

Design And Dynamic Modelling Of A Low-Speed Electric Generator For Electricity Generation From Renewable Energy Sources

Safarov Alisher, Bukhara State Technical University, 200100, 15 Q. Murtazoyev Street, Bukhara city, Uzbekistan

[*a-safarov91@mail.ru](mailto:a-safarov91@mail.ru)

Xojiyev Muhammadjon, Bukhara State Technical University, 200100, 15 Q. Murtazoyev Street, Bukhara city, Uzbekistan

[*xojiyevmuhammadjon5@gmail.com](mailto:xojiyevmuhammadjon5@gmail.com)

Abstract. The article presents information on the current state and development prospects of renewable energy utilization in the world and in the Republic of Uzbekistan, as well as on the selection of efficient electric generators to ensure the stable operation of wind and micro-hydropower systems under low-flow conditions. The availability of energy resources in the form of low-speed wind flows and low-head irrigation canals across large areas of our region creates opportunities for continuous electricity generation using low-speed electric generators. Considering that wind and micro-hydropower turbines operating under low-flow conditions are driven at relatively low rotational speeds, a simple-structured multipole electric generator based on permanent magnets has been designed for these systems. In this generator, the stator and rotor rotate in opposite directions relative to each other. SolidWorks was used for the design of the electric generator, while MATLAB/Simulink was employed for simulation modelling and theoretical investigation of its dynamic operating modes. Mathematical relationships describing the variation of the generator's output parameters, including voltage, current, frequency, electromagnetic power, and other characteristics, depending on the geometric dimensions of the generator, the number of permanent magnets, the number of turns in the stator windings and their connection method, as well as the minimum air gap between the rotor and stator, are presented. Based on the results of the conducted research, a 600 W electric generator with oppositely rotating stator and rotor was developed. The generator consists of 32 permanent magnets, with 4 windings in each phase of the stator and 200 turns in each winding. It was determined that when the stator and rotor rotate in opposite directions relative to each other, the electromagnetic torque and electromagnetic power of the generator increase by 20% compared with the operating mode in which the stator remains stationary and only the rotor rotates.

Keywords: renewable energy, wind energy, micro-hydropower, permanent-magnet generator, stator winding, rotor, electromagnetic systems.

Introduction: Globally, increasing attention is being paid to the use of renewable energy sources as a means of addressing problems related to energy security, the conservation of fuel and energy resources, and environmental protection. Since renewable energy sources are environmentally friendly and virtually inexhaustible, their efficient utilization is becoming increasingly widespread. Considering the global targets for the period from 2021 to 2030, which include reducing greenhouse gas emissions and waste by at least 40%, increasing the share of renewable energy sources to 32%, and improving energy efficiency by 32.5% [1], there is a growing need to introduce wind energy systems that can improve the continuity and reliability of electricity supply.

Currently, China, the United States, Brazil, India, and Germany are the leading countries in the utilization of renewable energy sources worldwide. The renewable energy utilization capacities in 2020 are presented in **Figure 1**. As shown in the figure, the largest installed capacity, 895 GW, was recorded in China [2].

