Mathematical modeling of the magnetic field of a low-speed synchronous generator with permanent magnets

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Abstract. Increased scientific and practical interest in the development, design, research and implementation of low-speed synchronous generators with permanent magnets (SGPM) is caused by the need to completely equip various sectors of the economy with efficient renewable energy sources based on the principles of wind, hydro and pneumatic power. The impetus for the creative thinking of Russian and foreign science to create and introduce into production and operation new types of designs of magnetoelectric machines with excitation from permanent magnets was the emergence in the consumer market a wide range of available for use high-coercive permanent magnets based on rare earth elements of the alloy neodymium-iron-boron (NdFeB). In this paper we propose a design of low-speed synchronous generator with permanent magnets, taking into account the full list of requirements for renewable energy sources, accumulated in the practical experience of developing such electromechanical converters. The article presents the results of mathematical modeling of the magnetic field of low-speed synchronous generator using the package Ansoft Maxwell 16.0.

1. Introduction

In the development of vertical-axial wind turbines, various technical solutions for the geometry and design of low-grade SGPM are used. The variety of designs of synchronous generators offered by the developers indicates the complexity of the search for optimal solutions in which it would be a combination of specified technical conditions with economic parameters associated with a decrease in the mass and size of the synchronous generator, low cost of active materials, installation, start-up and commissioning, repair and maintenance. The definition of the SGPM design is mainly heuristic. After the design stage, the process of direct development of the synchronous generator itself begins, consisting of a sequence of preliminary and verification stages of calculation. At the preliminary stage, the main dimensions of the magnetic system and the winding data of the generator are determined by the methods of the theory of magnetic and electric circuits. At the stage of verification calculations, the electromagnetic loads of the synchronous generator, the main dimensions of the magnetic system and the armature winding data, the mass of active materials, losses and efficiency are specified. The specified sequence of stages of design of SGPM represents the general approach characteristic for electric machines of different function which is realized in offers of developers in the form of concrete algorithms and programs for the PC. At all design stages, special attention should be paid to the ways of improving the efficiency and reliability of the synchronous generator. In this case, important in solving the problem of optimal design is the study of numerical models of magnetic fields using the finite element method [1-2]. By default, in the heuristic search for the optimal design of the SGPM, which is resulted in the development of a large number of patents and applications for the invention, there is a fuzzy concept of choosing in the magnetic system of the same cross-sectional shape of steel poles and permanent magnets. A possible error in decision-making at this stage can have negative
consequences, both in terms of the efficiency of the synchronous generator itself and the manufacturability of its production. The solution of the electro-technical problem of induced EMF in a coil with the relative motion of a permanent magnet with a different cross-section shape allows to prevent an error in the design of new types of SGPM.

The main criteria that should be followed for the optimal choice of SGPM structure are: a slight moment of straining, independent start of the synchronous generator at low winds, low self-oscillation, limiting the rotor speed, manufacturability of construction, installation, repair and maintenance of the synchronous generator, improving reliability, specific energy performance, reducing the size and weight of active materials compared with the designs of prototypes.

The design of low-speed SGPM proposed in the patent for the invention corresponds to the specified criteria in the model range of wind turbines with a capacity of 0.1-100 kW [3-5].

2. Construction
The magnetic system of the prototype of the developed design of low-speed SGPM is shown in Fig. 1[6].

![Figure 1. Assembled SGPM low-speed magnetic system (a) and rotor/inductor (b) design](image)

The sample of the proposed design of low-speed SGPM is characterized by the following parameters: nominal power \( S_n = 500 \text{ VA} \), rated voltage at the terminals of the armature winding \( U_n = 220 \text{ B} \) (effective value), rated rotational speed \( n = 400 \text{ rpm} \), rated current frequency \( f = 20 \text{ Hz} \), the number of phases \( m = 1 \), the number of pairs of poles \( p = 3 \), the number of electromagnets with a U-shaped charge magnetic circuit \( N = 8 \). Nominal speed of the shaft rotation \( n_s = 400 \text{ rpm} \). On every core of the electromagnet there are two coils with the number of windings \( w = 300 \). High-coercive permanent magnets made of NdFeB alloy of \( n = 38 \) grade in the form of a disk with a diameter of 55 mm and a height of 25 mm, having an axial direction of magnetization, residual induction \( B_r = 1.2 \text{ TL} \), coercive force \( H_c = 955 \text{ kA/m} \) and magnetic energy \( BH_{max} = 300 \text{ kJ/m}^3 \) are used in the design of SGPM. The resistivity and density of the material of the permanent magnet are, respectively \( \rho_m = 1.4 - 1.45 \text{ Ohm} \cdot \text{m} \) and \( \gamma_m = 7500 \text{ kg} / \text{m}^3 \).

