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The influence of the design of the stator winding of a synchronous-reactive generator on increasing its energy efficiency

Introduction. *Increasing the energy efficiency of electric generators is a pressing task for various areas of energy, in particular for autonomous systems and transport. Synchronous-reactive generators (SRGs) are becoming increasingly widespread due to their simple design, absence of magnets and mechanical contacts, and high reliability. The* ***task*** *of the proposed work is to study the influence of the design of the double winding of the stator of a SRG on its energy characteristics, determine the optimal parameters of the mutual arrangement of the windings, and develop recommendations for increasing the generator efficiency.* ***Goal.*** *Analysis of the influence of the design of the double winding of the stator of a SRG on the output energy characteristics and determine recommendations when designing this type of electrical machines.* ***Methodology.*** *The analysis was carried out using numerical modeling by the finite element method in the ANSYS Maxwell environment. Various options for the mutual arrangement of the main and excitation windings in the generator stator were considered.* ***Results.*** *The influence of the single-layer and double-layer winding design on the output characteristics of the generator was studied. It was found that a two-layer arrangement with a phase shift of 2 slots provides minimal torque ripple, improves the stability of the generator operation and helps to increase the efficiency to 92.5 %.* ***Scientific novelty.*** *For the first time, the effect of the phase shift of the windings on electromagnetic processes in the SRG has been studied in detail, which allows optimizing its design and improving operational performance.* ***Practical value.*** *The results can be used in the design of new generators with improved characteristics for use in wind power, diesel generator sets and autonomous electrical systems.* References 19, table 1, figures 12.

Key words: **synchronous-reactive generator, winding, rotor, speed, torque, energy efficiency.**

Вступ. *Підвищення енергоефективності електричних генераторів є актуальною задачею для різних сфер енергетики, зокрема для автономних систем та транспорту. Синхронно-реактивні генератори (СРГ) завдяки простій конструкції, відсутності магнітів та механічних контактів, а також високій надійності набувають все більшого поширення.* ***Задача*** *даної роботи полягає у дослідженні впливу конструкції подвійної обмотки статора СРГ на його енергетичні характеристики, визначенні оптимальних параметрів взаємного розташування обмоток та розробці рекомендацій для підвищення ефективності генератора.* ***Мета.*** *Аналіз впливу конструкції подвійної обмотки статора СРГ на вихідні енергетичні характеристики та визначення рекомендацій при проєктуванні такого типу електричних машин.* ***Методологія.*** *Аналіз проводився за допомогою чисельного моделювання методом скінченних елементів у середовищі ANSYS Maxwell. Розглянуто різні варіанти взаємного розташування головної та збуджуючої обмоток у статорі генератора.* ***Результати.*** *Досліджено вплив одношарової та двошарової конструкції обмотки на вихідні характеристики генератора. Встановлено, що двошарове розташування з фазовим зміщенням на 2 пази забезпечує мінімальні пульсації крутного моменту, покращує стабільність роботи генератора та сприяє підвищенню ККД до 92,5 %.* ***Наукова новизна.*** *Вперше детально досліджено вплив фазового зміщення обмоток на електромагнітні процеси в СРГ, що дозволяє оптимізувати його конструкцію та покращити експлуатаційні показники.* ***Практична значимість.*** *Результати можуть бути використані при проєктуванні нових генераторів з покращеними характеристиками для застосування у вітроенергетиці, дизельних генераторних установках та автономних електричних системах.* Бібл. 19, табл. 1, рис. 12.

Ключові слова: **синхронно-реактивний генератор, обмотка, ротор, частота обертання, обертовий момент, енергоефективність.**

Introduction. Currently, there is a growing need to create energy-efficient AC electric generators. They are widely used in many energy devices and facilities, such as wind power plants, diesel generators, as sources of electricity in railway, aviation and road transport [1].

The most widespread generators are self-excited generators, namely synchronous generators with permanent magnets, induction generators with dual power supply and phase rotor, asynchronous generators with excitation capacitors, synchronous generators with excitation windings on the armature.

