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ELECTRIC MACHINE WITH AXIAL MAGNETIC FLUX, PERMANENT MAGNETS AND MULTILAYERED PRINTING WINDINGS

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The use of printed windings in electric machines with permanent magnets and axial magnetic flux allows to reduce their axial size and significantly to increase the current density in the windings. Experimental studies of printed windings for heating confirmed that at a current density of $J = 22\ A / mm^{2,}$ the steady-state temperature of the printed windings does not exceed 80 °C. For given dimensions of an electric machine with axial magnetic flux, permanent magnets and multilayer printed windings (outer diameter of the stator, axial length of the stator), numerical studies were carried out and the optimal thickness of the permanent magnets was determined at which the maximum value of the electromagnetic torque is reached. Also, as a result of numerical studies, it was found that the presence of teeth on the stator allows you to increase the electromagnetic torque of the electric machine by about 25% compared with the version of the magnetic system without teeth on the stator. A prototype of an electric machine with multilayer printed windings was made and the dependences of voltage and power in the generator mode were determined when connecting the windings through the rectifier diode bridge to the active load. The computational model of the generator adequately describes the physical model. The difference discrepancy between the calculated and experimental values does not exceed. It is shown that the average difference discrepancy between the experimental and calculated values does not exceed ε = 5.5%. The characteristics of the studied generators are calculated in the Simcenter MagNet and Simcenter MotorSolve software packages. References 10, figures 7, table 1.

Key words*:* permanent magnets, printed windings, electromagnetic torque, external characteristics, experimental sample.

Introduction. Nowadays electromechanotronic actuators with printed windings and axial magnetic flux (disk type) for various applications are being intensively developed. This type of design of the electromechanical actuator be composed of printed windings that are fixed in the stator, and the rotor with permanent magnets that are fixed in a special holder. A stator with a printed winding simplified the design of the electromechanotronic device and allowed to significantly reduce the axial length of such a device. Another positive property is small thickness and correspondingly large widths and coil conductors. Therefore, the cooling of the printed conductor is much better. These factors can increase the current in the conductors and reduce the size and weight of the electric machine.

For example, in [1], the results of a study of an electromechanical device based on a brushless direct current electric motor with an axial magnetic flux and a printed winding for a low-power vortex pump are presented. In [2], the design and analysis of an electric motor with a printed winding, permanent magnets and axial flux for use in nanosatellites are presented. In [3], a miniature motor design with a diamond-shaped printed winding and axial flux is proposed, the axial length of which is only 3 mm. In [4, 5], a methodology for designing engines with printed windings and axial flux is presented, which is used as miniature engines for computer hard drives. In [6], studies are presented of a high-speed electric motor with an axial flux and a printed winding and permanent magnets on the rotor, the magnetization vectors of which have a direction in accordance with the Halbach concept. The small axial length of the electric motor with printed windings

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allows it to be embedded in the wheel hub of a vehicle [7]. In [8], an original layout of a permanent magnet motor with an axial magnetic flux and a two-phase wave printed winding was proposed. This configuration of the printed winding allows you to increase the number of pole pairs and the frequency of the motor.

The motors listed above are used for actuators and, as a rule, have a low power. However, the technology of printed windings is being used in industry for electric motors and generators with permanent magnets of high power. One of such already proven technologies is the technology developed by ThinGap, which is based on a special structure of windings made by printing [9].

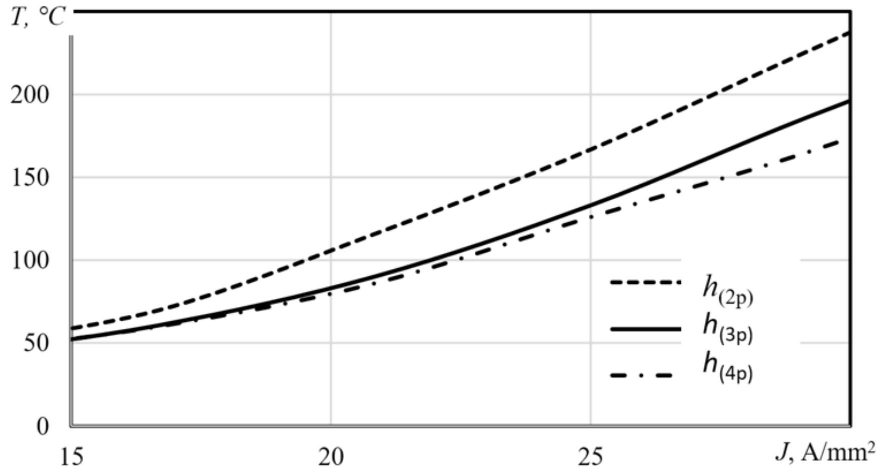
Due to the high use of the working volume in which the process of electromechanical energy conversion takes place, this technology is an attractive alternative to traditional cylindrical machines. ThinGap, a company that implements this technology, has achieved high results, and its products are brushless motors based on a patented progressive technology with cylindrical printed windings. The windings of ThinGap engines are manufactured with high precision and due to this and the small gap, such machines have large specific torques and powers (per unit mass) compared to traditional machines.

