ЕЛЕКТРИЧНІ МАШИНИ ТА АПАРАТИ

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STRUCTURAL OPTIMIZATION OF CONTACTLESS MAGNETOELECTRIC TACHOGENERATORS

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The paper is devoted to the structural optimization of brushless tachogenerators with permanent magnets on the rotor and a smooth slotless stator. The structures of rotors with surface-mounted magnets, with tangentially magnetized magnets, as well as with radially and tangentially magnetized magnets mounted on the magnetic core are considered. The effect of changing the rotor parameters on the form of the curve and the pulsation coefficient of the rectified EMF when installed in a stationary stator structure is analyzed. Recommendations are given for choosing the configuration of a brushless magnetoelectric tachogenerator with the lowest EMF pulsation. Ref. 9, fig. 8.
Keywords: brushless magnetoelectric tachogenerator, pulsation coefficient, slotless stator, permanent magnet.

An integral part of many automatic electromechanical feedback systems is the device for measuring the angular speed of the actuator motor. Such angular speed sensors can be very different in their operating principle.

One of the known subtypes of such devices is electromechanical tachogenerators, at the output of which an isolated analog voltage signal is formed proportional to the angular speed of the rotating motor. For many decades, tachogenerators have traditionally been based on a DC generator with mechanical brushes [1, 2, 3, 4]. Such devices are currently used in the mechanical industry, robotics, military equipment and other industries. The advantage of collector tachogenerators is their ease of use, since they do not require any additional signal converters in the control system, and information about the rotation speed of the actuator motor is obtained by measuring the DC voltage induced in the stator windings and converted by the brush-collector unit. At the same time, the presence of a mechanical commutator in a collector tachogenerator limits its operating life and causes a drop in voltage and pulsation on the sliding contact.

An effective solution to eliminate the shortcomings of a collector tachogenerator is to use a brushless synchronous multiphase magnetoelectric generator. However, in this case, there is a task of generating an output analog signal. To improve the quality of this signal, many approaches to implementing a brushless electric machine and signal conversion circuits are used [5-8].

One of the options for implementing a brushless tachogenerator is to choose its structure with a smooth slotless stator [9]. A distinctive feature of this design is that the stator winding is not located in slots, but is installed on a smooth cylindrical surface of the stator magnetic circuit. Compared with a slot design, this arrangement significantly reduces the winding inductance, which in turn leads to improved switching and increased response time due to a decrease in the electromechanical time constant. The absence of slots on the stator eliminates the occurrence of EMF pulsations caused by uneven magnetic conductivity of the air gap. To compensate for a significant non-magnetic gap consisting of the air gap's length and the stator winding's thickness, high-energy magnets made of NdFeB composition are used on the rotor. These magnets have a relative magnetic permeability close to the magnetic permeability of air, which also helps to reduce the inductance of the winding. In addition, neodymium magnets have high temperature stability within the operating temperature range - from -0.09% to -0.13% per degree Celsius. This means that

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as the temperature increases, the magnet force decreases, and vice versa. Such a change in induction affects the magnitude of the stator EMF, but does not affect the shape of the output characteristic of the tachogenerator. Therefore, this study does not consider parameter changes caused by temperature fluctuations.

The purpose of the paper is the structural optimization of brushless magnetoelectric slotless tachogenerators to minimize the pulsations of rectified EMF induced in the stator winding and to develop recommendations for choosing the structure of tachogenerators for various applications.

Main materials and research. A brushless magnetoelectric tachogenerator [7] is generally an m-phase AC electric machine. Fig. 1 conventionally shows a three-phase system of EMF of stator windings, which in the simplest case are described by sinusoidal functions

$$e_A = k_m \omega \sin\theta;\ e_B = k_m \omega \sin(\theta - 2\pi/3);\ e_C = k_m \omega \sin(\theta - 4\pi/3), \qquad (1\text{-}3)$$

where k_m, ω are the constant coefficient and the angular speed of rotation of the generator rotor; θ is the electrical angle of rotation of the rotor shaft, which is determined as $\theta = p\omega t$, where p is the number of pairs of rotor poles; t is time.

