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INVESTIGATION OF THE EFFICIENCY OF AN ELECTRIC GENERATOR WITH COUNTER-ROTATING ROTOR AND STATOR DESIGNED FOR OPERATION IN LOW-SPEED WATER AND WIND FLOWS

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Abstract. This article examines the design of a multi-pole electric generator featuring a counter-rotating rotor and stator, intended to enhance the efficiency of electricity generation from low-head water flows and low-speed wind currents. Utilizing conventional high-speed generators for low-speed energy flows necessitates the use of gearboxes or other mechanical transmission systems; this increases the structural complexity of the unit, leads to energy losses, and raises operational costs. To address this issue, a design utilizing the counter-rotation of the rotor and stator is proposed.

Key words: Renewable energy, low-speed wind, low-head water flow, electric generator, permanent magnet synchronous generator, radial flux, axial flux, counter-rotation, micro-hydropower plant (micro-HPP), wind energy.

Introduction. Today, the growing demand for electricity, the need to ensure the reliability of energy systems, and the imperative to reduce greenhouse gas emissions necessitate an expansion in the use of renewable energy sources. In particular, generating electricity from low-potential water flows and low-speed wind currents represents a promising avenue for small or remote areas. Research highlights the critical importance of utilizing generators with enhanced technical specifications when harnessing such low-potential water and wind resources.

This approach holds particular significance within the context of Uzbekistan. Studies indicate that regions such as Bukhara, Navoi, and Karakalpakstan offer promising potential for wind energy, while irrigation canals and other watercourses possess significant technical hydropower potential. Specifically, the Amu-Bukhara Canal has an estimated average annual technical hydropower potential of 19.2 MW, with an electricity generation capacity of 165.8 million kWh per year. However, a primary challenge in extracting energy from low-speed flows relates to the generator's nominal rotational speed. Traditional generators are often designed to operate at high rotational speeds, which limits the possibility of connecting them directly to low-speed turbines. Consequently, the use of gearboxes becomes necessary. However, gearboxes introduce additional mechanical losses, necessitate maintenance, and increase capital expenditures. To address this issue, this study examines the prospects of rotating the generator's rotor and stator in opposite directions.

Literature Review. Research conducted by scholars—both internationally and within the Republic—on the use of synchronous generators to achieve efficiency in electricity generation from low-velocity wind and water flows was analyzed. Factors that improve output parameters during the selection of generators and the design of new configurations were investigated. The analysis focused primarily on adapting electric generators for use with turbines that operate efficiently in low-velocity wind and water flows, while minimizing the need for gearboxes. This is because the use of gearboxes

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not only increases the weight, noise, and cost of the power-generating system but also has a negative impact on torque [1]. Currently, there is a growing global demand for electric generators capable of operating without a gearbox in low-velocity wind and water currents. In synchronous generators that utilize excitation windings, energy losses occur due to sparking at the brush-ring interface. The use of permanent-magnet synchronous generators can serve as an effective solution to these issues.

Generating electricity from the potential energy of water using high-speed turbines has a negative impact on the development of certain fish and plant species. Employing low-speed generators can be an effective way to address this problem. In an experiment involving a generator designed to operate in underwater currents of 0.3 m/s to 1 m/s, a 96% survival rate was observed among more than 300 fish species, demonstrating the advantages of using such low-speed generators [3].

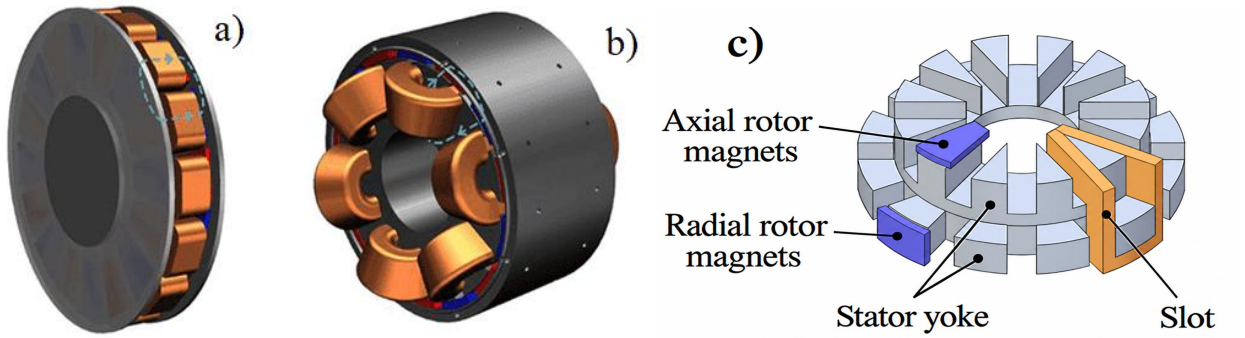


Figure 1. Classification of synchronous electric generators based on their structural design. a) Axial-flux synchronous generator (SG), b) Radial-flux SG [4], c) Hybrid axial-radial-flux SG [5].