Permanent magnet synchronous generators have higher efficiency, higher power density, which does not require an additional power source to excite the magnetic field, and higher reliability due to the absence of mechanical components, such as carbon brushes and slip rings [2] and include rare-earth magnetic materials, namely neodymium-iron-boron (NdFeB). Recently, the increased demand for electric vehicles has led to a sharp increase in the demand and cost of such magnets [3].

Induction generators with dual power supply and phase rotor have good energy characteristics, but the presence of a mechanical brush contact for supplying excitation to the rotor winding reduces their operational characteristics [4].

Generators with excitation capacitors have advantages over traditional AC generators, which consist in the absence of brush contact systems in their design, as well as in the simplicity of the design of the machine itself [5]. However, the operation of these generators is characterized by extreme instability, the dependence of the induced voltage on the value of the connected load and the frequency of rotation of the generator rotor.

Synchronous generators with excitation windings on the armature are the most studied electric machines today. They have good control and external characteristics.

However, the main disadvantage is the mechanical brush contact for supplying excitation windings.

A synchronous-reactive generator (SRG) with a double stator winding is a promising source of electricity, capable of operating effectively in many energy facilities and systems.

The goal of the work is to analyze the influence of the design of the double stator winding of the SRG on the output energy characteristics and to determine recommendations when designing this type of electrical machines.

Literature review. In recent years, the SRG has become a major competitor to synchronous generators with permanent magnets and induction generators due to its reliability, simple rotor design, no losses in the rotor winding, no magnets (thus eliminating the problem of demagnetization), and lower cost [6]. Numerous research works have been devoted to the study of SRG. In [7], the results of studies of SRG with a double stator winding with different variants of air barriers in the rotor are presented. It is shown that the use of SRG with a slotted rotor core allows inducing an open-circuit voltage 10 % higher than for SRG with a rotor of conventional air barriers. In [8], the operation of SRG with a series and shunt connection and its influence on transient processes in the generator are reported.

Works [9, 10] present the results of studies of the vibration characteristics of synchronous-reactive machines depending on the design of the rotor air barriers. In [11–13], a dynamic and performance analysis of a three-phase SRG was carried out to check the operation of the generator under various load conditions. The dependencies of the output voltage and power of the generator on the excitation current supplied to the winding located on the stator are presented. Work [14] presents the results of the finite element analysis to determine the generator performance depending on its design. Modeling the influence of the electromagnetic field on structural elements is also considered in [15].

The analysis of the literature indicates that the interest in SRG is significant, but questions remain regarding the influence of the design of the stator winding and the mutual influence of the working winding and the excitation winding on its energy characteristics. Therefore, this issue is devoted to the study, the results of which are presented in this work.

Presentation of the main material. Analytical and conditional-analytical dependencies used in the design and assessment of the operating properties of an electric machine based on its electrical parameters (resistance, inductance) and variables (voltages, currents) have sufficient convergence of the results of calculations and tests. Currently, in the design of SRGs, methods for determining the optimal design and energy parameters using the finite element method have also become widespread [12, 16]. In particular, research using multispheroidal models is presented in [17]. When modeling SRGs in a fixed coordinate system, difficulties arise in taking into account the change in parameters (inductance) of the stator phases during rotor rotation. To obtain the most acceptable result, it is better to consider the equations of synchronous machines in the *d-q* coordinate system rotating with the rotor [18]. The *d* axis is the axis of the highest magnetic rotor conductivity (rotor magnetic axis), the *q* axis is the axis of the lowest rotor conductivity (Fig. 1).

