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Design and Modeling of Dynamic Modes of Low Speed Electric Generators for Electric Power Generation from Renewable Energy Sources

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Abstract. This article provides information on the current state and prospects for the development of renewable energy sources in the world and in our country, as well as on the choice of efficient power generators to ensure stable operation at low flows of micro hydroelectric and wind power plants. When designing a simulation model and a theoretical study of the dynamic modes of an electric generator, Solidworks and Matlab/Simulink software were used. Mathematical expressions are given for the output parameters of an electric generator (voltage, current, frequency, electromagnetic power, etc.) depending on its geometric dimensions, the number of permanent magnes, the connection diagram and the number of turns of the stator winding, the minimum distance between the stator and the rotor. According to the results of scientific research, an electric generator was developed with a power of 600 W, with the number of permanent magnets 32, the number of windings in each phase of the stator 4, the number of turns in each winding 200, the stator and rotor of which rotate in opposite directions. It was found that with opposite rotation of the stator and rotor relative to each other, the electromagnetic torque and electromagnetic power of the generator increase by 20% compared to a rotating rotor and a stationary stator of an electric generator. It is scientifically substantiated that by using this type of electric generator in micro hydroelectric power plants and wind power plants, it is possible to significantly increase the efficiency of installations at low currents.

INTRODUCTION

In the world, special attention is paid to the use of renewable energy sources to stabilize problems related to energy security, saving fuel and energy resources and environmental protection [1-15]. Since renewable energy sources are environmentally friendly and inexhaustible, the efficient use of these energy sources is constantly evolving [16-28]. Considering that the planned increase in the share of the use of renewable energy sources by 32%, energy efficiency by 32.5%, reduction of emissions and greenhouse gases by at least 40% at the global level in the period from 2021 to 2030 [28], requires the implementation in practice of wind energy installations that increase the continuity and reliability of energy.

Certain results have been achieved in the energy networks of our republic and comprehensive measures have been taken to develop improved wind power plants based on energy-saving technologies. The Strategy of Actions for the Further Development of the Republic of Uzbekistan for 2017-2021 defines the tasks: "... the introduction of innovative technologies, scientific and technical developments in the development of renewable energy and energy efficiency, expansion of production and localization of energy-saving equipment and devices, including through the transfer of technologies and the creation of engineering centers ..." [27].

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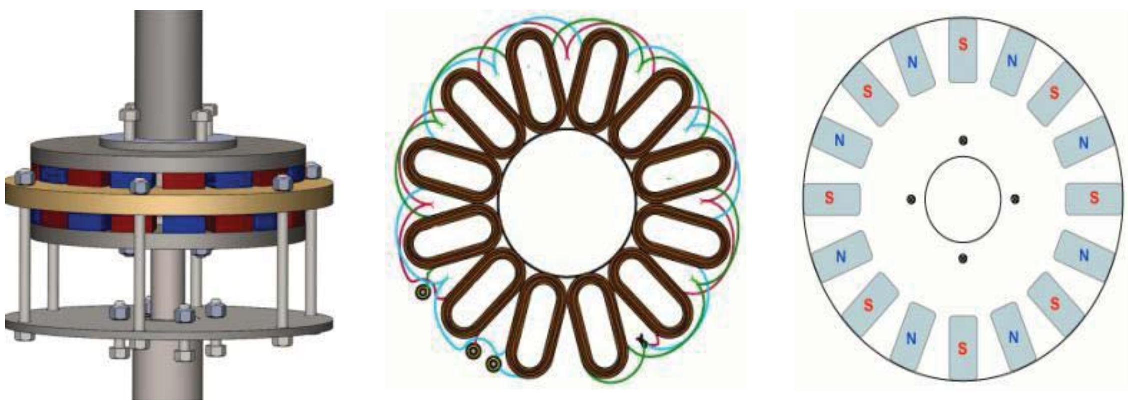
It is important to develop the use of renewable energy sources, in particular wind and water energy in regions where there are problems with a shortage of electricity [29-33]. Through the development and implementation of micro-hydroelectric power plants [16, 17, 18, 23, 24] and wind power plants adapted to climatic conditions, it is possible to provide uninterrupted and reliable electricity to autonomous consumers located far from the central power supply and to develop the socio-economic sphere in these regions.
Wind energy has been used for almost two thousand years, with windmills harnessing wind power using a constant speed rotor assembly from 200 Bc. Wind energy is an obvious choice among all renewable energy sources for generating electricity because it is free, abundant, and internationally available. A wind turbine uses a generator to convert the captured kinetic energy in the wind to electrical energy. Wind turbine generators should utilize more dependable, effective, and efficient structures to enhance wind power capture and create higher quality output electricity [29-33]. This work aims to establish the optimal generator designs of dynamic modes of low speed electric generators for electric power, with criteria based on the speed range, and power quality.