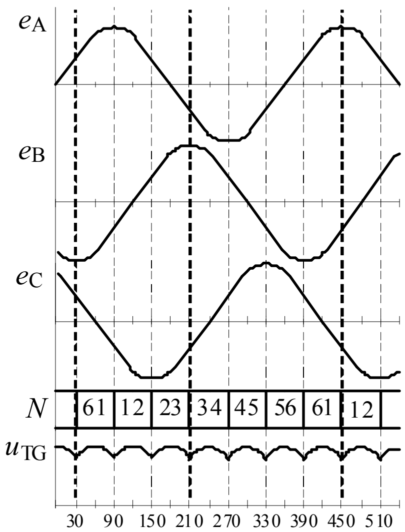


Fig. 1. Three-phase system of stator windings EMF

To form an analog voltage signal proportional to the angular speed of the rotating motor, a three-phase bridge active rectifier is used based on controlled keys with two-way conductivity, for example MOSFETs (Fig. 2). The conductivity intervals of the controlled keys are indicated in Fig. 1 by the letter N, which denotes the numbers of the included pairs of transistors. In this case, the output signal u_{TG} of the tachogenerator rectifier at each repeatability interval of 60 electrical degrees is described as the sum of two phase EMFs, for example, at interval N=61, with the sixth and first transistors turned on, two variables are summed – e_A and e_B.

The main problem in developing brushless tachogenerators is the presence of pulsations in the output rectified signal due to the peculiar form of the phase variables of the stator EMF. To assess the quality of the rectified signal of the tachogenerator, a pulsation coefficient is used, which can be calculated using simple formulas based on the parameters of the induced EMF in the stator windings

$$k_P = 100\frac{U_{\max} - U_{\min}}{U_{\max} + U_{\min}} = 100\frac{2E_{60} - E_{90} - E_{30}}{2E_{60} + E_{90} + E_{30}},$$

where U_{max}, U_{min} are the maximum and minimum values of the output signal; E_{30}, E_{60}, E_{90} are the EMF values in the tachogenerator phase at 30, 60 and 90 electrical degrees on the first quarter of the half-wave of the EMF curve [8].

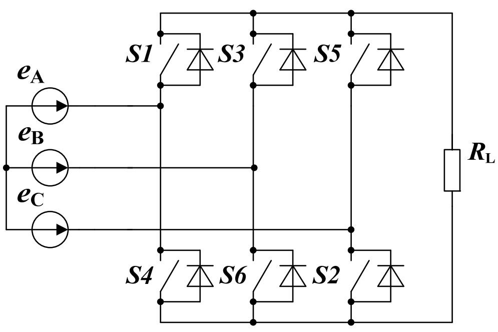


Fig. 2. Three-phase bridge active rectifier based on controlled keys with two-way conductivity

One of the ways to overcome the pulsation problem is to choose such an EMF form that the output pulsations are minimal. Based on expression (1), the pulsation coefficient k_p reaches its minimum at $E_{30}=E_{60}=E_{90}$ and at $E_{60}=E_{90}+E_{30}$, which corresponds to the trapezoidal and triangular forms of the EMF.

Another important indicator of the tachogenerator is the output characteristic slope equal to the ratio of the average value of the output signal to the rotor speed. The higher this value, the more sensitive the tachogenerator and the better it responds to speed changes. Based on this, the trapezoidal form of the EMF is preferable to the triangular one since, with equal amplitude values, their average values differ by almost two times. The output signal can also be increased by reducing the cross-section of the winding wire and winding a larger number of turns in the winding, but technological restrictions on the minimum permissible cross-section of the conductor limit the possibility of its manufacture. Therefore, in the future, the authors consider various design solutions for magnetoelectric tachogenerators to obtain a phase EMF form as close as possible to the trapezoidal one.

For comparative analysis, slotless magnetoelectric machines with identical stators and with different, most popular, designs of six-pole rotors were selected. Fig. 3 shows the structure of a tachogenerator with surface-mounted magnets on the rotor, which consists of a shaft 1, a rotor magnetic circuit 2 installed on it and permanent magnets 3, as well as symmetrical three-phase stator windings 4, fixed in an air gap *d* on the inner surface of the slotless stator magnetic circuit 5.