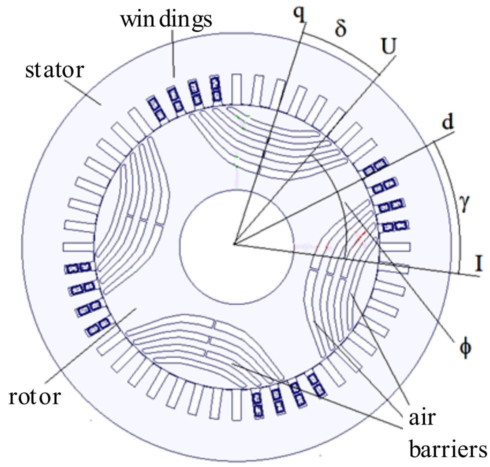

Fig. 1. Determining the relationship between angles ϕ, δ, γ

When writing the equations of the steady-state mode of the SRG, it is necessary to determine the electrical load factor, which should determine the external torque, for example, from a wind turbine or a diesel internal combustion engine. The angle δ or the angle γ is used as the load factor. The balance of the generator phase angles can be represented as:

$$\phi = \pi/2 - \delta + \gamma, \quad (1)$$

where ϕ is the phase angle between the current and voltage vectors; δ is the phase angle between the q axis and the voltage vector; γ is the phase angle between the d axis and the current vector.

The energy parameters of the SRG depend on the value of the angle γ. An increase in the electrical load connected to the generator stator winding leads to an increase in the value of this angle.

In [6], the influence of the phase angle between the magnetic axis of the rotor and the current vector of the stator winding on the characteristics of a synchronous-reactive motor was considered. Since a synchronous-reactive machine is a reversible machine, even when it operates in generator mode, we can talk about the dependence of the generator parameters on the angle γ. In the nominal mode of operation of the motor, the equations of longitudinal and transverse voltages have the form:

$$\dot{U}_d = (r + jx)i_d + jL_q \omega i_q ; \quad (2)$$

$$\dot{U}_q = (r + jx)i_q + jL_d \omega i_d , \quad (3)$$

where L_d, L_q are the total stator inductances along the d and q axes; i_d, i_q are the stator winding currents along the d and q axes; r is the stator phase resistance; x is the stator phase leakage resistance; ω is the generator shaft angular frequency.

In the operating mode, the electrical equilibrium equation at synchronous frequency for one phase of the SRG stator can be written as:

$$\dot{U} = I(r + jx) + jI_d x_d + jI_q x_q . \quad (4)$$

The dependence of the longitudinal and transverse resistances on the inductances L_d an L_q can be expressed as follows:

$$x_d = 2\pi f L_d; \quad (5)$$

$$x_q = 2\pi f L_q. \quad (6)$$

The currents of the longitudinal and transverse components of the generator winding can be found as:

$$I_d = \frac{U_i}{x_d}\cos\delta ; \quad (7)$$

$$I_q = \frac{U_i}{x_q}\cos\delta . \quad (8)$$

The expression for the stator current can be written [6] as:

$$\dot{I} = \frac{U_i}{r + j(x + x_d)} + \frac{U_i}{\dfrac{r_\gamma}{\text{tg}\gamma} + jx_\gamma} . \quad (9)$$

Variable values of the angle γ can be simulated by rotating the rotor relative to the stator at a constant value of the load on the stator winding in a fixed coordinate system, which corresponds to a constant amplitude of the phase current. At the same time, in a stationary coordinate system, the direction and value of the stator MMF vector will remain unchanged, and the position of the d axis will change. This was the basis for research on the SRG with different design options and mutual arrangement of the working winding and the stator excitation winding.

The research was carried out when designing a SRG with a power of 160 kW with a rotor speed of 1500 rpm and linear voltage at the output of 380 V for a diesel generator set. The diesel engine, which is supposed to be used with the SRG, develops a torque of 1100 N·m, at a shaft speed of 1500 rpm. The mechanical output power from the diesel engine will be 172.8 kW. Therefore, the useful electric power of the generator, taking into account losses, will be ≈160 kW. The outer diameter of the stator is 450 mm, of the rotor is 299 mm, the length of the stator and rotor packages is 265 mm. The geometry of the rotor air barriers and the electrical symmetrical load on the phases of the main winding, which was purely active, remained unchanged. This allowed us to conduct a comparative assessment of the options and select, in the opinion of the authors, the most optimal generator in terms of efficiency and dynamic characteristics. Of course, the dimensions of the rotor air barriers, the geometry of the rotor and stator, the materials of the stator or rotor affect the characteristics of the SRG, but the goal of this study is to determine the influence of the stator windings and their location on the output characteristics. Therefore, SRGs with the same geometry of the stator, rotor and unchanged magnetic core materials were studied.