The purpose of the work is to study an electric machine of low power (up to 2 kW) with axial magnetic flux, multilayer printed windings and permanent magnets with variations in the geometry of the stator magnetic system and the thickness of permanent magnets, as well as a comparison of the calculated and experimental characteristics obtained when testing a prototype of an electric machine.

The heating study of the printed winding. The using of a printed winding can significantly simplify the design, increase manufacturability and reduce the axial length of the electric machine. Another positive quality of printed windings is the ability to work at higher current densities compared to a traditional winding due to more efficient heat removal from the surface of the printed winding. Therefore, at the first stage, experimental heating studies of multilayer printed windings were carried out and the nominal current density at which the printed winding was heated to a temperature of not more than 80 ° was determined.

For this, samples of printed windings (coils, Fig. 1, *a*) were made. Each winding consists of 18 layers of copper, the thickness of one layer is 0.05 mm. Between the even layers of copper there is an insulating layer "core", the thickness of which is 0.13 mm, between the odd layers of copper there is an insulating layer "prepreg", the thickness of which is 0.062 mm. Three coils with different prepreg layer thicknesses were made: two layers $h_{(2p)}$ = 0.124 mm; three $h_{(3p)}$ = 0.186 mm; four $h_{(4p)}$ = 0.248 mm.

a



b

Fig. 1

Tests for heating were carried out as follows. The tested winding was connected to a current source, a certain current value was set, and after a given period of time, the temperature on the surface of the coil was measured. In fig. 1b shows the temperature on the surface of the printed windings as a function of the current density in these windings. Analyzing the heating data of the printed windings, it should be noted that the double-layer windings prepreg ($h_{(2p)}$) are the most heated. Coils with three layers of prepreg ($h_{(3p)}$) and four ($h_{(4p)}$, respectively, are heated almost the same. Therefore, it is proposed to use the variant with three layers of prepreg to make a prototype of an electric machine. As a result of heating tests, it was found that printed with three layers of prepreg ($h_{(2p)}$) heats up to a steady temperature of 80° in a time t = 10 min and a current in the winding I_{coil}=2.9 A, which corresponds to a current density of J=22 A/mm^2. For short-term heating (t=2 min), the current density can be increased to J=38 A/mm^2. Therefore, in further calculations, the current density J=22 A/mm^2 was assumed to be nominal for a printed winding with three prepreg layers.

Numerical studies of various configurations of the magnetic system. At the next stage of research using computer simulation in the Infolitica Magnet package, a study was made of the influence of the configuration of the magnetic system on the maximum value of the electromagnetic torque. For the given dimensions of the electric machine (the outer diameter of the stator, the axial length of the stator), three options were considered: model 1 – (18 coils, 24 magnets); model 2 – (27 coils, 24 magnets); model 3 – (18 coils, 20 magnets). The simulation results showed that the best performance has a 3 – model (18 coils, 20 magnets). Therefore, this model was taken as the basis for further research. In fig. 2 shows a computer model of the investigated electric machine, the main parameters are in table.

