DEVICE OF SYNCHRONOUS GENERATOR WITH INCREASED MAGNETIC EFFICIENCY FOR USE IN WIND POWER PLANTS WITH CAPACITY OF UP TO 5 KW

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Abstract. The article offers a description of a permanent magnet synchronous generator (PMSG) developed with a capacity of up to 5 kW. The electric generator is designed to generate electricity by the magnetic-and-electrical method and conversion of mechanical energy produced by a rotating wind engine. The main feature of the generator is its magnetic core, made of ferromagnetic inserts for the redistribution of magnetic fluxes Φ_1- Φ_5, which are presented in the article as a design and a model of probabilistic similarity in Fig. 1. The generator design has been improved also by optimizing windings with additional magnetic poles. The PMSG is manufactured from light and durable materials using layer-by-layer synthesis based on 3D printing additive technologies. The generator under development is a concept-product having advantages over analogs, the conceptual advantages are based on the following. The generator magnetic efficiency factor increases up to 82% as a result of a decrease in magnetic flux losses on leakage and buckling, and increase in induction, magnetic potential, magnetic field intensity and energy. The article shows the research on the distribution of magnetic fluxes Φ and magnetic-and static values in the section of the magnetic circuit of the generator, conducted in the computer simulation environment Elcut. Because of the improved redistribution of the magnetic flux to the winding area, the electric current at the generator output increases by 60%, and hence its conversion intensity increases. Since the generator runs on accumulator battery power, the charge time decreases by 10%, and it leads to accelerated using of the energy storage unit at rotation speed from 300 to 1,500 rpm. The generator shaft breakaway occurs at a wind speed of 2 m·s^{-1}, and the period of accelerated shaft rotation is 25% less than in the analogs. The wind engine will ensure a stable power supply to the consumer at a wind speed of 2-5 m·s^{-1}. To charge 4 accumulator batteries (each 12 V 200 Ah), the generated current range is 0.1-25 A at a voltage of 12-48 V in windings with the wire cross-section of 1.12 mm. Rewinding the coils with a wire of a higher nominal diameter allows increasing the generated current up to 62 A for creating an active load on the heating element. The generator is made of lightweight carbon (composite) elements to reduce weight and production costs. The weight-size parameters of the magnetic system design are improved. The dimensions of the device of the developed synchronous generator are limited by the stator length of 0.25 meters, width of 0.4 meters and weighing 14 kilograms.

Keywords: synchronous generator, permanent magnets, PMSG, ferromagnetic inserts, magnetic flux, wind power, additive technologies.

Introduction

The development of remote agricultural areas in the North Caucasus is associated with limited connections to power grids. Small rural energy-consuming facilities are often at a long distance from centralized power supply systems. Laying power lines to create a new facility is costly and not always economically advisable. Most often, these facilities are commercial farm units that consume up to 10 kWh·day^{-1}. Due to the fact, consumer agricultural services and engineering infrastructure distant from the centralized power supply need efficient and reliable autonomous power supply systems based on alternative energy resources. Due to high prices and low productivity, there is a low demand for existing autonomous power supply systems in the North Caucasus regions.

To date, research on the development of wind energy in the southern regions with mountainous rural areas is being carried out by scientists in Russia O. Grigorash [1], G. Nikitenko, S. Voronin [4], as well as in the world R. Lo, H., J. Wang, M. Duner, J. Clark [2] and Dr. Vadirajacharya, P.K. Katti [3]. The scientists' works are mainly about optimizing autonomous power supply systems for remote agricultural facilities with wind and solar energy conversion. The researches [5-7] are devoted to improving the efficiency of electromechanical converters for autonomous power supply of agricultural facilities. The features of simulating the magnetic circuit of a synchronous generator with permanent magnets were discussed by V.A. Sobolev and E.V. Konoplev and A.V. Bobryshev [8]. Among others, Yu.A. Makarichev in his works considered the main types of synchronous electrical machine design and also gave their main characteristics and approached the issue of competent electromagnetic calculation of synchronous generator magnetic systems. The use of inductor generators in low-power wind engines was considered from a professional point of view by N.N. Levin in his work.