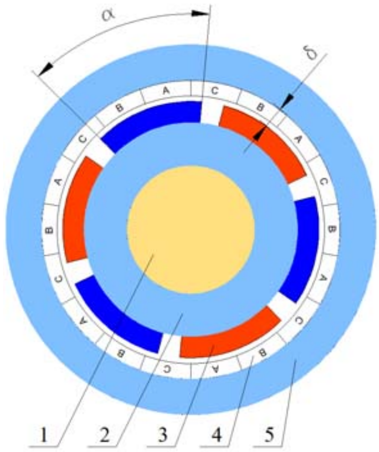
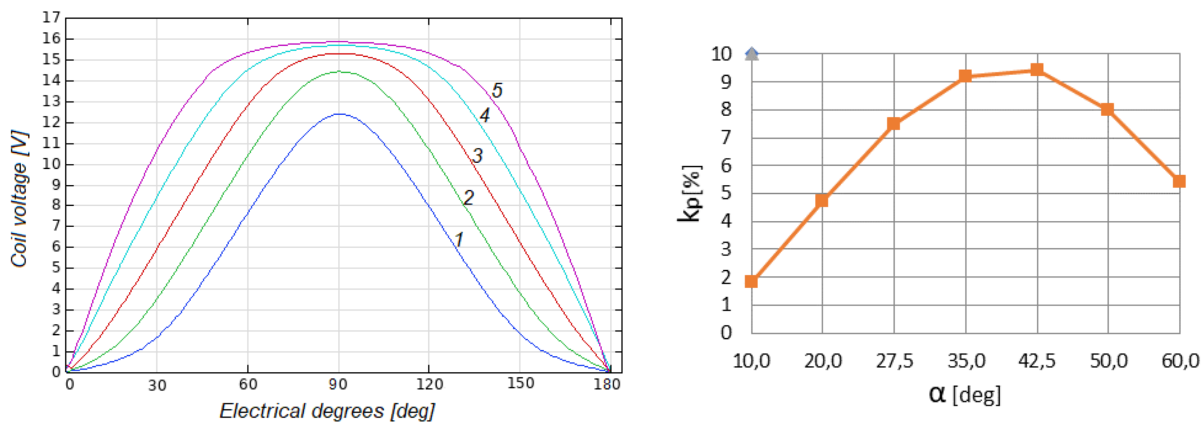


Fig. 3. Tachogenerator with surface mounted magnets on the rotor

At the first stage, using the COMSOL Multiphysics software package, we will analyze the dependence of the EMF pulsation coefficient on the angular size of the magnet. We will assume that the length of the tachogenerator significantly exceeds its diameter and the edge effects can be neglected. This will allow us to limit ourselves to considering the problem in a two-dimensional formulation.

As a result of modeling a tachogenerator with some arbitrarily specified sizes of its components, the number of turns and the rotation speed, a family of EMF curves induced in one phase of the stator as a function of the angular size of the magnet α (Fig. 4a) was obtained, and the pulsation coefficients $k_p(\alpha)$ were calculated (Fig. 4b). The EMF curves as a function of the angular size of the magnet α from 10^0 to 60^0, respectively, are designated by numbers from 1 to 5.



a *b*

Fig. 4. Stator phase EMF (*a*) and the pulsation coefficient $k_p(\alpha)$ (*b*)

The graphs show that the smaller the angular size of the magnet, the closer the EMF form is to a triangle, and with an increase in the angle α, the curve acquires trapezoidal outlines. The same tendency, following (1), is reflected in the dependence of the pulsation coefficient on the angle α. From this, we can conclude that to obtain a trapezoidal EMF form with a given distribution of windings on the stator, the angular size of the magnet α must be maximum, i.e. equal to π/p, where p is the number of pole pairs.

In addition to the rotor design shown in Fig. 3, we will consider two more rotor designs - a rotor with tangentially magnetized magnets and ferromagnetic inserts (Fig. 5 *a*), and a rotor with built-in magnets that form poles (Fig. 5 *b*). In order not to complicate the comparative analysis, we will not use relative units of measurement, but will specify specific dimensions and parameters of tachogenerators. This approach will allow us to display each structure's quantitative and qualitative aspects more clearly.

