} = \frac{1}{L_f} \left(u_f - R_f i_f + L_m(i_f) \frac{di_d}{dt} \right) \\ \frac{d\omega}{dt} = \frac{1}{J} (M - M_c) \\ M = \frac{3}{2} Z_p \left[\Psi_0 i_q + L_m(i_f) i_q i_f \right] \end{cases},$$

where $L_s = L_q = L_d$ is stator inductance along the q and d axes; R_s is active resistance of the stator winding; i_q, i_d are stator currents along the q and d axes; u_q, u_d are stator voltages along the axes q and d ; ω is angular speed of the generator rotor; Ψ_0 is flux linkage created by permanent magnets; Z_p is the number of pole pairs; L_f, R_f are inductance and active resistance of the additional magnetizing winding; u_f, i_f are voltage and current of the additional winding; $L_m(i_f)$ is the mutual inductance of the windings; M, M_c are electromagnetic moments of the generator and wind turbine; J is the total moment of inertia.

An important feature of the model is taking into account the saturation of the ferromagnetic system through the dependence of the mutual inductance of the windings on the current of the additional magnetizing winding $L_m = f(i_f)$. This dependence was obtained in previous works [1, 2] as a result of field mathematical modeling.

The windings of the double stator are connected in parallel to the load, so the EMF of the generator and the voltage on its terminals are determined by the parameters of the stator windings according to equations (2–5) of the system. Indices s_1 and s_2 denote the parameters of the first (a – b – c) and second (x – y – z) stator winding, and the matrices R_{s1} and R_{s2} are 3×3 diagonal matrices of active resistances for a – b – c and x – y – z windings, respectively. The f function is responsible for the voltage, current, and flux vectors.

$$\begin{aligned} u_{abc} &= R_{abc} i_{abc} + \frac{d\Phi_{abc}}{dt} \Rightarrow u_{s1} = R_{s1} i_{s1} + \frac{d\Phi_{s1}}{dt}; \\ u_{xyz} &= R_{xyz} i_{xyz} + \frac{d\Phi_{xyz}}{dt} \Rightarrow u_{s2} = R_{s2} i_{s2} + \frac{d\Phi_{s2}}{dt}; \\ f_{s1} &= [f_{as} f_{bs} f_{cs}]^T; \\ f_{s2} &= [f_{xs} f_{ys} f_{zs}]^T. \end{aligned}$$

In the complex vector form, the equations are the following

$$\begin{aligned} \underline{u}_{s1} &= R_{s1} \underline{i}_{s1} + p \Psi_{s1}; \\ \underline{u}_{s2} &= R_{s2} \underline{i}_{s2} + p \Psi_{s2}. \end{aligned}$$

Complex vector variables f_{s1} and f_{s2} are calculated as follows

$$\begin{aligned} \underline{f}_{s1} &= \frac{2}{3} (f_{as} + \underline{a} f_{bc} + \underline{a}^2 f_{cs}); \\ \underline{f}_{s2} &= \frac{2}{3} (f_{xs} + \underline{a} f_{yc} + \underline{a}^2 f_{zs}), \end{aligned}$$

where $\underline{a} = e^{j\frac{2\pi}{3}}$.

The flux linkage of each of the stator windings is determined by the combination of component flux linkages

$$\begin{aligned} \Psi_{s1}(i_f) &= \Psi_{s1s1} + \Psi_{s1s2} + \Psi_{s1r} + \Psi_m(i_f); \\ \Psi_{s2}(i_f) &= \Psi_{s2s2} + \Psi_{s2s1} + \Psi_{s2r} + \Psi_m(i_f), \end{aligned}$$

where Ψ_{s1s1} , Ψ_{s2s2} are the flux linkages of $a-b-c$ and $x-y-z$ stator windings; Ψ_{s1s2} , Ψ_{s2s1} are mutual flux linkages of $a-b-c$ and $xy-z$ stator windings; Ψ_{s1r} , Ψ_{s2r} are resulting flux linkages of $a-b-c$ and $x-y-z$ stator windings and flux linkage of permanent magnets; Ψ_m is flux linkage of the additional magnetizing winding.