DESIGN OF POWER GENERATORS AND MODELING OF DYNAMIC MODES

To increase the efficiency of micro hydroelectric power plants and wind power plants operating at low flows, it is necessary to correctly select the electric generators used in these devices. Currently, three types of power generators are used in wind turbines and micro hydroelectric power plants. These are alternators, asynchronous generators, synchronous generators.



a b c

FIGURE 1. Low-speed electric generator device: a - general view of the generator; b - connection diagram of the stator winding;c - appearance of the generator rotor

TABLE 1. The technical parameters of the developed electric generator

Rated power (W)	600	Number of turns in one winding	200
Number of windings	12	Brand and cross-section of the winding wire, mm^2	PETV-15 0.87
Number of phases	3	Air gap distance between magnet and stator, (mm)	1.5
Number of pole pairs of permanent magnets	16	Rotor outer diameter, mm	220
Brand and dimensions of magnets, mm	NdFeB, N48 40x15x10	Inner diameter of the rotor, mm	80
Magnetic field induction of permanent magnets, T	1.25-1.3	Rotor material and thickness, mm	Steel 10
Magnetic field strength of permanent magnets, kA/m	955	Mass of permanent magnets, kg (32 pcs)	1.12
Stator outer diameter, mm	250	Rotor weight, kg	3
Stator inner diameter, mm	100	Total mass of the stator, kg	2
Stator thickness (mm)	18	Stator winding connection diagram	star

The use of multi-pole electric generators with permanent magnets in wind power plants and micro-hydroelectric power plants of low power is superior in their simplicity of design and efficient operation at low flows in relation to other types of electric generators.
Figure 1 a) shows a 3D model of an electric generator, b) a connection diagram of the stator winding of an electric generator, c) the location of magnets on the rotor of the generator. The figure shows that each of the stator phases consists of 4 windings and is connected by a star connection. Permanent magnets with 16 pole pairs are located on the rotor of the generator.
Table 1 shows the technical parameters of the developed electric generator, the stator and rotor of which rotate in opposite directions. This type of generators are currently used in wind power plants and micro-hydroelectric power plants operating at low flows.
Mathematical modeling in the energy sector, even the simplest and most common devices, leads to huge cost savings and improved product quality. The more complex the designed object, the more important is the role of modeling in its study and creation.
Representation of any electrical machine in any software package begins with the construction of equations describing this machine, and the introduction of some assumptions to simplify the calculations.
When simulating a dynamic model of an electric generator consisting of permanent magnets, we use an equivalent switching circuit with axes d and q. The generator dynamic model can be simplified by applying the circuits shown in Figure 2.

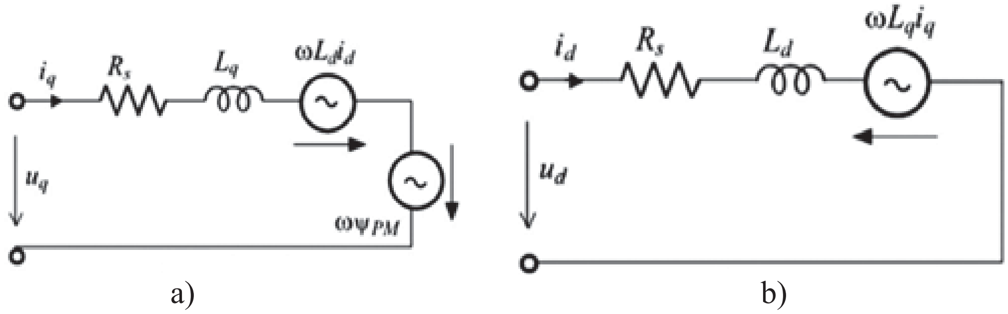


FIGURE 2. Equivalent generator circuit (a) q-axis and (b) d-axis

The equation of voltage generated in time in the stator winding of synchronous generators consisting of permanent magnets [34, 35, 36]:

$$\begin{cases} U_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \\ U_q = R_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega\psi_{PM} \end{cases}, \quad (1)$$

Calculation of the electromagnetic power of a three-phase electric generator consisting of permanent magnets is determined by the following formula [37, 38]:

$$P_э = \frac{3}{2}\omega[\psi_{PM} + (L_d - L_q)i_d]i_q \,, \quad (2)$$

The electromechanical moment of the generator consisting of the number of pole pairs p is determined by the formula [39]:

$$M_э = \frac{3}{2}p[\psi_{PM} + (L_d - L_q)i_d]i_q \,, \quad (3)$$

where ψ_{PM} is the magnetic flux, Wb.

$$\psi_{PM} = \frac{\sqrt{2}E_ф}{\omega} \,, \quad (4)$$

The electromagnetic speed of the generator, the stator and rotor of which rotate in opposite directions, is determined by the formula:

$$\omega = p(\omega_{м1} + \omega_{м2}) \,, \quad (5)$$

where p is the number of pole pairs.