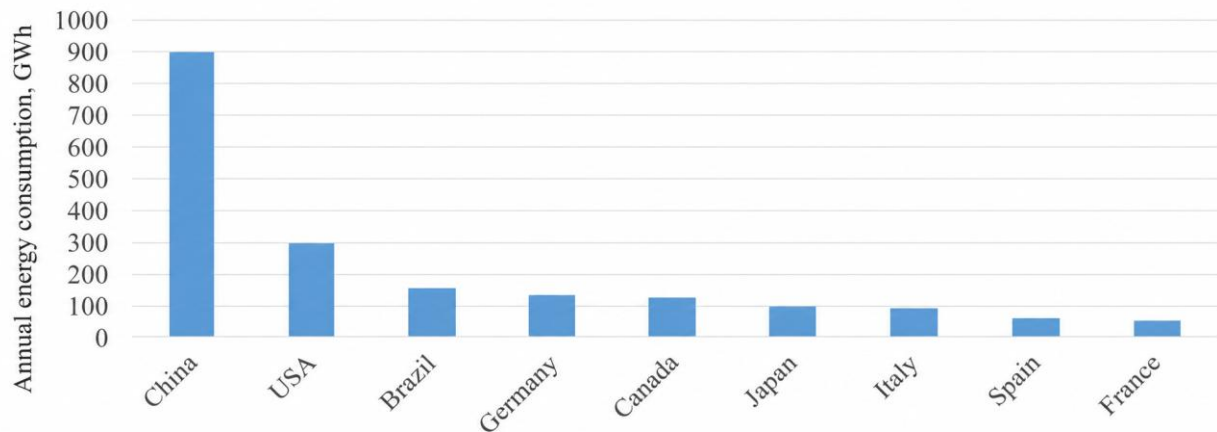


Figure 1. Renewable energy utilization capacities worldwide

In the energy sector of the Republic of Uzbekistan, comprehensive measures are being implemented to expand the utilization of renewable energy sources and to develop advanced renewable energy technologies based on energy-efficient solutions. As a result, significant progress has been achieved in this field. The Action Strategy for the Further Development of the Republic of Uzbekistan for 2017–2021 identified a number of important objectives, including “...expanding the use of renewable energy sources, reducing the energy intensity of production, introducing innovative technologies and scientific and technical developments in the field of renewable energy development, and increasing energy efficiency...” [3].

The development of wind and hydropower utilization from renewable energy sources is becoming increasingly important in regions where energy security remains a challenge [4]. The development and implementation of wind and micro-hydropower systems adapted to the climatic conditions of the region for autonomous electricity consumers located far from centralized power supply networks can contribute to the social and economic development of these areas.

Design and Dynamic Modelling of the Electric Generator: To improve the operating efficiency of wind and micro-hydropower systems under low-flow conditions, it is essential to properly select the electric generators used in these systems. Currently, three main types of electric generators are commonly used in wind and micro-hydropower systems: direct-current (DC) generators, induction generators, and synchronous generators. For small-scale wind and micro-hydropower systems, multipole permanent-magnet electric generators have significant advantages over other types of generators due to their simple construction and higher efficiency at low rotational speeds. These characteristics make them particularly suitable for energy systems operating under low-flow conditions.

Figure 2(a) shows the three-dimensional view of the electric generator, **Figure 2(b)** presents the connection scheme of the generator stator windings, and **Figure 2(c)** illustrates the arrangement of the permanent magnets on the generator rotor. The stator contains four windings in each phase, which are connected in a three-phase star (Y) configuration. The rotor of the electric generator is equipped with 16 pairs of permanent-magnet poles [5].

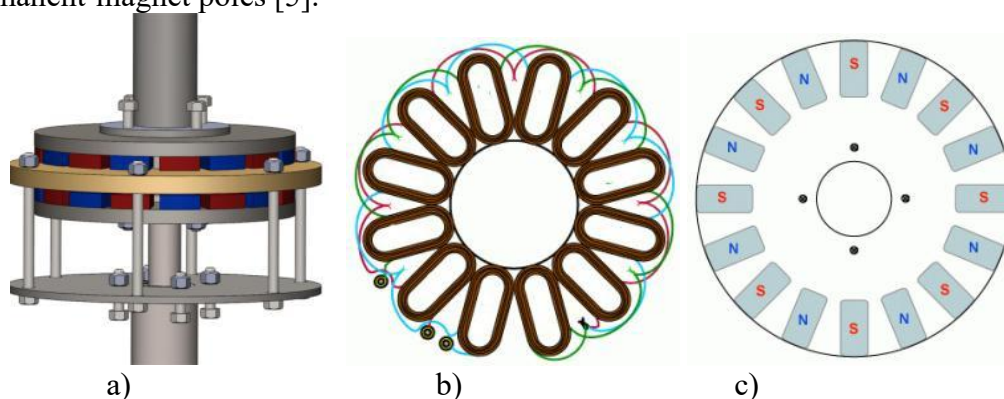


Figure 2. Structure of the electric generator. a – general view of the generator; b – stator winding connection scheme; c – external view of the generator rotor.

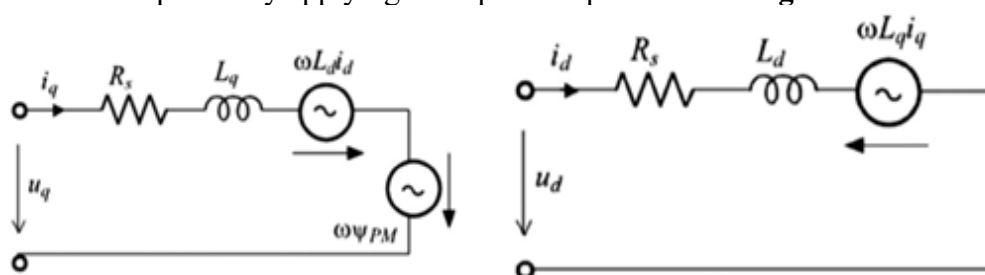
Mathematical modelling in the energy sector can significantly reduce costs and improve product quality, even for the simplest and most widely used systems and devices. In general, the more complex the system being designed, the more important the role of mathematical modelling becomes in its analysis, development, and implementation.