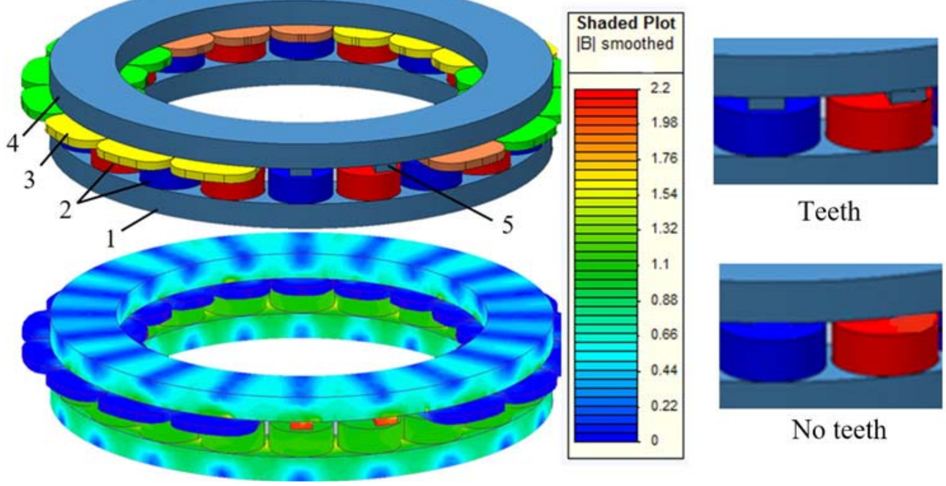


Fig. 2

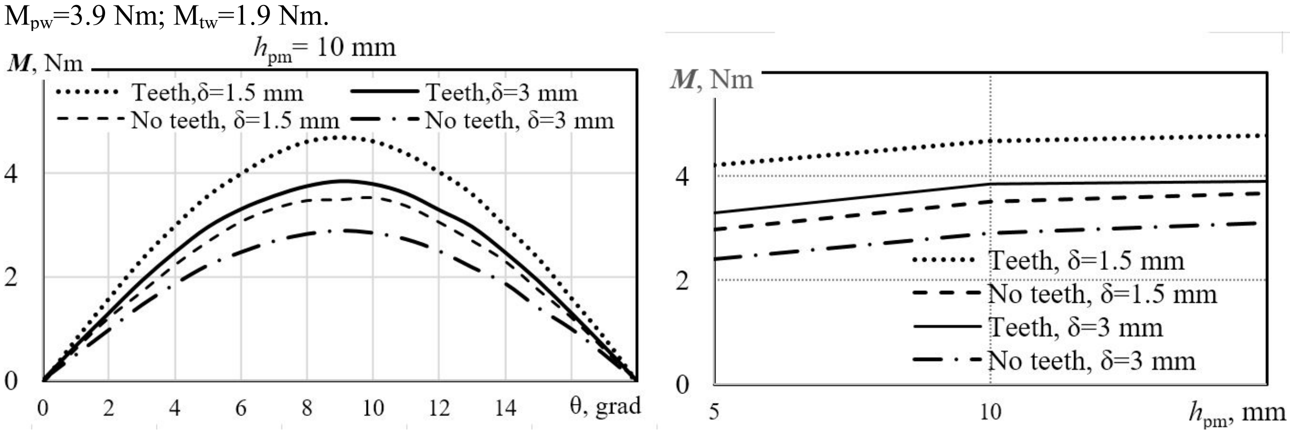
The rotor of this electric machine consists of a steel core *1*, on which cylindrical permanent magnets are fixed *2*. Multilayer printed windings *3* are fixed on the stator *4*. Modeling was carried out both for the magnetic system with teeth *5* on the stator, and without teeth. For the convenience of displaying the stator teeth, two printing coils in Fig. 2 are not shown and Fig. 2 on the right shows fragments of the magnetic system with teeth on the stator and without teeth

The calculations of model 3 were carried out by the finite element method in the Infolytica Magnet package in a three-dimensional setting. The dependence of the electromagnetic torque on the angle of rotation of the rotor was calculated for the time when the current in phase A is maximum and conditionally positive A(+), phase B and C are conditionally negative and equal to half of the maximum B(-0.5) and C(-0.5). Thus, when calculating the magnetic field and electromagnetic torque in the model under study, the current density in phase A was set equal to J_A=22 A/mm^2, and in phases B and C it was set J_B=J_C=11 A/mm^2.