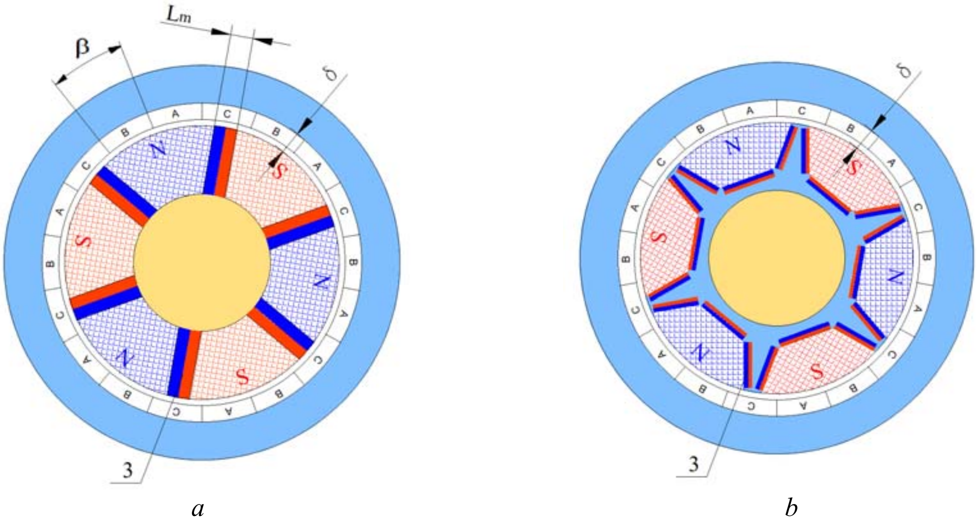


Fig. 5. Structure of a tachogenerator with tangentially magnetized (*a*) and built-in magnets (*b*) on the rotor.

All three design options have the same stator, with a three-phase winding wound with a wire of 0.45 mm in diameter; the technological gap between the stator and the rotor is 0.8 mm. The rotor diameter is the same and equals 36 mm. To excite the magnetic field, neodymium magnets of the VMN–42N brand are used, and the volume of magnetic material used in each rotor is the same, so the length of the magnets L_m in each design is different. The rotor speed is taken to be 200 rpm. We select ferromagnetic materials for magnetic circuits and their dimensions according to the criterion of absence of saturation, to prevent distortion of the magnetic field pattern.

As a result of the simulation, the values of the induced EMF in the phase of each of the tachogenerators were obtained with varying winding layer thickness. Fig. 6 shows the EMF curves in tachogenerators with surface mounted of magnets on the rotor (Fig. 6a), with tangential magnetization of magnets (Fig. 6b) and with built-in magnets (Fig. 6c). Numbers 1, 2, 3, 4 indicate the dependences of the EMF on the air gap size, changing from 1 mm to 7 mm with an interval of 2 mm. The dependences of the pulsation coefficients calculated by formula (1) on the air gap size d are shown in Fig. 7.

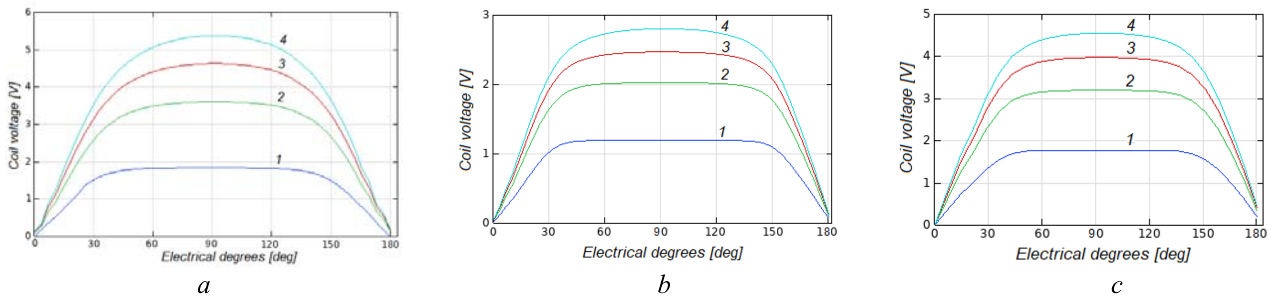


Fig. 6. Phase EMF of tachogenerators with surface mounted magnets on the rotor (*a*), with tangentially magnetized (*b*) and with built-in (*c*) magnets

It is obvious that the rotor design with tangentially magnetized magnets ensures the operation of the tachogenerator with the lowest pulsation of the rectified output voltage. At the same time, its amplitude is approximately 35% lower than when using the other two structures, which decreases the steepness of the output characteristic and limits the possibilities of using such a design in automatic systems with low rotation speeds of the actuator motor.

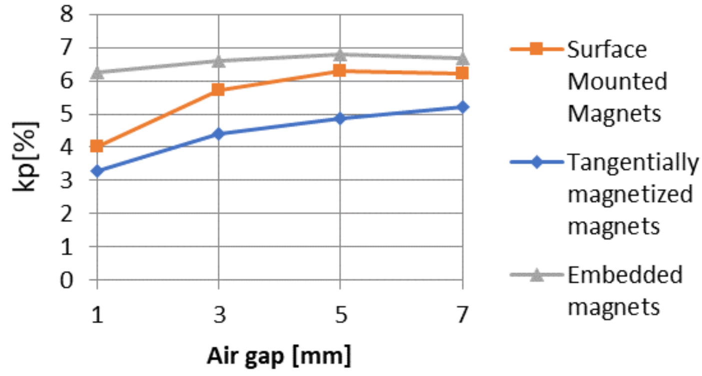


Fig. 7. Dependences of the output signal pulsation coefficient on the air gap value d