Table 1 presents the technical parameters of the electric generator with counter-rotating stator and rotor to be developed. Electric generators of this type are currently being used in wind and micro-hydropower systems operating under low-flow conditions.

Table 1.

Parameter	Value	Parameter	Value
Rated power, (W)	600	Number of turns per winding	200
Number of windings	12	Type and cross-sectional area of winding wire, mm ²	PET-15 / 0.87
Number of phases	3	Air gap width between magnet and stator, mm	1,5
Number of permanent magnet pole pairs	16	Rotor outer diameter, mm	220
Magnet type and dimensions, mm	NdFeB, N48 / 40x15x10	Rotor inner diameter, mm	80
Magnetic 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 mass, kg	3
Stator inner diameter, mm	100	Total stator mass, kg	2
Stator thickness, mm	18	Winding connection	Star (Y)

The representation of any electric machine in a software environment begins with the formulation of equations describing the machine and the introduction of certain assumptions to simplify the computational procedures. Accordingly, the periodic coefficients in the differential equations of a synchronous machine can be eliminated by expressing the machine variables that characterize the processes—such as magnetic flux, current, and voltage in each phase of the three-phase system—in terms of transformed variables associated with a new coordinate system. To model the dynamic behavior of the vertical-axis electric generator based on permanent magnets, an equivalent d–q axis transformation model is employed. The dynamic model of the generator can be simplified by applying the equations presented in **Figure 3**.



a) b)
Figure 3. Equivalent circuit of the generator: (a) along the q-axis and (b) along the d-axis.

In synchronous generators with permanent magnets, the voltage equation generated in the stator winding as a function of time is given by [6,7,8]:

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

The electromagnetic power generated by a three-phase permanent-magnet generator is determined using the following expression [9,10,11]:

$$P_3 = \frac{3}{2} \omega [\psi_{PM} + (L_d - L_q) i_d] i_q, \quad (2)$$

The electromechanical torque of a generator with p- pole pairs is determined by the following expression [12,13]:

$$M_3 = \frac{3}{2} p [\psi_{PM} + (L_d - L_q) i_d] i_q, \quad (3)$$

where ψ_{PM} is magnetic flux vb:

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

The electromagnetic angular velocity of the generator when the stator and rotor rotate in opposite directions is determined by the following expression:

$$\omega = p(\omega_{M1} + \omega_{M2}), \quad (5)$$

where p- is the number of pole pairs.

The moment of inertia used in the dynamic modeling of the generator is determined from the following expression [14,15]:

$$J \frac{d\omega_M}{dt} = M_M - M_E - k\omega_M, \quad (6)$$

where J- is the moment of inertia of the rotor mass, kg·m²; M_M and M_3 are the mechanical and electromagnetic torques of the generator, respectively, N·m; k- is the friction coefficient; and ω_M — is the mechanical angular velocity of the generator, rad/s.

The stator winding inductance is calculated as follows [16,17]:

Along the d-axis and the q- axis respectively:

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

Where N-is the number of windings in one coil; R_1 — pairs of poles is the diameter, m; R_2 — is the inner diameter of the stator, m; p — number of pole pairs; k_w — stator winding filling factor; m — number of phases.

For the surface configuration of the permanent magnets, the equivalent air-gap lengths along the d- and q-axes are determined using the following expressions [18],

for the case of a coreless stator:

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

If $\mu_{rec} \approx 1$ is satisfied, the surface configuration of the permanent magnets is assumed to be $k_{fq} = k_{fd} = 1$. In this case, the armature-reaction inductances along the d- and q-axes can be reduced to the following simplified expression:

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

The electromotive force (EMF) generated in the generator windings is determined by the following relationship [19,20]:

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

where Φ_ϕ – is the magnetic flux, Wb; B_g – is the magnetic flux density, T; and f is the frequency, 1/c.

Figure 4 presents the mathematical model of an electric generator developed in the MATLAB/Simulink environment, in which the stator and rotor rotate in opposite directions relative to each other.