In the first case, the design of the SRG with an equal distribution of the main winding and the excitation winding in 48 stator slots was considered (Fig. 2).

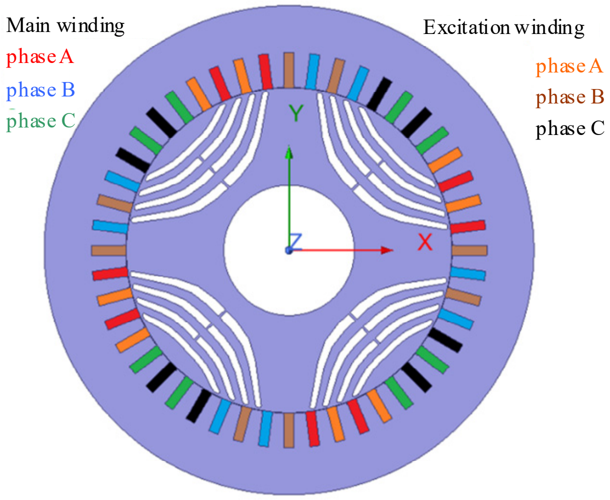

Fig. 2. Single-layer arrangement of the main and excitation windings of the SRG stator

Simulation and results. As mentioned above, by changing the angle γ, i.e., rotating the rotor relative to the stator, it is possible to simulate a change in the operating mode of the SRG at constant values of load and excitation. The results of this study are shown in Fig. 3.

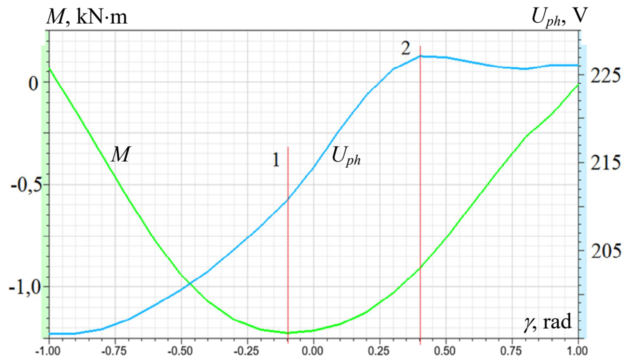

Fig. 3. Dependencies of external torque and output phase voltage on the angle γ

Lines 1 and 2 show the values of the angle γ for the maximum value of the torque (and, therefore, for the maximum input power of the generator) and for the maximum value of the output voltage. It can be seen that the values of these maxima do not coincide, which reduces the characteristics of the generator.

Figure 4 shows the distribution of magnetic flux density in the magnetic core with a single-layer arrangement of the main and exciting stator windings. The value of magnetic flux density in the stator tooth zones is 2 T, which leads to an increase in losses in the magnetic core. A similar analysis of the distribution of currents in the winding is presented in [19].

Figure 5 shows the graphs of the SRG torque and the output phase voltage.

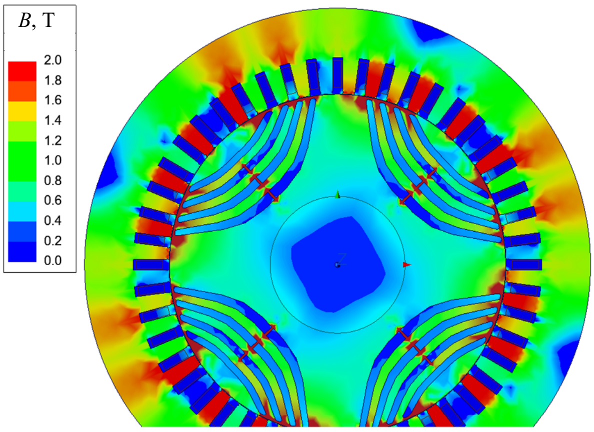

Fig. 4. Distribution of magnetic flux density in the magnetic core with a single-layer arrangement of the main and exciting windings of the SRG stator