Further reduction of the pulsation level is possible by changing the design of the stator windings. In particular, in the above stator structure, it is possible to change the cross-sectional area of the active zone of the coils of each phase by reducing the angle β (Fig. 5 a) while maintaining the value of the pole division. This will lead to the maximum approximation of the law of change in the flux linkage of the stator coils with the rotor pole field to a triangular form, and the phase EMF, in turn, to a trapezoidal distribution law. Ideally, the angle β should tend to 0, since only in this case the maximum flux linkage of the rotor flux with the stator coil is achieved, and when the rotor rotates at a constant speed, as well as uniformly distributes the magnetic induction flux over the pole surface, the derivative of the mutual flux linkage will have the shape of a trapezoid with a wide upper section. For real coils formed by finite-section conductors, the law of flux linkage change will differ from linear, which in turn will lead to a distortion of the trapezoidal distribution of the EMF.

The graphs of the change in the output signal pulsation coefficient in Fig. 8 clearly demonstrate that with a decrease in the angular size of the cross-section of the active part of the stator coils β leads to a decrease in pulsations up to their complete disappearance. However, as a result of reducing the angle β, the cross-sectional area of the stator coils also decreases, and, consequently, the number of turns in the phase. The steepness of the output characteristic also decreases, and the sensitivity of the tachogenerator drops.

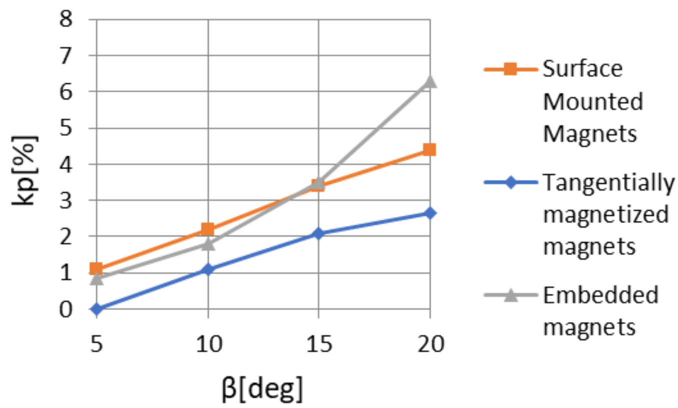


Fig. 8. Dependences of the output signal pulsation coefficient on the angular size of the stator coil cross-section β

Another way to achieve minimum pulsation of the tachogenerator output signal is to increase the number of phases. However, such a solution complicates the design of the stator windings and the circuit of the semiconductor rectifier. At the same time, the influence of the considered tachogenerator structures on the pulsation coefficient remains the same.

Conclusions. The study showed that the lowest coefficient of pulsation of the output signal of a brushless slotless tachogenerator is achieved when using a rotor with tangential magnetization of magnets. It was also established that in order to obtain a trapezoidal form of the EMF induced in the stator windings, the thickness of the winding layer and the angular size of the cross-section of the active part of the stator coils, with equal pole divisions of the phase windings of the stator and rotor, should be minimal. It should also be noted that, with worse pulsation indicators of the tachogenerator signal, structures with rotors with surface mounting of magnets and with built-in magnets have a steeper output characteristic and, accordingly, better sensitivity when measuring changing rotation speed.

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СТРУКТУРНА ОПТИМІЗАЦІЯ БЕЗКОНТАКТНИХ МАГНІТОЕЛЕКТРИЧНИХ ТАХОГЕНЕРАТОРІВ

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Статтю присвячено структурній оптимізації безконтактних тахогенераторів із постійними магнітами на роторі та гладким безпазовим статором. Розглянуто структури роторів з поверхневою установкою магнітів, з тангенціально намагніченими магнітами, а також з вмонтованими в магнітопроводи радіально та тангенціально намагніченими магнітами. Проаналізовано вплив зміни параметрів роторів на форму кривої та коефіцієнт пульсацій випрямленої ЕРС при встановленні їх у незмінну конструкцію статора. Дано рекомендації щодо вибору конфігурації безконтактного магнітоелектричного тахогенератора з найменшою пульсацією ЕРС. Бібл. 9, рис. 8.

Ключові слова: безконтактний магнітоелектричний тахогенератор, коефіцієнт пульсацій, безпазовий статор, постійний магніт.

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