As a result of previous studies [10], it was found that in electric machines with axial flow it is advisable to use cylindrical permanent magnets instead of trapezoidal ones. The electromagnetic torque for cylindrical magnets is approximately 10% less than in an electric machine with trapezoidal magnets, however, the manufacture of a rotor with cylindrical magnets is greatly simplified. It should also be noted that the cost of cylindrical magnets is lower than the cost of trapezoidal magnets, and the holes for the magnets can made with a standard mill at one pass. Thus, the use of cylindrical magnets for electric machines with axial magnetic flux is preferable to trapezoidal magnets. Therefore, in further studies, the option with cylindrical magnets was taken as the basis. Two models were studied: without teeth on the stator and with teeth located in the inner part of the coils (Fig. 2). The simulation results showed that the magnetic system is saturated only in the corners of the stator teeth, while in the back of the stator there is no saturation of the magnetic system, the induction does not exceed B=1.1 T.

We investigated models with a magnet thickness h_{pm}=5, h_{pm}=10 and h_{pm}=15 mm and a working gap of δ=1.5, δ=3 mm. The dependence of the electromagnetic torque acting on the rotor on the angle of rotation of the rotor for the models under study was calculated in the range from the d axis (the field of the corresponding rotor poles is directed according to the field created energized stator phases) to the q axis (the field of the corresponding rotor poles is directed opposite to the field created energized stator phases) For the models under study, this range is 18°. The dependence of the electromagnetic torque on the angle of rotation of the rotor for the thickness of the magnets h_{pm}=10 mm is shown in Fig. 3, *a*, which illustrates that the presence of teeth in the stator can increase the electromagnetic torque of an electric machine by about 25%. In fig. 3, *b* shows the maximum values of the electromagnetic torque depending on the thickness of the permanent magnets, the magnitude of the working gap for the two configuration options of the stator magnetic system (with teeth and without teeth).

Analyzing these curves, it should be noted that an increase in the thickness of the magnets leads to an increase in the maximum torque, however, the calculated value of the torque for magnets with a thickness of h_{pm}=15 mm is only 1% higher than the value of the torque for magnets with a thickness of h_{pm}=10 mm, therefore, taking into account the high cost of permanent magnets, the thickness of the magnets equal to 10 mm was accepted as optimal. It should be noted that the maximum value of the electromagnetic torque for a model with teeth on the stator and a working gap of δ=3 mm is larger than that of a model without teeth on the stator and a working gap of δ=1.5 mm. A comparison was also made of the maximum electromagnetic torque for the model with teeth on the stator and printed windings, the nominal current density of which is J = 22 A/mm^2, and the fill factor of the winding window is $k_{fill\ factor}$=0.19 and for the model with a traditional winding with a round wire (J=5 A/mm^2, $k_{fill\ factor}$=0.4). The comparison results are as follows: for a model with printed windings, teeth on the stator and a working gap of δ=1.5 mm, the maximum value of the electromagnetic torque is M_{pw}=4.7 Nm; for a model with a traditional winding – M_{tw}=2.2 Nm. For the size of the working gap equal to δ=3 mm, the maximum values of the electromagnetic torque are respectively equal: M_{pw}=3.9 Nm; M_{tw}=1.9 Nm.



a *b*

Fig. 3

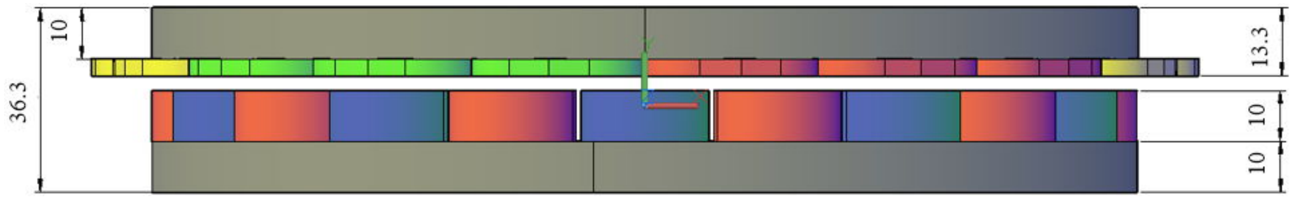
Name	Value
Stator Outer Diameter – D_a, mm	195
Stator Inner Diameter – D_i, mm	144
Magnets Diameter – D_{pm}, mm	25
Magnet Thickness – h_{pm}, mm	10
Number of magnets – n_{pm},	20
Type of magnets	N42
Width of the conductive layer – b_{layer}, mm	12
The number of layers in the circuit board – k_{layer}	18
Thickness of one conductive layer – h_{layer}, mm	0.05
The thickness of the printed winding – h_{pw}, mm	3.3
The number of turns in one layer – W_1	4
The number of turns in one winding – W_{coil}	68
Coil width in each layer – b_{coil}	2.4
The distance between the turns in each layer – $b_{b.t}$, mm	0.5
Area of the one turn in the layer–S_{1turn}, mm^2 ($h_{layer}\times b_{coil}$)	0.12
Winding window area – S_{wa}, mm^2	42.7
Area of copper in the winding window – S_{Cu}, mm^2	8.16
Winding window fill factor, $k_{fill\ factor}$	0.19
Coil current density – J, A/мм^2	22
The number of ampere-turns in the coil – IW, A	180
Phase current in the winding – I_{ph}, A (J = 22 A/mm^2)	2.64
Load current – I_{load}, A (J = 22 A/mm^2)	3.4