The analysis of sources has showed that wind-driven power plants have a complex system of automatic adaptation to constant fluctuations in the wind flow and low specific characteristics of asynchronous generators. On the other hand, in some wind engines, one can find out that their designs are complicated by starting systems, stabilizers of asynchronous converters' rotation speed. Moreover, they are equipped with additional power sources for automatic stabilizers of electromechanical part rotation speed. The synchronous electric induction excited generators integrated into the wind engines are complex and dimensional. These generators used in wind-driven power plants (WPP) are quite metal-consuming and provide huge losses of magnetic energy in the steel sections of the coil flux guide. Their design is complicated by a magnetizing winding with additional power supplies. Metal parts magnetizing and additional excitation make the wind engine design and start more complex. As a result, the efficiency of their use in autonomous power supply at low wind speed decreases. On this basis, in autonomous low power wind-driven engines it is recommended to use synchronous generators with a big energy reserve of magnetic power at low rotation speed. The efficient solution for small wind-driven engines is using permanent magnet synchronous generators. They are efficient for generating electricity with wide ranges of rotation speed. The generator magnets' multi-pole arrangement allows the system to reach the rated power at low generator speed. However, the magnetic systems of such permanent magnet generators are still far from perfect. These magnetic systems cause big magnetic energy losses, such as leakage and buckling fluxes outside the energy conversion area of the electromagnetic field. Due to high magnetic loss, most magnetic energy necessary for conversion into electricity in the winding is lost in the stator and rotor steel parts. As a result, an insignificant part of the magnetic field lines pass through the generator coil sections and decrease the converter's magnetic efficiency. It leads to poor flux linkage with winding coils, the magnetic flux of small amounts, low current values, and, as a consequence, low power output. This contradiction does not allow synchronous generators to operate more efficiently with a wide range of rotation. At low wind speed, the low current strength in the coil negatively affects both the battery cells' charge time and efficiency of the autonomous power supply system with an integrated wind engine.

On this basis, it is necessary to develop autonomous power supply systems with synchronous permanent magnet (PM) generators. During the generators development, special attention should be paid to reducing the percent of magnetic leakage and buckling fluxes. It can improve the magnetic efficiency of the system for the conversion of magnetic flux produced by permanent magnets into electrical energy. Resolving the above contradiction is possible by integrating ferromagnetic elements and additional magnetic poles into the generator design. They are intended to increase the magnetic efficiency of the system by redistributing the leakage and buckling magnetic fluxes towards the winding section. This will allow increasing strength, induction, and magnetic field power in the winding turns.

Considering the development of new additive manufacturing technologies, the task of improving the specific power characteristics of a synchronous generator becomes urgent. By combining the additive prototyping technology and generator magnetic circuit improvement due to using ferromagnetic inserts of a new configuration, it is possible to achieve optimized mass-dimensional parameters and increased magnetic efficiency of the electric generator. Therefore, it is proposed to replace the generator metal parts with lightweight composite materials having high mechanical strength and manufacture the magnetic core of ferromagnetic inserts and additional magnetic poles. Thus, the magnetic flux will be redistributed into the coils to increase the magnetic conversion efficiency.

These modifications will allow increase the specific power characteristics of the generator and autonomous power supply system efficiency.

Materials and methods

Figure 1 shows a new design of a synchronous generator with excitation from permanent high-coercivity magnets. The main feature of this electric generator is the armature magnetic core 1 made of ferromagnetic plates of specific configuration 2 and triangular magnetic poles 3 [9]. The stator 8 of the engine is also improved by windings 9 optimized with adding magnetic poles in the form of flat ferromagnetic plates 10. They are in the bottom base plate of the trapezoidal coil turns 9. This arrangement of the magnetic elements of the magnetic circuit is aimed at the increase in the magnetic-and-electrical conversion efficiency. It is