The moment of inertia of dynamic simulation of the generator is determined using the expression [40]:

$$J\frac{d\omega_м}{dt} = M_м - M_э - k\omega_м\ , \tag{6}$$

where J is the moment of inertia of the rotor mass kg · m^2, M_m va M_e is the mechanical and electromagnetic moment of the generator, N·m; k - coefficient of friction, ω_m - mechanical angular velocity of the generator, rad/s.

Calculation of the stator winding inductance [41]:

along the d and q axes

$$\begin{cases} L_d = m\mu_0\frac{1}{\pi}\cdot(\frac{Nk_w}{p})^2\cdot\frac{(R_1^2-R_2^2)}{g'}\cdot k_{fd} \\ L_q = m\mu_0\frac{1}{\pi}\cdot(\frac{Nk_w}{p})^2\cdot\frac{(R_1^2-R_2^2)}{g'_q}\cdot k_{fq} \end{cases}, \tag{7}$$

where N is the number of turns in one winding; R_1- outer diameter of the stator, m; R_2- stator inner diameter, m; p is the number of pole pairs; k_w is the duty cycle of the stator winding; m is the number of phases.

For the configuration of the surface of permanent magnets, the equivalent air gap along the d and q axes is determined by the following expressions [42]

in the case of a core without a stator:

$$\begin{cases} g' = 2[(g + 0{,}5t_w)\cdot k_{sat} + \frac{h_m}{\mu_{rrec}}] \\ g'_q = 2(g + 0{,}5t_w + h_m) \end{cases}, \tag{8}$$

At $\mu_{rrec}\approx 1$, the surface configuration of permanent magnets is assumed to be $k_{fq} = k_{fd} = 1$. Then the inductance of the armature response along the d and q axes is determined as follows:

$$L_d = L_q = m\mu_0\frac{1}{\pi}\cdot(\frac{Nk_w}{p})^2\cdot\frac{(R_1^2-R_2^2)}{g'}, \tag{9}$$

EMF generated in the stator winding of the generator is determined by the following relationship:

$$E_\phi = \sqrt{2}\pi f p N k_w \Phi_\phi = \sqrt{2}\pi n N k_w B_g(R_1^2 - R_2^2)\ , \tag{10}$$

where Φ_ϕ- magnetic flux, Wb; B_g-magnetic induction, T; f - frequency, 1/s.