Thereby, with the same area of the winding window, the use of the printed winding, despite a 2.1 times smaller value of the fill factor of the winding window, allows you to increase the maximum value of the electromagnetic moment by 52% due to a 4.4 times higher nominal current density in the printed winding.

According to the results of numerical studies, a prototype of an electric machine with multilayer printed windings on a stator was made, the main parameters of which are given in the table. It should be noted that the main purpose of manufacturing the prototype was to compare the calculated and experimental characteristics of the electric machine with printed windings, therefore, to simplify the design of the prototype, the working gap between the stator and rotor was δ=3 mm.

Fig. 4, *a* shows the main dimensions of the magnetic system of the prototype, and Fig. 4, *b* is a photograph of a multilayer printed winding (the photo shows half of the winding). The stator winding is three-phase. Each phase consists of 6 coils. In this case, two coils of each phase are turned on counter to the other coils. In fig. 4, *b* schematically shows the directions of currents in the coils of the printed winding, which can be schematically represented as follows: A1 (+), A2 (-), A3 (+), B1 (-), B2 (+), B3 (-), C1 (+), C2 (-), C3 (+), B4 (-), i.e. alternating three coils of each phase. This direction of currents in the coils and their alternation provides the maximum electromagnetic torque acting on the rotor of an electric machine with a ratio of (18 coils, 20 magnets). A multilayer printed winding is fixed on the stator core, which is a 10 mm thick ring core with triangular teeth made of lined electrical steel. The height of the teeth corresponds to the thickness of the printed winding. The dimensions of the tooth cross section are such that a permanent rotor magnet with a diameter of 25 mm can completely overlap the stator tooth.

The rotor core is made of structural steel, on which permanent cylindrical magnets are fixed; a multilayer printed winding is mounted on a stator with teeth made of lined electrical steel.



a

b

Fig. 4

Numerical and experimental studies. At the next stage, the prototype of electric machine in the generator mode with active load was studied. The research mode is as follows: the phases of the generator are included in the "star", an active load is connected through a rectifier bridge with six diodes (Fig. 5). In this case, 6 windings of each phase were connected in series. Tests of the prototype and numerical simulation of the corresponding computer model were carried out. In numerical and experimental studies, the following values of the rotor speed of the generator were set: n=1250 rpm; n=1500 rpm and several values of the active resistance of the load: R_{load}=22, 45, 67, 1000 Ohms.