achieved by shielding leakage magnetic fluxes Φ_5^* from permanent magnets behind the outer side of the armature ring 1 with ferromagnetic plates 2 and redistribution of buckling magnetic fluxes Φ_2^* from the side of the rotation axis 6. As a result, the flows Φ_1 - Φ_5 enhance and are redistributed into winding turns to generate electricity, thereby increasing the magnetic efficiency of the magnetic system.
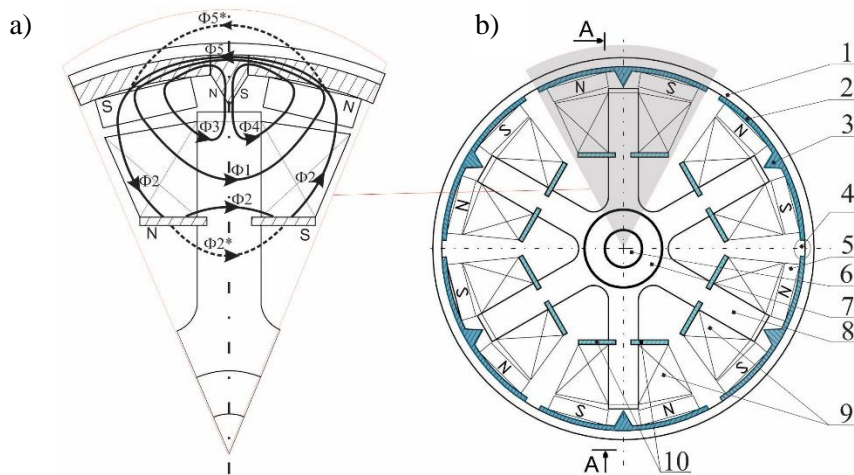
Fig. 1. **Synchronous generator, probabilistic similarity model of distribution of magnetic fluxes Φ_1- Φ_5 (a); construction drawing (b):** 1– non-magnetic material armature ring; 2 – ferromagnetic plates; 3 – triangular magnetic poles; 4 – air gap; 5 – permanent magnets; 6 – axis of rotation; 7 – bearing; 8 – stator poles; 9 – phase windings; 10 – flat ferromagnetic plates

As proof of the proposed conceptual advantages of a synchronous generator having the increased magnetic efficiency, computer simulation and study of the magnetic system were made using the ELCUT software version 6.1. The software for magnet-and-electrical calculations uses the finite element method and can be described by Poisson and Laplace equations with specified boundary conditions of Dirichlet and Neumann potential for induction tangential component. Permanent magnets have high nonlinear magnetic characteristics and are field sources in magnet statics specification. In the simulated section of the synchronous generator magnetic circuit, the properties of high-coercive permanent magnets NdFeB of N50 grade are specified, which have a magnetic field intensity $H = 796 \text{ kA·m}^{-1}$ and magnetic induction $Br = 1.45$ T. The material used for the ferromagnetic elements manufacture is electrical steel.
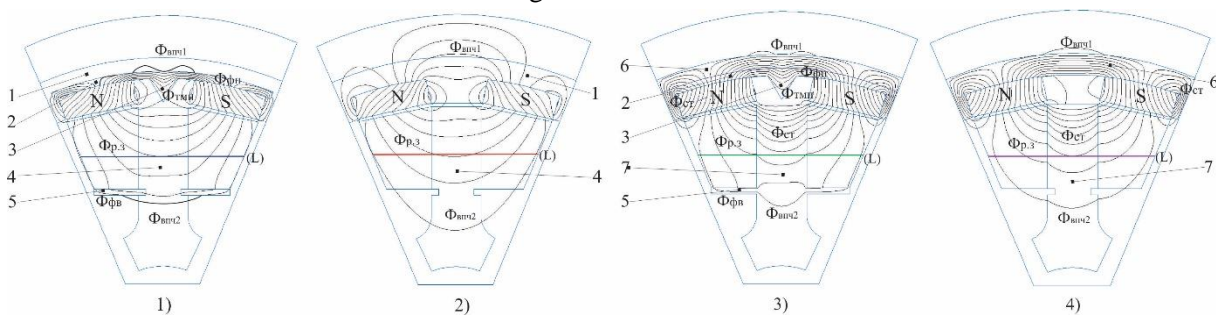
Fig. 2. **Simulation of magnetic flux in the section of a permanent magnet synchronous generator:** 1 – with ferromagnetic plates 2, triangular magnetic pole 3 fixed on the non-magnetic armature ring 1, and flat ferromagnetic inserts 5 mounted on the non-magnetic stator core 4; 2 – without ferromagnetic elements with permanent magnets (N, S) fixed on the armature non-magnetic ring 1 and with non-magnetic stator core 4; 3 – with a ferromagnetic plate 2 and a triangular magnetic pole 3 fixed on the armature steel cage 6 and flat ferromagnetic inserts 5 mounted on the stator steel core 7; 4 – with magnets fixed on the armature steel cage 6 without ferromagnetic elements and stator steel core 7 without flat ferromagnetic plates

The task of computer simulation is to obtain the analysis of magnetic fluxes distribution in models of salient-pole generators with permanent magnets, which have both a traditional steel-magnetic design and a magnetic circuit consisting of flat ferromagnetic plates, triangular magnetic poles, and flat ferromagnetic inserts. Also, the task includes the study of magnetic field characteristics in the generator model proposed by the authors. The result of the task solved is in Figures 2, 3.