The number of pole pairs of both stator windings of the electric generator is the same, so the mutual flux coupling between them is zero

$$\begin{aligned} \Psi_{s1s2} &= \Psi_{s2s1} = 0; \\ \Psi_{s1}(i_f) &= \Psi_{s1s2} + \Psi_{s1r} + \Psi_m(i_f); \\ \Psi_{s2}(i_f) &= \Psi_{s2s2} + \Psi_{s2r} + \Psi_m(i_f). \end{aligned}$$

In matrix form, the expressions will take the form

$$\begin{bmatrix} \Phi_{s1}(i_f) \\ \Phi_{s2}(i_f) \end{bmatrix} = \begin{bmatrix} L_{s1} & 0 \\ 0 & L_{s2} \end{bmatrix} \begin{bmatrix} i_{s1} \\ i_{s2} \end{bmatrix} + \begin{bmatrix} \Phi_{s1r} & 0 \\ 0 & \Phi_{s2r} \end{bmatrix} + \begin{bmatrix} \Phi_m(i_f) \\ \Phi_m(i_f) \end{bmatrix},$$

where

$$L_{s_i} = \begin{bmatrix} L_{1s_i} + L_{ms_i} & -\frac{L_{ms_i}}{2} & -\frac{L_{ms_i}}{2} \\ -\frac{L_{ms_i}}{2} & L_{1s_i} + L_{ms_i} & L_{1s_i} + L_{ms_i} \\ L_{1s_i} + L_{ms_i} & -\frac{L_{ms_i}}{2} & L_{1s_i} + L_{ms_i} \end{bmatrix}, \quad i = 1, 2.$$

The magnitude of inductances L_q and L_d is the result of the relationship between the phase inductance and the position of the rotor. For example, the inductance measured between phases a and b (when c is opened) is described by the following equation

$$L_{ab} = L_d + L_q + (L_q - L_d) \cos\left(2\theta_e + \frac{\pi}{3}\right),$$

where θ_e is the electrical angle of the generator rotor position.

The block diagram of an axial flux synchronous generator with a double stator and a combined excitation system based on permanent magnets and an additional magnetizing winding in the MATLAB/Simulink software complex is shown in Fig. 2. It is developed by modifying the standard blocks with the differential equations shown above. A feature of this generator model is the presence of an additional control channel for the excitation voltage u_f , which is taken into account in the system of differential equations. With the help of voltage u_f it is possible to change the magnitude and direction of the magnetizing current i_f , which allows you to stabilize the output power or voltage of the generator when the

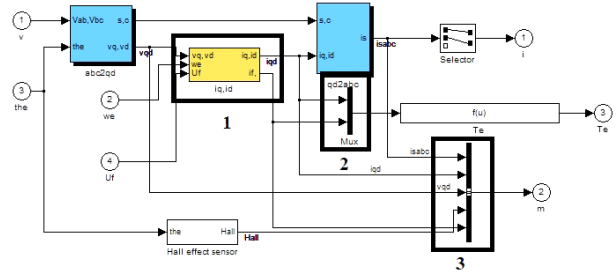


Fig. 2. Block diagram of magnetolectric synchronous generator with axial magnetic flux and double stator

load or rotor speed changes. Block 1 implements the first three equations, and block 2 forms the variables to implement the electromagnetic moment. Block 3 provides indication and control of generator variables. The block diagram also contains blocks for converting the generator voltage from the abc coordinate system to the d and q coordinate system, forming the stator currents i_q , i_d and feedback on the speed of rotor rotation.

Based on the model of the electric generator, a simulation mathematical model of the autonomous wind power plant was developed (Fig. 3).

The model is built in such a way that when the load of the generator (block 2, Fig. 3) changes, the electromagnetic moment of the generator (block 4, Figs. 3, 2) changes, which leads to a change in the operating point on the mechanical characteristics of the rotor of the wind turbine, which is an important feature of the developed model. Conversely, when the wind parameters change, the output parameters of the generator also change: its output power P_1 , voltage U_1 , current I_1 and electromagnetic moment.