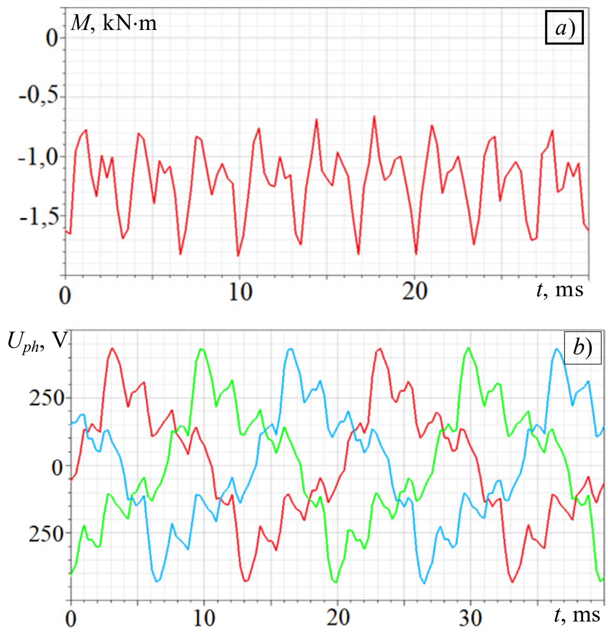

Fig. 5. Torque (*a*) and output phase voltage (*b*)

The «–» sign of the torque indicates that it is an external torque from the diesel engine rotating the generator rotor. Large torque pulsations can be observed, which indicate a significant change in the stator inductances along the d and q axes during rotor rotation.

The bearings of the generator mechanical system will experience large pulsating loads, which will affect their performance. The rated value of the output phase voltage is 222 V, which corresponds to 385 V of line voltage at an electrical load of 158 kW. The efficiency of the generator with such a stator winding was 91.2 %.

The option of a two-layer stator winding was considered (Fig. 6). Two-layer windings are very widely used as stator windings in modern production of high-power electric motors and the process of their manufacture is technologically advanced.

The main three-phase winding is located closer to the outer diameter of the stator, and the excitation winding is closer to the rotor surface. A study was conducted of four options for the mutual arrangement of the phases of the main and exciting windings with their two-layer arrangement (Fig. 7,*a*–*d*).

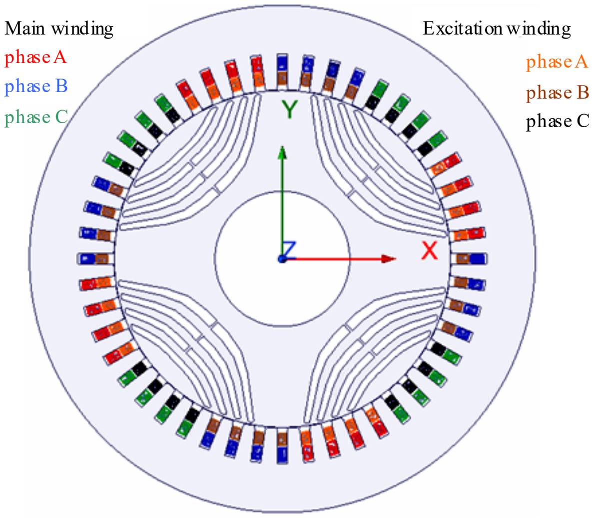

Fig. 6. Two-layer arrangement of the main and excitation windings of the SRG stator