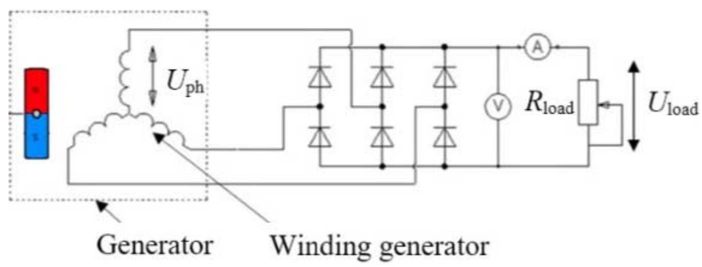
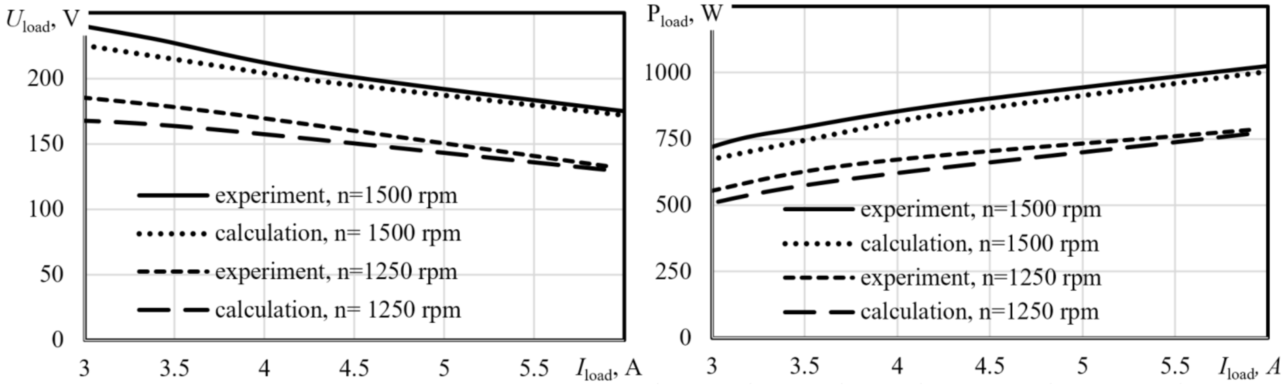


Fig. 5

Fig. 6, *a* shows the dependences of the voltage at the load, and Fig. 6, *b* – power in the load from the load current at the rotor speed of 1250 and 1500 rpm. Analyzing the results shown in Fig. 6, it should be noted that the average discrepancy between the experimental and calculated values does not exceed ε=5.5%. At a nominal phase current equal to I_{ph}=2.64 A, the current in the load is I_{load}=3.4 A. At this current and rotation speed n=1500 rpm, the power in the load was equal to P_{load}=780 W, the current density in the windings at this current was J=22 A / mm^2. However, with such a high current density, intense heating of the printed windings was not observed; the windings did not heat above 80 °C. Short-term (up to t=2 min) the current density can be increased to J=38 A/mm^2, in this case the power at n=1500 rpm is P_{load}=1000 W.



a ***b***

Fig. 6

The discrepancy between the calculated and experimental values does not exceed 5.5%. This indicates the adequacy of the calculation models and the calculation results can justifiably be applied to other power values of generators with a different configuration of the magnetic system and its other sizes. Additional numerical studies of an electric machine with printed windings in the generator mode were carried out with a working gap of δ=1 mm and a rotational speed of n=3000 rpm.

Fig. 7 shows the dependences of the voltage and power of the generator on the phase current of the model without teeth and with teeth on the stator at a rotor speed of n=3000 rpm. With a nominal phase current equal to I_{ph}=2.64 A, the nominal phase voltage for the model without teeth is U_{ph}=175 V, the rated power in the generator mode for this model is P_{load}=1470 W. For the model with teeth, the nominal phase voltage is significantly higher than U_{ph}=250 V, and the power is P_{load}=2000 W. Thus, the use of a stator with teeth made it possible to increase power by 27%.

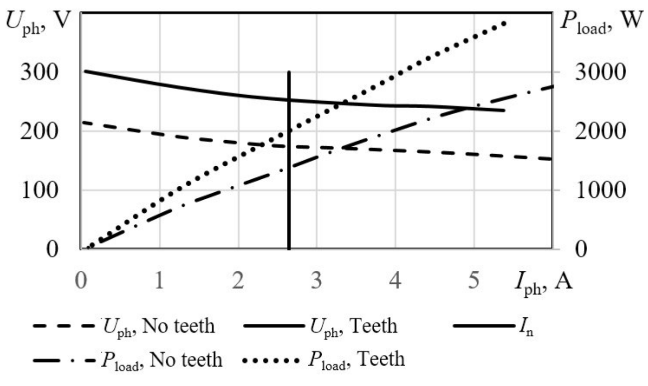


Рис. 7

Conclusions. The proposed models will allow to fulfill calculations of electromechanical processes in an electric machine with axial flow, permanent magnets and multilayer printed windings. For given sizes of an electric machine with multilayer printed windings (outer diameter of the stator, axial length of the stator), numerical studies were carried out and the optimal thickness of permanent magnets was determined at which the maximum value of the electromagnetic torque is reached. Also, as a result of numerical studies, it was found that the presence of teeth on the stator allows you to increase the electromagnetic torque of the electric machine by about 25% compared with the version of the magnetic system without teeth on the stator.