Simulation results. The study on the wind turbine was carried out when the wind speed changed and when working on an active load in a DC circuit connected to the generator through an unregulated bridge rectifier. The influence on the process of electricity generation by the wind turbine was considered, provided that an additional capacity is connected to the output terminals of the generator in the AC circuit and when controlling the current of the additional magnetizing winding. The numerical experiment program is as follows:

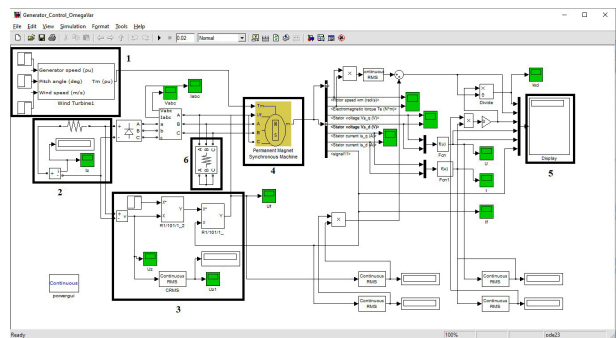


Fig. 3. Simulation mathematical model of autonomous wind power plant:

1 – wind turbine rotor block with NASA 40 blade and wind parameter settings; 2 – load block in the rectified DC voltage circuit; 3 – block of the system of automatic regulation of the rectified voltage of the generator; 4 – AFGPM block, whose structure is shown in Fig. 2; 5 – block of indication of simulation results, which includes phase voltage U_{ij} , phase current I_{ij} , full active power of the generator P_1 , parameters of the magnetization winding and efficiency of the generator under current parameters; 6 – a block that allows you to change the type of load connected to the clamps of the alternating voltage generator, namely – active, inductive, capacitive or any combination thereof

- 1) the active load in the DC circuit is assumed to be constant $R = \text{const}$ and equal to the average value of the internal resistance of the battery (block 2, Fig. 3);
- 2) the excitation voltage of the magnetization winding is set equal to zero (block 3, Fig. 3);
- 3) the load in the alternating current circuit is disconnected (block 6, Fig. 3);
- 4) the study on the operation of the wind power plant under variable wind speed in the range from 3 to 5 m/s was carried out. In particular, the fixation of the voltage, current and active power values U_{1ph} , I_{1ph} , P_1 . The values of the specified wind speed correspond to the values of the statistical average wind speed for Kyiv region;
- 5) points 1 and 4 are repeated when connecting an additional capacitor to the clamps of the $C = 30 \mu\text{F}$ generator (block 6, Fig. 3);
- 6) points 1 and 4 are repeated when constant voltage applied to the magnetization winding u_f (block 3, Fig. 3).

The results of calculations of the characteristics without control of the wind turbine – electric generator system for a wind speed of 5 m/s and a constant load are given in Table 2.

Table 2 shows:

- the speed of rotation of the turbine, r.u. – speed of rotation of the turbine in relative units, which is selected from the initial characteristics of the wind turbine;
- output power of the wind turbine, r.u. – the output power of the wind turbine, which is developed at the specified input parameters of the wind turbine – generator system;
- generator voltage, V – voltage on the generator clamps at given input parameters of the wind turbine – generator system;
- generator current, A – generator phase current at a given load;
- active power of the generator $3f$, W – full output active power of the generator at the given parameters;
- generator rotor rotation speed, rpm – real generator shaft rotation speed;
- electromagnetic moment of the generator, $N \cdot m$ is electromagnetic moment of the generator at the given initial parameters.

According to the specified characteristics of the wind turbine, at certain values of the wind turbine rotation speed (at a given wind speed), negative values of the output power of the turbine and the rotation speed of the generator rotor are observed. This results from the fact that at the given initial values of the system, the generator switches to engine mode. At a given electrical load of the generator, the power of the wind turbine is not enough to maintain the active power of the generator, so the generator “overturns”. In real conditions, this means that the electric generator will stop.