A comparative illustration of the result of computer simulation made with similar scope of investigation in models 0.0018 Wb is shown in Figure 3. The model with ferromagnetic inserts and magnetic poles 1 compared with model 2 without ferromagnetic inserts and magnetic poles, has fewer external $\Phi_{ВПЧ1}$ and internal $\Phi_{ВПЧ2}$ of bulging field lines. Figure 3 shows the magnetic field lines that are not used in the process of converting the energy of the magnetic field and are designated $\Phi_{ВПЧ1}$ and $\Phi_{ВПЧ2}$. In the image $\Phi_{ВПЧ1}$ is a magnetic flux representing a set of magnetic lines of force extending from the permanent magnets beyond the outer boundaries of the rotor, and $\Phi_{ВПЧ2}$ is a magnetic flux bulging towards the axis of rotation of the generator. The more bulges of the magnetic fluxes $\Phi_{ВПЧ1}$ and $\Phi_{ВПЧ2}$ in the generator section, the less magnetic energy in the winding zone that affects the generation of electricity at the generator output. The magnetic field leaking lines produced by permanent magnets, due to the shielding effect of the ferromagnetic plates 2 and the action of the triangular magnetic pole 3, pass into a magnetic flux running through the working gap $\Phi_{Р.З.}$, that is, to the coil area. The triangular magnetic pole 3 forms a flux of the lowest magnetic resistance $\Phi_{ТМП}$ between the magnets and enhances the field lines potential. From the coil base, the magnetic lines run through the flat ferromagnetic inserts 5 with forming a shunt flux $\Phi_{ШВ}$ that runs through its magnetic cross-section. Flat ferromagnetic inserts 5 in the coils increase the induction and evenly distribute the magnetic line density in the winding.

Closer consideration of model 3 shows that a synchronous generator with stator poles and an armature cage made of electrical steel with added ferromagnetic inserts, triangular poles, and flat ferromagnetic inserts has advantages over models 2 and 4 manifested as a minimum external $\Phi_{ВПЧ}$ and bulging $\Phi_{ВПЧ2}$ magnetic fluxes, as well as a higher density of force lines produced by permanent magnets tending to close through a steel salient pole. In the coil area close to the triangular magnetic pole in model 3 the uniform orientation of the flux between the magnets is obvious. However, due to the armature steel cage and the core made of electrical steel, this model has a bad shortcoming manifested as a sharp increase in the steel-magnetic system weight and size parameters compared to model 1, moreover, the magnetic flux in the system is unevenly distributed over the coil, where large field lines tend to close through the steel, while part of energy is wasted on saturating the steel core. It is obvious that the magnetic flux density in model 3 is uneven and has an increased concentration of magnetic lines in steel, therefore, it does not allow using the entire volume of the conductor winding with sufficient efficiency. The design has prospects for use in systems where stable armature rotations are observed since saturation and, consequently, the magnetization of steel at a high angular rate provides the generator's magnetic system with the maximum efficient characteristics of the magnetic field in the turns of the coils.

Based on a clear illustration of magnetic field line distribution in the synchronous generator models in Fig. 2, it can be assumed that the model 1 design has magnet-static advantages. Due to the magnetic circuit produced by ferromagnetic plates 2, a triangular magnetic pole 3, and flat ferromagnetic inserts 5, a positive effect occurs in the form of an increase in the magnetic flux circulation and density, where its force lines without energy loss for buckling and leakage run through the generator winding. However, this assumption must be justified by studying the magnetic induction characteristics in the generator working gap, where the winding turns are located.
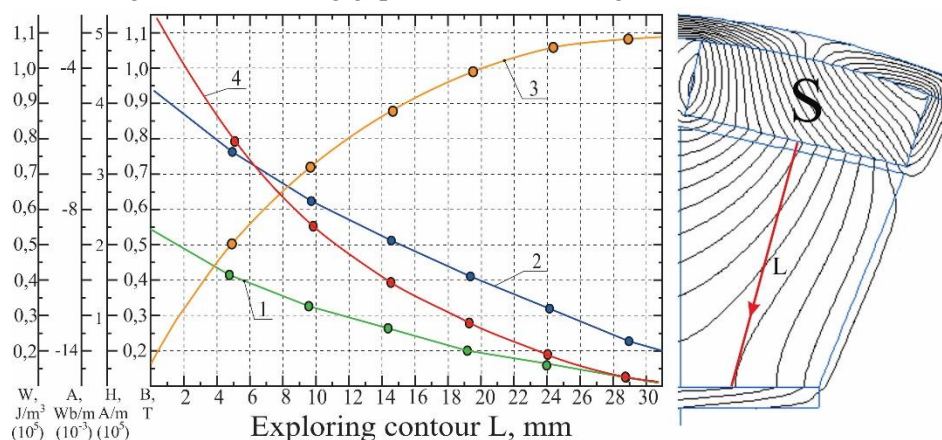