A prototype of an electric machine with multilayer printed windings was made and the dependences of voltage and power in the generator mode were determined. The discrepancy between the calculated and experimental values does not exceed 5.5%. This indicates the adequacy of the calculation models and the calculation results can justifiably be applied to other values of the power of generators with a different configuration of the magnetic system and its other sizes.

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УДК 621.313.8

ЭЛЕКТРИЧЕСКАЯ МАШИНА С ОСЕВЫМ МАГНИТНЫМ ПОТОКОМ, ПОСТОЯННЫМИ МАГНИТАМИ И МНОГОСЛОЙНЫМИ ПЕЧАТНЫМИ ОБМОТКАМИ.

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Применение печатных обмоток в электрических машинах с постоянными магнитами и осевым магнитным потоком позволяет уменьшить их осевой размер и существенно увеличить плотность тока в обмотках. Экспериментальные исследования печатных обмоток на нагрев подтвердили, что при плотности тока $J = 22$ А/мм^2 установившаяся температура печатных обмоток не превышает 80 °С. Для заданных размеров электрической машины с осевым магнитным потоком, постоянными магнитами и многослойными печатными обмотками (наружный диаметр статора, осевая длина статора) проведены численные исследования и определена оптимальная толщина постоянных магнитов, при которой достигается максимальное значение электромагнитного момента. Также в результате численных исследований установлено, что наличие зубцов на статоре позволяет увеличить электромагнитный момент электрической машины примерно на 25% по сравнению с вариантом магнитной системы без зубцов на статоре. Изготовлен опытный образец электрической машины с многослойными печатными обмотками и определены зависимости напряжения и мощности в генераторном режиме при подключении обмоток через диодный мост выпрямителя к активной нагрузке. Расчетная модель генератора адекватно описывает физическую модель. Расхождение между *расчетными и экспериментальными значениями не превышает ε = 5.5%. Расчет характеристик исследуемых генераторов проводится в пакетах программ Infolytica MotorSolve и Magnet.* Бібл. 10, рис. 7, табл. 1.

Ключевые слова: постоянные магниты, печатные обмотки, электромагнитный момент, внешние характеристики, экспериментальный образец.

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ЕЛЕКТРИЧНА МАШИНА З ОСЬОВИМ МАГНІТНИМ ПОТОКОМ, ПОСТІЙНИМИ МАГНІТАМИ І БАГАТОШАРОВИМИ ДРУКОВАНИМИ ОБМОТКАМИ

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Застосування друкованих обмоток в електричних машинах з постійними магнітами і осьовим магнітним потоком дозволяє зменшити їхній осьової розмір і суттєво збільшити щільність струму в обмотках. Експериментальні дослідження друкованих обмоток на нагрівання підтвердили, що при щільності струму J = 22 А/мм² усталена температура друкованих обмоток не перевищує 80 °С. Для заданих розмірів електричної машини з осьовим магнітним потоком, постійними магнітами і багатошаровими друкованими обмотками (зовнішній діаметр статора, осьова довжина статора) проведені чисельні дослідження і визначена оптимальна товщина постійних магнітів, при якій досягається максимальне значення електромагнітного моменту. Також у результаті чисельних досліджень встановлено, що наявність зубців на статорі дає змогу збільшити електромагнітний момент електричної машини приблизно на 25% в порівнянні з варіантом магнітної системи без зубців на статорі. Виготовлено дослідний зразок електричної машини з багатошаровими друкованими обмотками і визначено залежності напруги і потужності в генераторному режимі при підключенні обмоток через діодний міст випрямляча до активного навантаження. Розрахункова модель генератора адекватно описує фізичну модель. Розбіжність між розрахунковими і експериментальними значеннями не перевищує ε = 5.5%. Розрахунок характеристик досліджуваних генераторів проводиться в пакетах програм Simcenter MagNet і Simcenter MotorSolve. Бібл. 10, рис. 7, табл. 1
Ключові слова: постійні магніти, друковані обмотки, електромагнітний момент, зовнішні характеристики, експериментальний зразок.

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