Table 2

Characteristics of an uncontrolled wind turbine – electric generator system

Rotation speed of the turbine, r.u.	0.4	0.6	0.8	1	1.2	1.4
Output power of the wind turbine, r.u.	0.16	0.45	0.61	0.54	0.3	0.1
Generator current, A	0.32	0.59	0.59	0.4	0.19	0.1
Generator voltage, V	5.46	10.3	10.3	7.7	3.7	0.5
Active power of the generator $3f$, W	5.1	18.2	18.1	8.8	1.83	-0.5
Rotation speed of the generator rotor, rpm	17.5	31.6	31.6	24.5	11.6	1.4
Electromagnetic torque of the generator, $N \cdot m$	-0.43	-0.78	-0.78	-0.5	-0.4	-0.3

Fig. 4 shows the dependence of the output active power of the wind power plant for two wind speed values of 4 and 5 m/s on the speed of rotation of the rotor of the wind plant for following three cases:

- 1) under the condition that additional capacity is disconnected and there is no excitation voltage;
- 2) under the condition of additional capacity adding;
- 3) under the condition that excitation voltage is applied to the magnetization winding.

In the previous works by the authors, it was shown that for this design and power of the end generator, the optimal value of the magnetizing capacity is $\approx 30 \mu\text{F}$ per phase. The value of the voltage of the additional winding u_f was selected so that the value of the current in the additional winding was 1 A. At the same time, the control power of the additional winding is no more than 7.5 % of the useful power of the generator. In this case $u_f = 8V$.

As can be seen from Fig. 4, the maximum output power of the generator is obtained at a relative rotor rotation speed at $n = 0.6$ at wind speed of 4 m/s and at a rotor speed of the wind turbine at $n = 0.7$ at wind speed of 5 m/s. The maximum power of the generator is correlated with the maximum mechanical power of the rotor of the wind turbine at the specified parameters of the blade [1].

Connecting additional capacity to the stator winding of a three-phase generator leads to appearance of additional reactive power that magnetizes the ferromagnetic system of the generator. This leads to an increase in the active power on the generator clamps by 7–12 % for a wind speed of 4 m/s and by 8–16 % for a wind speed of 5 m/s, depending on the rotation speed of the rotor of the wind turbine. As the wind speed increases, this effect improves, which is explained by the influence of the aerodynamic characteristics of the rotor of the wind turbine.

The drop in the active power of the generator with the further increase in the rotation speed of the rotor of the wind turbine is explained by the increase in mechanical losses, the additional saturation of the ferromagnetic system, the increase in active losses in the stator winding and the drop in voltage on the active and reactive resistances of the stator circuit.

When a voltage of constant magnitude u_f is applied to the magnetizing winding, an increase in the active power of the generator is observed. This is explained by an increase in the main magnetic flux and the magnitude of the induced EMF in the armature winding, respectively. Since the magnetic flux of the additional winding is closed through the ferromagnetic system of the stator, this circumstance limits the maximum value of the voltage of the additional winding u_f , and therefore the maximum value of the active power P_1 . Further increase in voltage u_f leads to saturation of the ferromagnetic core of the stator and the ferromagnetic system as a whole, which leads to

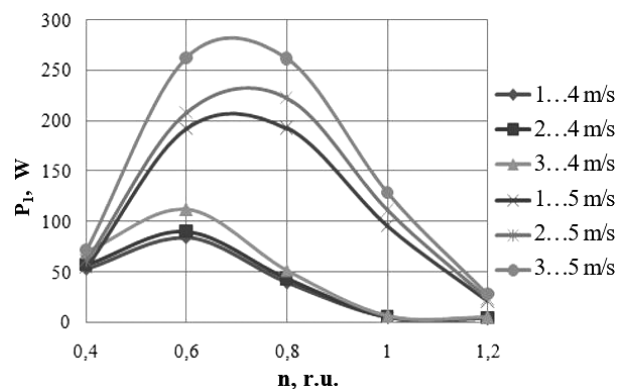


Fig. 4. Dependence of the output active power of the wind power plant on the rotation speed of the rotor of the wind plant at different values of the wind speed

a decrease in the useful power of the generator. By applying voltage to the additional winding, it is possible to increase the output of active power by approximately 32 % at a wind speed of 4 m/s and by 35 % at a wind speed of 5 m/s.