Fig. 3. **Graph of distributing functions of magnetic-and-static values in the copper winding area according to the research contour, where:** 1 – induction B, T; 2 – tension H, A·m⁻¹; 3 – magnetic potential A, Wb·m⁻¹; 4 – magnetic energy density W, J·m⁻³

Fig. 3 shows the graphs illustrating the distribution of induction, strength, magnetic potential, and magnetic energy density in the copper winding area along the contour of the study carried out perpendicularly from the midpoint of the permanent magnet surface to the flat ferromagnetic insert.

The combination of the above-mentioned ferromagnetic elements in the synchronous generator magnetic system increases the induction by 70%, that is, 1.8 times compared to a generator without ferromagnetic elements and additional poles. As a result, the magnetic flux value in the coil and also the values of induction and magnetic field strength increase by 1.5 times compared to the electric generator without these elements.

As a study of the operation of a synchronous generator with ferromagnetic inserts and magnetic poles in the battery charge mode, the consumed current and charge voltage values were defined in the range of armature rotation speed from 0 to 1800 min^{-1}. The study results are in the nomogram in Fig. 4.

The experiment was carried out with generator coils with a wire diameter of 1.12 mm. At idle speed, with an increase in the armature rotation, a constant voltage was formed at the rectifier output and reached 108 V. During the experiment, 4 series-connected accumulator batteries delta 12 V 200 Ah were used. When the generator under study works to charge the accumulator batteries, there is no need to maintain a voltage above 55 V in an autonomous power supply system. By increasing the wire diameter in winding phases, it is possible to artificially decrease the voltage at the generator phases and increase the generated current intensity. Therefore, for the adjusted operation of the electric generator for charging the coil accumulator, the pole coils were rewound with a wire of 2.12 mm diameter. Figure 4 shows the processed dependencies of the experiment described above.
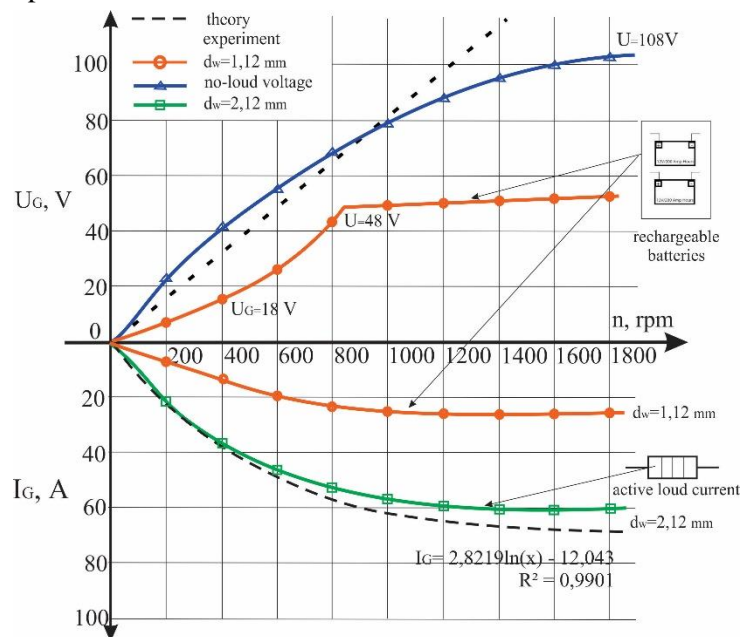

Fig. 4. **Relations between a synchronous generator voltage and current and rotation speed during charging an accumulator battery with the winding phase wire diameter $dw = 2.12$ mm**

The graph shows that rewinding of coils with a wire of a higher nominal diameter allows to increase the generated current intensity to 62 A at the output of a synchronous generator with ferromagnetic inserts. In this case, the active load on the heating element was connected to the generator. The current intensity of a generator with a winding phase wire diameter of 2.12 mm has a curve on average 60% better than in the case with the winding with $do.\pi = 1.12$ mm. During operation, the generator voltage is balanced by the controller and also by internal EMF of storage batteries to the value of 48-55 V. The average value of variation between theoretical calculations and experiment data does not exceed 8%, which is quite acceptable for engineering calculations.