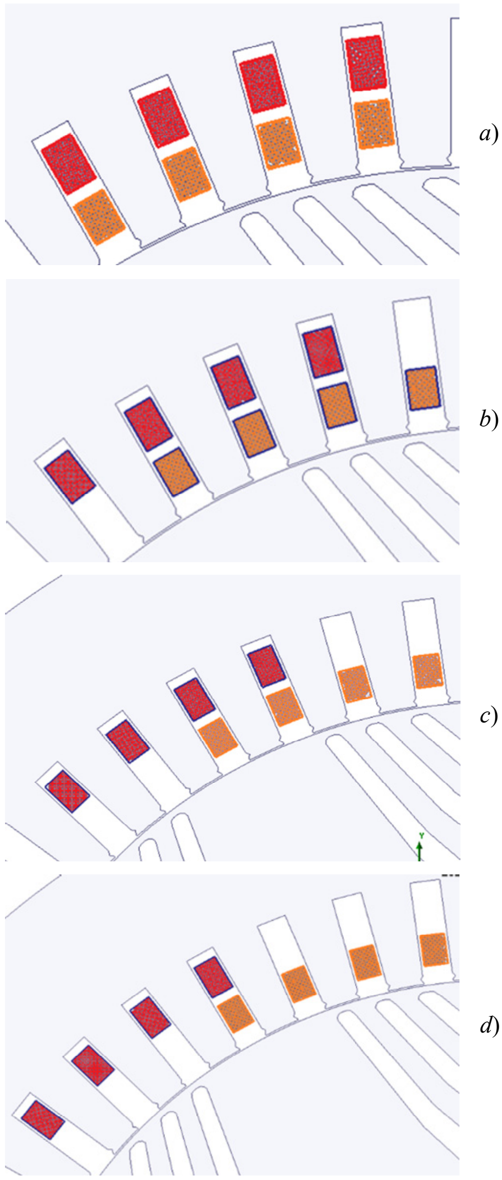

Fig. 7. Variants of the mutual arrangement of the phases of the main and exciting windings of the stator of the SRG: *a*) without phase shift; *b*) shift by 1 slot; *c*) shift by 2 slots; *d*) shift by 3 slots

The results of studies of the characteristics of the SRG with a two-layer arrangement of stator windings are shown in Fig. 8,*a*–*d*.