Thus, the obtained research results show that it is possible to adjust the output power of the generator when the wind speed changes in the range of 3–5 m/s. This makes it possible to ensure the operation of the generator at the maximum output power of the rotor of the wind turbine (for each value of the wind speed), and therefore the task of increasing the efficiency of the conversion of mechanical wind energy into electrical energy is solved.

One of the main functional parameters of the generation system is the output voltage of the electric generator [2, 3]. The stability and reliability of the autonomous consumer depends on it. Fig. 5 shows the dependence of the output voltage of the generator of the wind turbine at wind speeds of 4 and 5 m/s on the speed of rotation of the rotor of the wind turbine for following three cases.

When the speed of rotation of the rotor increases, the amount of EMF induced in the armature winding increases, and, therefore, so does the amount of the voltage, which reaches its maximum at the relative speed of rotation of the rotor of the wind turbine at $n = 0.6$ at wind speed of 4 m/s and at the speed of the rotor of the wind turbine at $n = 0.7$ at wind speed of 5 m/s. The further voltage drop at the generator terminals is associated with a decrease in the mechanical power of the rotor of the wind turbine, the action of the demagnetizing reaction of the armature and the voltage drop at the active and reactive resistances of the stator winding circuit.

When the capacitor is connected to the armature winding of the generator, a magnetizing reaction of the armature occurs, which leads to an increase in the main magnetic flux. At the same time, the voltage increase at the generator terminals is 6–12 % at a wind speed of 4 m/s and 7–15 % at a wind speed of 5 m/s.

When applying voltage u_f on the additional magnetizing winding, the voltage on the generator terminals increases by 16 % at a wind speed of 4 m/s and by 17.5 % at a wind speed of 5 m/s. The increase in voltage is due to the increase in the magnitude of the main magnetic flux, and therefore the EMF induced in the armature winding.

The operation of the simulated mathematical model is coordinated with the mechanical characteristics of the rotor of the wind turbine. The dependence of the mechanical moment on the generator shaft on the rotation speed of the rotor of the wind turbine at constant load is given in Fig. 6.

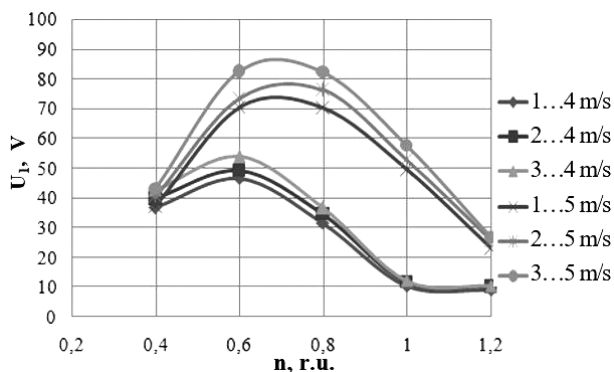


Fig. 5. Dependence of the output voltage of the wind turbine generator on the speed of rotation of the rotor at different values of the wind speed:

1 – under the condition that additional capacity is disconnected and there is no excitation voltage; 2 – under the condition of additional capacity adding; 3 – under the condition that excitation voltage is applied to the magnetization winding

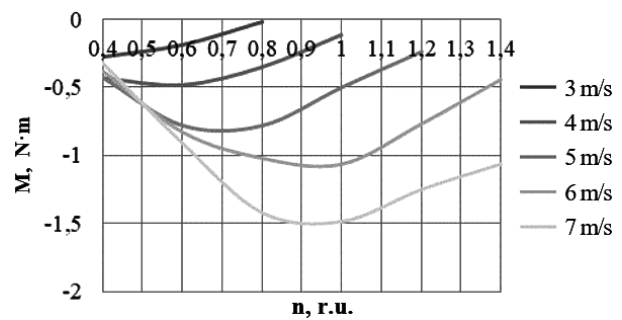


Fig. 6. Dependence of the mechanical moment on the shaft on the speed of the rotor rotation