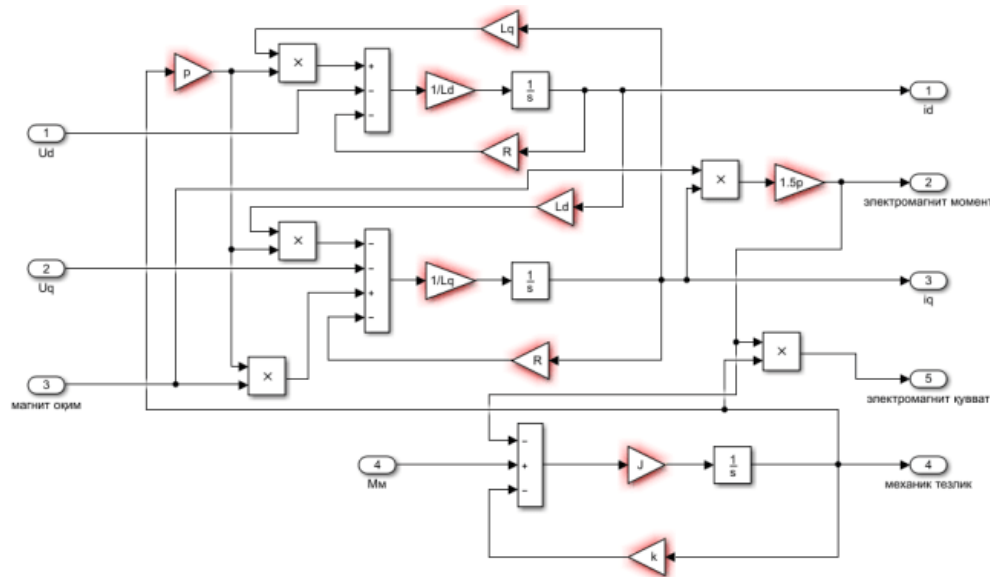


Figure 4. Developed simulation model of the electric generator in the MATLAB/Simulink environment.

Results: Figure 5 presents comparative plots of the parameters of two electric generators. The first generator represents the operating condition in which the stator is stationary and the rotor is rotating, whereas the second generator represents the operating condition in which the stator and rotor rotate in opposite directions. The output parameters of the two generators were calculated and compared. Figure 5(a) shows a comparison of the voltages induced in the stator windings under the above-mentioned operating conditions. The results indicate that when the stator and rotor of the generator rotate in opposite directions, the no-load voltage of the stator increases by 10% compared with the operating condition in which the stator is stationary and the rotor is rotating. Figure 5(b) presents a comparison of the electromagnetic power of the two generators. It was found that when the stator and rotor of the generator rotate in opposite directions, both the electromagnetic torque and electromagnetic power of the generator increase by 20% compared with the operating condition in which the stator is stationary and the rotor is rotating.

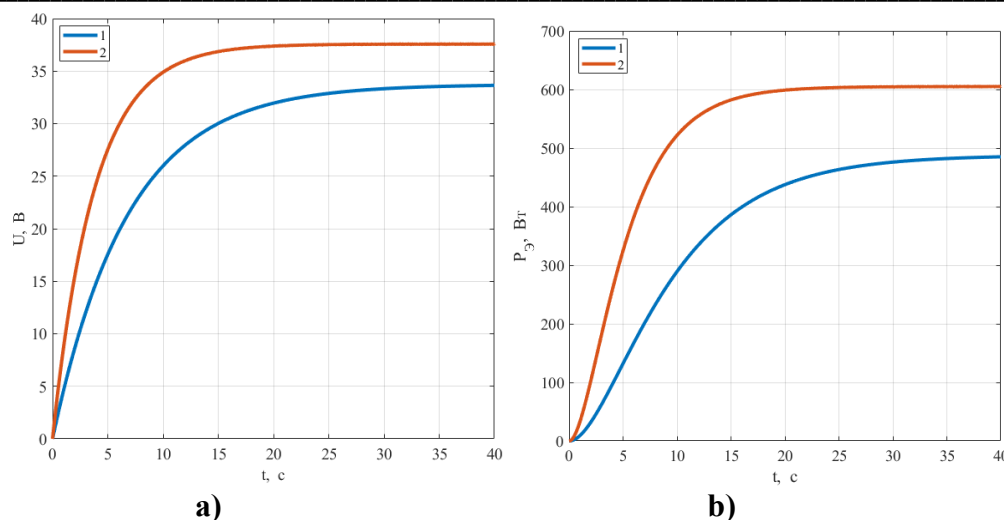


Figure 5. Comparative curves of the dynamic characteristics of the two types of electric generators.

Expression (2) was used to calculate this output parameter. To obtain the presented results, the mechanical rotational speed of both the stator and rotor of the generator was assumed to be **300 rpm**.

Conclusions: 1. An analysis of research on the utilization of renewable energy sources worldwide has shown that the development of renewable energy is one of the important strategic directions for mitigating environmental problems, conserving energy resources, and promoting economic and social development.

2. The possibility of providing autonomous electricity consumers located far from centralized power supply systems with continuous and reliable electrical energy through the use of wind and micro-hydroelectric power installations adapted to climatic conditions and capable of operating efficiently under low-flow conditions was investigated.