The nomogram area is of practical interest, where the generator voltage reaches the battery charge value of 18 V. The indicated voltage corresponds to the rotor rotation speed of 400 min^{-1}, while the energy storage devices' charging current is 16.4 A. These characteristics are most applicable for low converter rotation speed, which corresponds to the differential connection of accumulator batteries in a

parallel operation mode. If a generator rotation speed is high and is within 800-1800 min^{-1}, the current and voltage at its output increase to 55 V and 25 A. In this case, the charging system switches to a series connection of the accumulators.

In addition to the above results, the authors of the article propose technical solutions for improving the specific power characteristics of a synchronous generator. The innovation is aimed at manufacturing non-magnetic parts of the generator design from durable composite materials. These materials can be used to create generator products based on additive technologies using layer-by-layer synthesis methods. With the technology, it is planned to manufacture all-composite products of the stator salient poles (Fig. 5, b) and armature ring-shaped body (bracket) (Fig. 5, c).
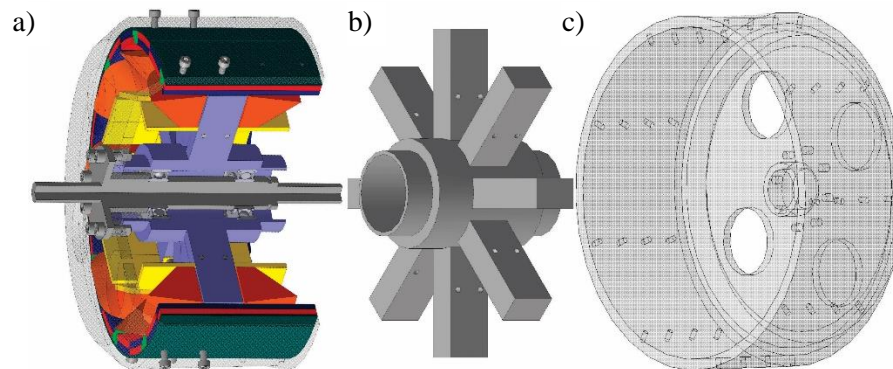
Fig. 5. **Three-dimensional model of a synchronous generator with ferromagnetic inserts and additional magnetic poles:** a – general view of the structure from the inside in section; b – salient stator poles made of non-magnetic material; c – ring-shaped armature body made of non-magnetic material

A suitable technology for creating structure elements of PMSG with ferromagnetic inserts is the layer-by-layer growth of plastic elements of a given shape with adding high-strength composite materials. It allows creating a product with unique properties in terms of strength and weight characteristics. A printer that operates with carbon fiber, a high-strength composite material, is patented by the Russian company Anisoprint. The essence of the technology is a continuous addition of reinforcing fiber to the polymer during three-dimensional printing. As a result, a composite material is produced with strength highly competitive to metals. Moreover, it is 2.5 times lighter and 2 times stronger than aluminum. The main advantage and feature of this additive printing method is the system that feeds the prepared carbon fiber together with plastic to a preheated two-channel extruder. Due to it, the reinforcement process is carried out. The monitored path of laying carbon fiber at every product point delivers strength where it is critical. With that, the generator structure parts become extremely resistant to rotational, vibrating, or impact loads. Compared to selective laser sintering technologies (Selective laser sintering SLS) or laser stereolithographic SLA printing of metal objects, the proposed prototyping method reduces the structure cost by 5 times and is equal in strength. A preliminary calculation showed that, if a device has a stator with a length and diameter of 0.25 meters by 0.4 meters, the generator weight should be approximately 14 kilograms.

The theses indicated by the authors in this article justify the increase in the energy efficiency of autonomous wind power supply systems for operation in the agricultural sector.