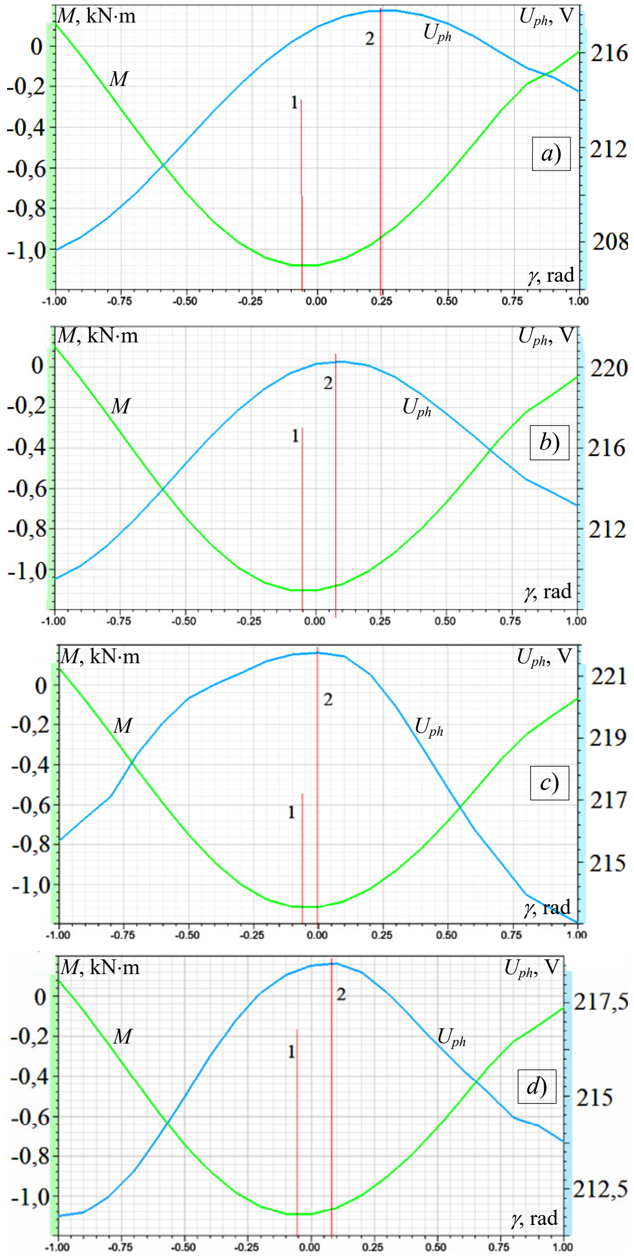

Fig. 8. Dependencies of external torque and output phase voltage on the angle γ at different mutual arrangements of the windings: *a*) without phase shift; *b*) shift by 1 slot; *c*) shift by 2 slots; *d*) shift by 3 slots

The SRG with a phase shift of the main and exciting windings by 2 slots practically has the coincidence of the maximum induced voltage and torque by the angle γ (Fig. 8,*c*). With this design of the stator windings, the largest phase voltage is also observed at the generator output (221.7 V) compared to other options.

The distribution of magnetic flux density in the magnetic core with a phase shift of the main and exciting windings by 2 slots is shown in Fig. 9.

The reduction in magnetic flux density in the tooth zones and the stator yoke compared to the single-layer winding option reduces losses in the magnetic core by 24 % (Fig. 10).

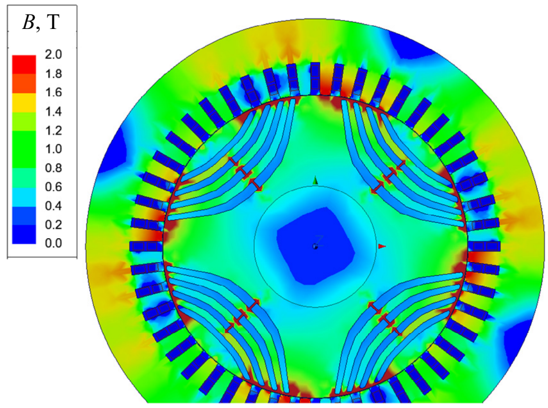

Fig. 9. Distribution of magnetic flux density in the magnetic core when the phases of the main and exciting windings are shifted by 2 slots

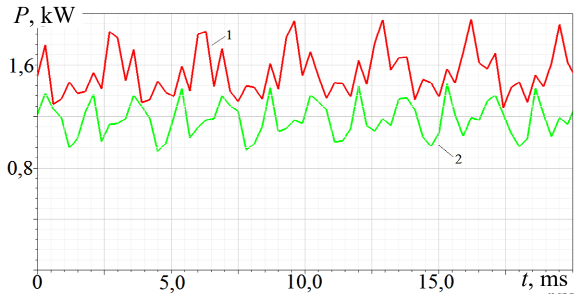

Fig. 10. Losses in the stator magnetic core with a single-layer stator winding (1) and with a double-layer winding with a phase shift of the main and excitation windings by 2 slots (2)

The conducted studies of the torque on the SRG rotor and the shape of the output voltage for the best option of a two-layer design of the stator windings show a reduction in pulsations compared to a single-layer design (Fig. 11).

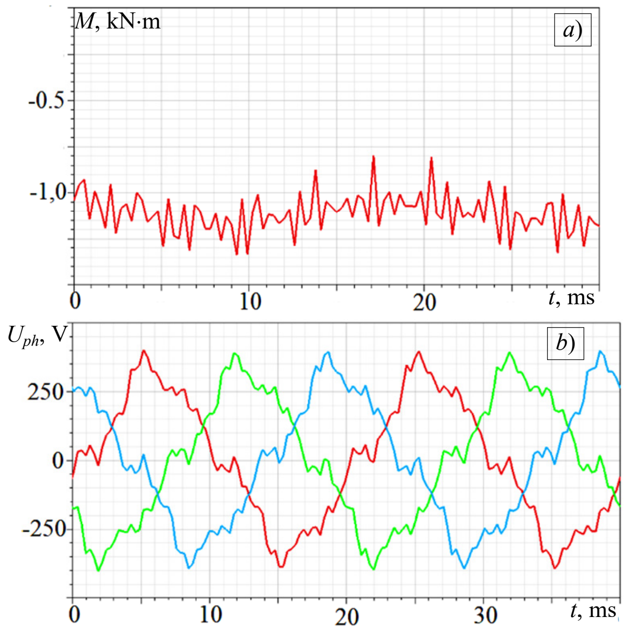

Fig. 11. Torque (*a*) and output phase voltage (*b*) for a SRG with a two-layer arrangement of the main and excitation windings and a mutual displacement of 2 slots