Negative values of the electromagnetic moment correspond to the generator mode of operation of the electric machine. With an increase in the frequency of rotation of the rotor, a gradual decrease in the magnitude of the electromagnetic moment is observed. This is explained by the fact that the frequency of remagnetization of the magnetic core increases, the losses in the steel increase and the saturation of the magnetic core increases. These factors lead to a further decrease in the magnitude of the electromagnetic moment of the generator. At the same time, feedback is implemented when the load parameters of the generator and rotor of the wind turbine are changed.

Conclusions. The use of an axial flux magnetolectric generator with a double stator and a combined excitation system based on permanent magnets and a magnetization winding allows increasing the specific power of the wind generating installation, due to the rational use of the useful volume of the electric generator. The use of an additional magnetization winding allows us to widely adjust the output parameters of the autonomous wind power plant.

A mathematical and numerical simulation model of an autonomous wind power plant based on an axial flux generator with hybrid excitation has been developed, which takes into account the two-sided arrangement of the generator stator and additional non-contact magnetization winding. The obtained model allows conducting research on the efficiency of converting wind energy into electrical energy under conditions of change in wind speed, type and amount of load.

Based on the results of numerous experimental studies, comparative indicators of the effectiveness of the use of additional capacity on the output terminals of the generator and the additional magnetization winding for changes in wind speed and for constant active load were obtained. With additional capacity, the active power of the generator increases by 7–16 %, and the voltage by 6–15 %. The additional magnetization winding provides an increase in active power by 32–35 %, and voltage increases by 16–17.5 %.

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Математичне моделювання автономної вітроелектричної установки на основі магнітоелектричного генератора

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Мета. Розробка математичної моделі автономної вітроелектричної установки на основі торцевого електрогенератора з подвійним статором і комбінованим збудженням для оцінки методів підвищення ефективності перетворення механічної енергії вітру в електричну.

Методика. Для проведення дослідження в роботі використовувались методи загальної теорії вітроелектричних установок, методи математичного моделювання, в основі яких лежить чисельне розв'язання нелінійних диференціальних рівнянь для оцінки способів корекції вихідної потужності в середовищі Matlab-Simulink шляхом модифікації стандартних блоків.

Результати. У роботі розроблена чисельна імітаційна математична модель автономної вітроелектричної установки у складі із магнітоелектричним генератором з аксіальним магнітним потоком із комбінованим збудженням і подвійним статором. Модель створена з метою дослідження параметрів і характеристик установки, а також оцінки методів і засобів підвищення ефективності перетворення енергії вітру в електричну енергію. За результатами досліджень встановлено, що більш ефективним методом регулювання вихідної потужності генератора у складі вітроустановки є використання додаткової обмотки для підмагнічування, порівняно з використанням додаткової ємності. Остання забезпечує до 7–16 % зростання вихідної потужності, у той час як використання обмотки підмагнічування дозволяє підвищити вихідну потужність до 32–35 %. Отримані авторами результати дозволяють надалі розвивати ряд методів підвищення ефективності перетворення механічної енергії ротора вітрогенератора в електричну.

Наукова новизна. Розроблена вперше математична модель, на відміну від існуючих, ураховує наявність подвійного статора, додаткової обмотки для підмагнічування магнітної системи та аксіального характеру замикання основного й додаткового магнітного потоку. Розроблена модель також ураховує зміну параметрів електрогенератора з аксіальним магнітним потоком при зміні параметрів вітру, ротора вітрової установки й навантаження. Модель розроблена для аналізу можливості регулювання вихідної потужності електрогенератора при зміні швидкості вітру.

Практична значимість. Результати моделювання свідчать про перспективність промислової реалізації вітроелектричної установки на основі магнітоелектричного генератора для їх використання в якості автономних електроустановок та у складі маневрених енергосистем.

Ключові слова: автономна вітроелектрична установка, торцевий генератор, подвійний статор, постійні магніти, обмотка підмагнічування

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