RESULTS

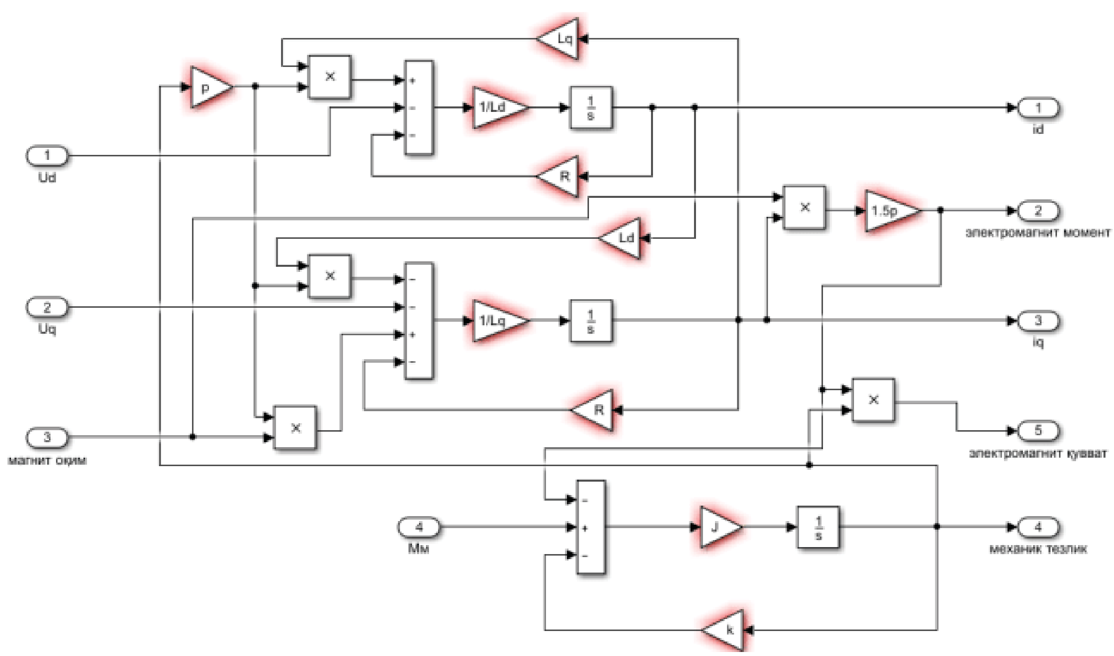


FIGURE 3. Simulation model of an electric generator built in the Matlab/Simulink program

Figure 3 shows the mathematical model of an electric generator, the stator and rotor of which rotate in opposite directions, developed in the Matlab/Simulink package.

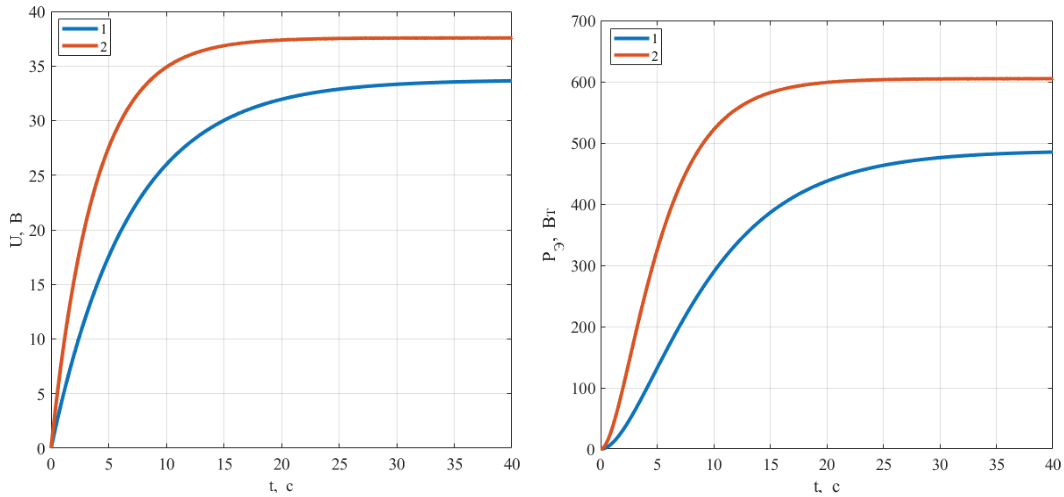


FIGURE 4. Curves comparing the values of two types of generators in dynamic mode

Figure 4 shows graphs comparing the values of two power generators. According to which, the generators were calculated and compared, in the first case, a generator with a fixed stator and a rotating rotor, in the second case, a generator with a stator and a rotor rotating in opposite directions was considered. Figure 4 (a) shows the relative voltages generated in the stator winding for the above cases.

An increase in the open-circuit voltage by 10% was found in the case when the stator and rotor of the generator rotate in opposite directions with respect to the case when the stator is stationary and the rotor rotates.

Figure 4 (b) shows a graph comparing the electromagnetic power of the two generators. It was found that in the case when the stator and rotor of the generator rotate in opposite directions, the electromagnetic moment and the electromagnetic power increase by 20% in relation to the case when the stator of the generator is stationary and the rotor rotates. Expression (2) was used to calculate this output parameter.

When obtaining the above results, the frequency of rotation of the stator and rotor of the generator was taken equal to 300 rpm.

CONCLUSIONS

1. Analysis of research on the use of renewable energy sources in the world has shown that the stabilization of environmental problems, energy saving is one of the important strategic directions for the development of the economic and social spheres.
2. It was studied that through the use of micro-hydroelectric power plants and wind power plants adapted to climatic conditions, efficiently operating at low flows, it is possible to provide uninterrupted and reliable electricity to autonomous consumers located far from the central power supply.
3. In the design and theoretical study in dynamic modes of a low-speed electric generator with a simple design, which increases the efficiency of operation at low flows of micro-hydroelectric power plants and wind power plants, Solidworks and Matlab / Simulink software were used.
4. It was found that in the case when the stator and rotor of the developed low-speed generator rotate in opposite directions, the electromagnetic moment and the electromagnetic power increase by 20% in relation to the case when the stator of the generator is stationary and the rotor rotates.

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