Energy systems with a capacity of 500 W, capable of generating 12 kWh of energy per day, have been utilized. Currently, synchronous electric generators can be categorized into three types based on their structure: radial-flux, axial-flux, and hybrid axial-radial-flux synchronous generators (SGs) [6]. Radial-flux generators have traditionally been used in hydroelectric power plant installations. The generators employed in these hydropower facilities are multi-pole machines characterized by a low rotational speed.

In a study conducted by Ketut Wirtayasa et al., nine types of generators were evaluated; when operated at a rotational speed of 835 rpm, each winding produced an output of 410.2 W at a magnetic flux density of 1.65 T, with an efficiency of 91.93% [7]. In an axial-flux generator with a capacity of 30 kW—comprising two stators and one rotor—the power loss amounted to 1.7 kW when the maximum temperature reached 150°C [8]. In axial-flux machines, the use of carbon and glass-fiber materials in component fabrication—combined with high resistance to high-speed vibrations—has resulted in reduced generator mass and an extended service life. Lowering the generator's weight also leads to reduced costs for constructing the supporting structures for wind turbines or micro-hydropower plants.

In electric generators, constructing the stator from thin steel laminations has been shown to reduce magnetic flux leakage while strengthening the magnetic field. A generator configuration consisting of one stationary stator and two rotating rotors achieved an output power of 3.7 kW at a rotational speed of 1400 rpm [9]. At high rotational speeds, the additional heat generated in electric generators can increase winding resistance, negatively affect insulation, and—at sufficiently high temperatures—cause permanent magnets to lose their magnetic properties. Such conditions can

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diminish operational efficiency or lead to complete failure of the generator. In a design combining axial-flux and radial-flux configurations—featuring a 1.5 mm air gap and an output of 3.4 kW at 1000 rpm—efforts were made to increase the magnetic flux density; a magnetic induction of B = 1.4 T was achieved within the windings. At a rotational speed of 1000 rpm, the generator was able to supply a load of 7.4 A at a voltage of 565 V. A key result is that a power density of 336 kW/m³ was achieved at the generator's nominal rating [10]. In conclusion, axial-flux electric generators are characterized by their low weight, high power-to-volume ratio, and a wide operating speed range.

Comparison of axial-flux and radial-flux generators. Recently, extensive research has been conducted on the application of axial-flux generators and the improvement of their efficiency. Some studies suggest that axial-flux machines are more efficient than radial-flux machines [11]. Furthermore, many studies highlight that axial-flux generators are lighter, feature a simpler design, offer higher efficiency, are easier to maintain, and are both more cost-effective and highly reliable compared to radial-flux generators. Table 1 presents a comparison of axial-flux and radial-flux generators as evaluated by various researchers. The findings are summarized in the table, which compares the techno-economic indicators of 3 kW axial-flux and radial-flux generators [12].

Table 1.3. Comparison of technical and economic indicators for axial- and radial-flux synchronous generators. [11, 12, 13]

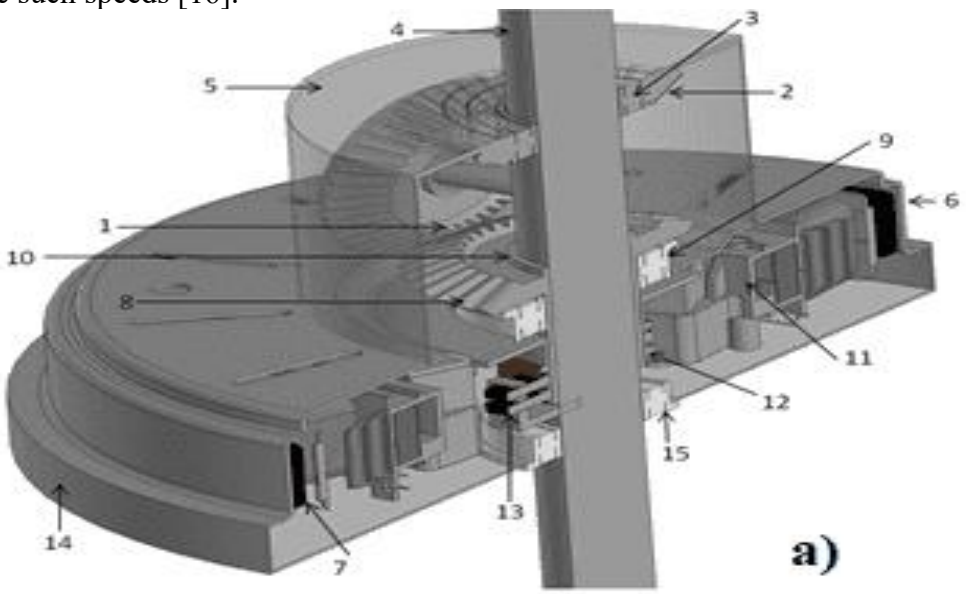
Nominal power 3 kW	AF-PMSG	RFOR-PMSG	RFIR-PMSG
Copper weight	11.64 kg	8.3 kg	9.14 kg
Steel (iron) weight	18.14 kg	32.8 kg	44.69 kg
Rotor shaft weight	Not available (data missing)	22.3 kg	5.41 kg
Total weight	39.84 kg	70.9 kg	59.39 kg
Efficiency	92 %	89.23 %	92.32 %
Number of turns per phase	2000	234	282
Turns per slot	500	39	47
Conductor diameter	0.56 mm^2	1.4 mm^2	1.4 mm^2
Phase resistance	12 Ω	3.4 Ω	2.54 Ω
Air gap length	1 mm	0.8 mm	1 mm
Number of poles (PM-rotor)	16	30	30
Outer radius	295 mm	250 mm	140 mm
Axial length	Not available (data missing)	300 mm	200 mm
Estimated cost of magnetic materials	609.8 EUR	535.65 EUR	478.12 EUR