3. Modeling
The distribution of the magnetic field in the magnetic system of low-speed SGPM has a significant impact on the value of EMF in the coils of electromagnets and the reaction of the armature. In this regard, it is expedient to conduct mathematical modeling of the magnetic system of low-speed SGPM on a PC using the software package Ansoft Maxwell 16.0 [7]. This package is a high-level software used for simulation of two-dimensional and three-dimensional magnetic fields of electromechanical transducers and allows to determine the moment and speed of rotation of the moving part. The
simulation of the magnetic field of low-speed SGPM is carried out on a PC Pentium Core 2 Duo E8400 with a processor clock speed of 3 GHz, set the amount of RAM 8 GB, the amount of disk space occupied on the HDD program Ansoft Maxwell 16.0 and the task 1 GB and 247 MB, respectively, video card 4 GB. The number of finite elements used in the task does not exceed 100 000.

In the process of creating a model in the software Ansoft Maxwell 16.0, the following statements and assumptions were accepted:

- the electromagnetic field of SGPM is not stationary and has no symmetry;
- due to the lack of symmetry in the computational domain, a complete three-dimensional solid-state model of low-speed SGPM is presented;
- coils of electromagnets with current are presented in the form of parallelepipeds with rounded side edges having a cutout for fixing on the U-shaped magnetic core;
- the current density is evenly distributed over the cross section of the electromagnets coils;
- the relative magnetic permeability of laminated steel U-shaped magnetic cores is determined in accordance with the magnetization curve of electrical steel;
- to set the boundary conditions, the three-dimensional model of the CGS is placed in a cube (Region), the size of which along x, y, z axes exceeds the model size by 15% (Fig. 3);
- the boundary condition for the vector magnetic potential $\mathbf{A} = 0$ is accepted on the external surface of Region.

4. Results
On the basis of the constructed mathematical model of low-speed SGPM in the software module ANSYS/Maxwell we obtained a three-dimensional view of the magnetic field (Fig. 3), wave diagrams of voltage and current in the armature winding in idle and short circuit modes (Fig. 4 a, b).
5. Conclusion
1. The design of low-speed SGPM, which meets the criteria in the model range of wind turbines with a capacity of 0.1–5 kW, is proposed.

2. A mathematical model of low-speed CGS in the software module ANSYS/Maxwell Circuit Editor, which allows to study the dynamic characteristics of the synchronous generator based on the numerical calculation of the three-dimensional magnetic field in idle and sudden short circuit, is developed.

6. References
[1] Kerem K, Afzal S, Edward J P 2016 Analytical modeling of eddy current brakes with the application of time varying magnetic fields Applied Mathematical Modelling (Canada) 40 pp 1168-1179
[2] Kurbatov P A 2007 *Modeling Electromechanical Systems of Electromechanically Apparatus* (Moscow: MEI) 110 p

[3] Roberto Lacal-Aranegui 2019 Globalization in the wind energy industry: contribution and economic impact of European companies *Renewable Energy* 134 pp 612-628.

[4] G K Gugliani, A Sarkar, C Ley, S Mandal 2018 New methods to assess wind resources in terms of wind speed, load, power and direction *Renewable Energy* 129 Part A pp 168-182.

[5] L Battisti, E Benini, A Brighenti, S Dell’Anna, M Raciti Castelli 2018 Small wind turbine effectiveness in the urban environment *Renewable Energy* 129 Part A pp 102-113

[6] *Brushless permanent magnet synchronous generator* Tatevosyan A.A., Tatevosyan A.S. Pat. № 2565775, RF.

[7] Ansoft Maxwell 3D. User's Guide Ansoft Corporation 225West Station Square Drive Suite 2000 (Pittsburg)