Conclusions

1. A synchronous generator of new design with permanent magnet excitation is proposed, which is improved by ferromagnetic inserts of specific configuration and additional magnetic poles. The arrangement of ferromagnets in the magnetic system proposed by the authors allows increasing the conversion efficiency by minimizing magnetic losses and improving the specific power parameters.
2. With the computer simulation in the ELCUT software, it was possible to make a comparative analysis of magnetic fluxes distribution in the PMSG models with various magnetic systems. It was found out with the graphic-analytical method that an improvement in the redistribution of leakage fluxes in the cross-section area of the copper winding by 35% occurs due to the configuration of ferromagnetic elements that the authors propose.

3. During the electronic simulation, the contour values of magnetic field characteristics in the winding cross-section of the investigated PMSG were determined. The set of ferromagnetic elements in the PMSG magnetic system increases the coil induction by 1.8 times compared to a generator without ferromagnetic elements and additional poles. As a result, both the magnetic flux amount in the coil and the magnetic field strength value increase by 1.5 times compared to the electric generator design without innovations.

4. During the experiment, the dynamic work of the proposed generator was established both in terms of charging the accumulator batteries and supplying power with the active load. To charge 4 storage batteries (each 12 V 200 A • h), the ranges of the generated current and generator voltage were 0.1-25 A and 12-48 V with a wire section of 1.12 mm in the PMSG windings. Rewinding the coils with a wire of a nominal diameter of 2.12 mm allowed increasing the generated current to 62 A during producing the active load for the heating element.

5. Improvement of PMSG specific power characteristics with ferromagnetic inserts is possible with the manufacture of non-magnetic elements created with additive technologies. The authors propose to use the well-known Anizoprint technology of printing elements from high-strength composite materials with the addition of reinforcing carbon fiber. As a result, structures are obtained that are not inferior in strength to metals. Moreover, they are 2.5 times lighter and 2 times stronger than aluminum. A preliminary calculation showed that with the device length and stator diameter of 0.25 meters by 0.4 meters, the generator weight would be approximately 14 kilograms.

References

[1] Григраш О.В., Кривошей А.А., Смык В.В. Автономные гибридные электростанции (Autonomous hybrid power plants) Polythematic network electronic journal of the Kuban state agrarian University: Политематический сетевой электронный журнал Кубанского государственного аграрного университета. 2016. No.124 (In Russian).

[2] Luo X., Wang J., Dooner M., Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy, 137: 2015, pp. 511-536.

[3] Vadirajacharya Dr., Katti P.K. Rural Electrification Through Solar and Wind Hybrid System: A Self Sustained Grid Free Electric Power Source. Energy Procedia, 14, 2012, pp. 2081-2087.

[4] Воронин С.М., Закиров И.В., Закиров Ф.В., Определение параметров автономной ветроэлектростанции малой мощности с комбинированным аккумуляторным резервом (Determination of the parameters of an Autonomous low-power wind farm with a combined battery reserve) In book: Fundamental and applied science - 2015 Materials of the XI International scientific and practical conference. 2015. (In Russian).

[5] Кривцов В.С., Олейников А.М., Яковлев А.И. Неисчерпаемая энергия, Кн. 1. Ветроэлектрогенераторы: Учебник (Inexhaustible energy, Vol. 1. Wind Turbines: A Tutorial) National aerospace University Kharkiv Aviation Institute. Национальный аэрокосмический университет Харьковский авиационный институт, 2003. (In Russian).

[6] Лифанов В.А. Расчет электрических машин малой мощности с возбуждением от постоянных магнитов: Учебное пособие (Calculation of low-power electric machines with excitation from permanent magnets: tutorial) Учебное пособие: 2-е изд., перераб. и доп. - Челябинск: Издательский центр ЮУрГУ, 2010. (In Russian).

[7] Lui S., Li S., He L., Direct-driven Permanent Magnet Synchronous Wind-power Generating System with Two Three-level Converters Based on SVPWM Control. Procedia Engineering, 29, 2012, 1191 p.

[8] Nikitenko G., Konoplev E., Salpagarov V., Bobryshev A. Method of calculating magnetic system using finite difference method·m^{-1}aterials of the of 19th International Scientific Conference "Engineering for rural development", 20.-22.05.2020. Jelgava, Latvia, 2020. pp. 1373-1380.

[9] Devederkin I., Nikitenko G., Grinchenko V., Lysakov A., Antonov S. Development of an autonomous wind power system/materials of the International Multi-Conference on Industrial Engineering and Modern Technologies ("FarEastCon"), 01-04.10.2019. Vladivostok, Russky island.