3. To improve the operating efficiency of wind and micro-hydroelectric power installations under low-flow conditions, an electric generator with a simple design and low rotational speed was developed. SolidWorks was used for the design of the electric generator, while MATLAB/Simulink was employed for the theoretical investigation of its simulation model and dynamic operating modes. It was established that when the stator and rotor of the developed electric generator rotate in opposite directions relative to each other, the electromagnetic torque and electromagnetic power of the generator increase by 20% compared with the operating condition in which the stator is stationary and the rotor is rotating.

References:

1. https://ec.europa.eu/clima/policies/strategies/2030_en
2. <https://www.statista.com/statistics/267233/renewable-energy-capacity-worldwide-by-country/>
3. Decree of the President of the Republic of Uzbekistan No. PF-4947, dated February 7, 2017, "On the Strategy of Actions for the Further Development of the Republic of Uzbekistan."
4. Allaev, K.R. *Electric Power Engineering of Uzbekistan and the World*. Tashkent: Fan va Texnologiya, 2009, p. 172.
5. Safarov, A.B. *Development of an Efficient Wind Energy Installation Adapted to the Climatic Conditions of Bukhara Region*. Dissertation Abstract, Karshi, 2021, p. 44.
6. Wang W., Weijun Wang., Mi H., Mao L., Zhang G., Hua Liu., Wen Y. Study and Optimal Design of a Direct-Driven Stator Coreless Axial Flux Permanent Magnet Synchronous Generator with Improved Dynamic Performance. *Energies*, 2018, 11(11):3162
7. Laxminarayan S.S., Singh M., Saifee A.H., Mittal A. Design, modeling and simulation of variable speed Axial Flux Permanent Magnet Wind Generator. *Sustainable Energy Technologies and Assessments*, Volume 19, February 2017, Pages 114-124
8. Safarov, A.B. "Development and Analysis of an Efficient Generator for Low-Power Wind Energy Installations." *Innovative Approaches to Solving Current Problems in the Development of the Food and Oil and Gas Chemical Industries: Proceedings of the International Scientific and Practical Conference*. Bukhara, 2020, No. 3, pp. 135–137.

9. Rossouw F.G. Analysis and Design of Axial Flux Permanent Magnet Wind Generator System for Direct Battery Charging Applications, dissertation, South Africa, 2009. Pp. 140
10. Kim J.H., Sarlioglu B. Preliminary design of axial flux permanent magnet machine for marine current turbine, in Proceedings of the 2013 IEEE IECON, pp. 3066-3071, November 2013.
11. Latoufis K.C., Messinis G.M., Kotsampopoulos P.C., Hatziaargyriou N.D. Axial Flux Permanent Magnet Generator Design for Low Cost Manufacturing of Small Wind Turbines. Wind engineering. Volume 36, No.4, 2012. Pp 411-442.
12. Sadullaev, N.N., Safarov, A.B. "Development of an Efficient Wind Generator Operating under Variable and Low Wind Flow Conditions." *Problems of Energy and Resource Conservation*, Tashkent, 2018, Nos. 3–4, pp. 228–334.
13. Yadav Y.K. A Savonius Wind Turbine With Electric Generator: Model and Test, dissertation, 2016.pp.89
14. Akello P.O. Development of a low cost direct-drive permanent magnet generator for power generation in small wind turbines, dissertation, 2016. pp.153
15. Taran N. Optimum Design of Axial Flux PM Machines based on Electromagnetic 3D FEA, dissertation, 2019.pp.232
16. M. Dhifli, H. Bali, Y. Laoubi, G. Verez, Y. Amara, G. Barakat. Modeling and prototyping of axial flux permanent magnet machine for small wind turbine. International Conference on Electrical Science and Technologies (2014), pp. 1-7
17. A. Rolan, A. Luna, G. Vazquez, D. Aguilar, G. Azevedo. Modeling of a variable speed wind turbine with a permanent magnet synchronous generator. IEEE Int Symp Ind Electron (2009), pp. 734-739
18. Gieras J.F., Wang R.J., Kamper M.J., Axial flux permanent magnet brushless machines. Springer Science, Business Media (2004). Pp. 345.
19. Aydin M, Huang S, Lipo TA. Axial flux permanent magnet disc machines: a review. Research report. University of Wisconsin-Madison; 2004.
20. Antonino Di Gerlando, Gianmaria Foglia, Matteo Felice Iacchetti, Roberto Perini. Member, axial flux pm machines with concentrated armature windings: design analysis and test validation of wind energy generators. IEEE Trans Ind Electron, 58 (2011), pp. 3795-3805.