A review of the literature indicates that, among various types of generators, the radial-flux generator is the most cost-effective.

This involves the counter-rotational movement of a generator's rotor and stator. A specialized design has been developed to facilitate the rotation of the stator and rotor in opposite directions. By integrating this design with a standard radial-flux electric generator, a counter-rotating generator system is created. Such generators are utilized to produce electrical energy by efficiently

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harnessing low-speed wind or water currents. A primary drawback of existing counter-rotating generator systems is their high cost and the difficulty of maintenance, both stemming from their complex structural design [14]. In configurations where separate turbines are assigned to the rotor and the stator, it has been observed—based on our literature review—that the wind speed reaching the rear turbine is reduced to two-thirds of the speed striking the front turbine. This disparity causes the rotor and stator to rotate at different speeds, leading to frequent fluctuations in the generator's output voltage and frequency. Consequently, there is a need to develop a mechanism that ensures the rotor and stator rotate at a uniform speed to address this issue [15]. Generating electricity from low-speed wind or water currents requires an electrical generator with a low rotational speed. Most currently available generators operate at high rotational speeds, necessitating the use of additional gear mechanisms to achieve such speeds [16].



a) picture. The mechanical energy generated by the wind or water flow turbine is transmitted to the gear wheel (2) at the top of the electric generator. The gear wheel (2) rotating in the direction of the turbine in the upper part of the electric generator is connected to the rotor (6) through the cover (5). As a result, the rotor (6) with permanent magnets (7) of opposite polarity moves in the direction of the turbine. The gear wheel (1) placed on the shaft (4) reverses the rotational movement transmitted from the gear wheel (2) to the gear wheel (8). The gear wheel (8) is connected to the stator (11) through the bushing (10) and moves against the movement of the turbine. Bearings (3,9,15) are used to ensure rotational movement. The electrical power in the stator is transmitted to the consumer through the brush (12) and ring (13).

The advantages of using an electric generator whose stator and rotor rotate opposite to each other are as follows:

1. The generator is multi-pole and generates voltage even at relatively low currents due to the opposite rotation of the stator and rotor.
2. The generator is simple in structure, low in cost and easy to maintain.
3. Due to the fact that less details are used in the generator, the probability of failure of the device is reduced, its reliability can be increased and it can serve for a long time.

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Conclusion. As a result of the conducted research, the main factors affecting the structural characteristics, technical indicators and efficiency of electric generators used in the production of electricity from low-speed wind and low-pressure water currents were analyzed. The analysis shows that the use of conventional electric generators in combination with low-speed turbines may require the use of reducers and other mechanical transmissions to achieve the required rotational speed. This leads to an increase in the structural complexity of the device, mechanical energy losses, maintenance and operation costs. As a result of comparison of technical and economic parameters of radial, axial and hybrid axial-radial flux permanent magnet synchronous generators, it was determined that each of them has certain constructive and operational advantages. In particular, in the comparison of 3 kW generators presented in the article, it is shown that the efficiency of the axial flow generator is 92%, and the efficiency of the radial flow generators is 89.23% and 92.32%, respectively. These results show that it is necessary to take into account not only the useful work coefficient, but also the mass, material consumption, structural structure and production costs when choosing a generator type. As part of the research, a multi-pole electric generator design with rotor and stator rotating in opposite directions was proposed. In this design, the mechanical energy generated by the turbine is transmitted to the rotor and stator with the help of gear wheels and mechanical transmissions. As a result, their rotation in the opposite direction is ensured. Such a solution is a promising technical direction for improving the efficiency of obtaining electricity from low-speed water and wind currents, making it possible to increase the relative rotation speed associated with the magnetic field. The main advantages of the proposed generator include the possibility of using low-speed energy flows, electricity generation based on multi-pole construction, the possibility of simplifying the design solutions of the device, and the prospects for use in micro-hydroelectric power plants and small-power wind energy systems. At the same time, the presence of mechanical gears, bearings, brushes and contact rings can cause friction, corrosion and electrical losses. Therefore, these factors should also be taken into account when evaluating the overall efficiency of the generator. In general, the improvement of the multi-pole electric generator with counter-rotating rotor and stator is one of the promising directions for increasing the efficiency of using low-potential renewable energy sources.

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