To compare the oscillations of the torque of the SRG with a single-layer stator winding and with a double-layer winding when the phases of the main and exciting windings are shifted by 2 slots, spectrograms were created with the determination of amplitudes in the frequency range of 0–1 kHz (Fig. 12).

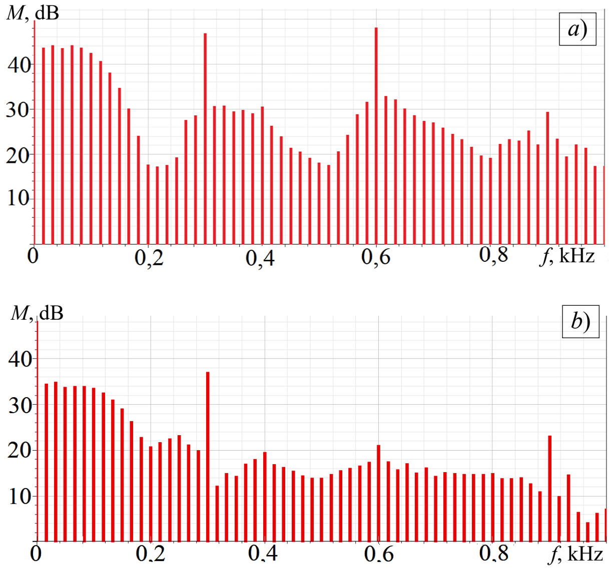

Fig. 12. Spectrograms of the torque with a single-layer stator winding (*a*) and with a double-layer winding with a phase shift of the main and exciting windings by 2 slots (*b*)

Comparison of the spectrograms of the SRG with a single-layer winding and a double-layer stator winding showed a decrease in amplitude at a frequency of 100 Hz by 26 %; for a frequency of 150 Hz – by 14 %. For both variants at a frequency of 300 Hz, a sharp increase in amplitude is observed, but for the SRG with a double-layer winding the amplitude is 53 % less than for the SRG variant with a single-layer winding. Reducing torque ripples will have a positive effect on the performance of bearing units and will lead to a decrease in vibrations during the operation of the SRG.

The results of determining losses and efficiency for the selected variant of the SRG with a double-layer stator winding with a phase shift of 2 slots are given in Table 1.

Table 1

Losses and efficiency of the SRG with a two-layer stator winding with a phase shift of 2 slots

No.	Parameter	Values
1	Electrical losses in stator windings, W	7152
2	Losses in the magnetic core steel, W	1621
3	Mechanical losses, W	2600
4	Additional losses, W	1600
5	Total losses, W	12973
6	Efficiency, %	92,5

Conclusions. The conducted studies of the SRG with the main and excitation windings of the stator showed that there is a significant dependence of the characteristics on the design of these windings. The considered variant with a single-layer arrangement of both windings in the stator slots is characterized by the fact that there are large torque pulsations (with an amplitude of 0.6 kN·m) and lower efficiency than in the other considered variants.

The two-layer arrangement of the main and exciting windings of the stator showed the best results in the analysis of the SRG. However, the research has established that the mutual arrangement of the phases of the main and exciting windings also has a significant impact on the SRG parameters. The results of the calculation experiments have determined the best option for the implementation of the two-layer SRG winding, namely with a phase shift of 2 slots from each other. This provides a significant reduction in torque fluctuations and an increase in the energy characteristics of the SRG and allows to obtain high efficiency (92.5 %) with a useful electric power of 160 kW at the SRG output.

Conflict of interest. The authors declare no conflict of interest.

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