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COMPARATIVE ANALYSIS OF ELECTRIC MACHINES CHARACTERISTICS WITH PERMANENT MAGNETS FOR ELECTRIC VEHICLES AND WIND TURBINES

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The results of a numerical and experimental study of an electric machine with cylindrical permanent magnets are presented. It is shown that if a squirrel-cage rotor in a standard induction motor is replaced by a rotor with permanent magnets, then a significant increase in the specific power of the electric machine can be obtained. Numerical studies and analyses of the characteristics of an electric machine with tangentially magnetized neodymium and ferrite magnets in the motor mode have been carried out. It is shown that in order to ensure maximum specific characteristics for use in electric vehicles, it is necessary to take into account the driving cycle and carry out liquid cooling of the electric motor. Also, a comparison of the characteristics obtained during testing of an experimental sample in the generator mode and the characteristics obtained in the calculation models was made. It is shown that the discrepancy between the calculated and experimental dependences for several values of the rotor speed is no more than 4%. The characteristics of the electrical machines under study were calculated using the Simcenter MagNet and Simcenter MotorSolve software packages. References 7, figures 6, tables 2.

Key words: numerical simulation, electric motor for electric car, permanent magnets, driving cycle, performance characteristics, thermal calculation, wind power plant.

In recent years, the research and production of electric machines with permanent magnets has been intensified. This is primarily due to the increasing production of electric vehicles, in the production of which there is a clear trend towards the use of electric motors with permanent magnets due to their high power density compared to other types of electric motors (asynchronous, direct current and SRM) [1]. From year to year, the use of electric generators with permanent magnets for wind turbines, as well as electric motors used in various industries where it is necessary to control the rotor speed, is also increasing. This article shows how a standard squirrel-cage induction motor can be converted into an efficient permanent magnet motor at low cost. Thus, it is possible to organize the production of highly efficient synchronous machines with permanent magnets without significant resources and investments [2].

The purpose of this article is to analyze and compare the characteristics of an electric machine in the motor and generator mode with the most common configuration of the rotor magnetic system, namely, with permanent magnets of tangential magnetization. The configuration of the magnetic system, made on the basis of the stator of a standard AIR112MV8 asynchronous motor with a rotation axis height of 112 mm and the number of pole pairs $2p$=4 [3].

Since the cost of rare earth magnets is quite high, there is considerable interest in machines with ferrite magnets, the cost of which is significantly lower. This article analyzes and compares the characteristics of motors with neodymium magnets (N40SH) and cheap ferrite magnets - such as Ceramic 10 (C10). Neodymium magnets (N40SH) have temperature stability up to 150°C, ferrite magnets (C10) have temperature stability up to 300°C.

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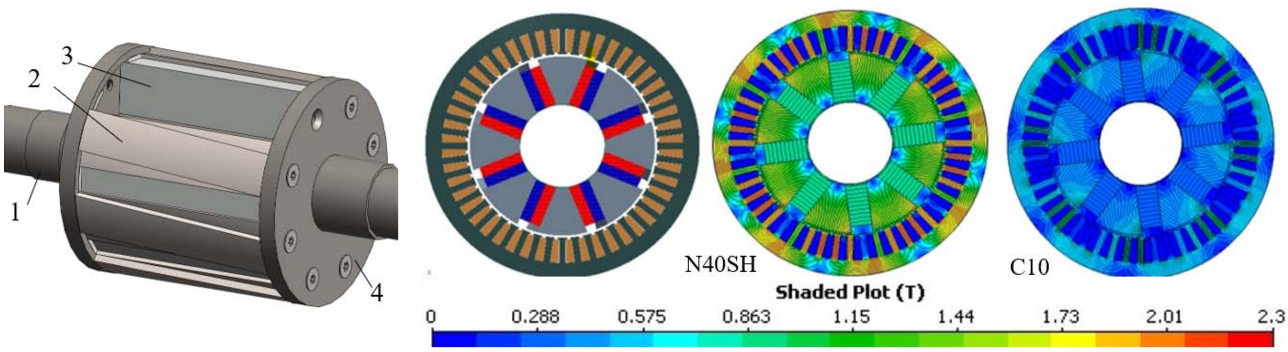
In the research, a stator of a standard asynchronous motor was used, the main technical characteristics of which are as follows: rated voltage when the stator windings are connected to a “star” – U_n=380 V, rated current – I_n=7.1 A, rated power – P_n=3 kW, rated rotation speed – n=710 rpm, efficiency – 80%, cos φ =0.73. The main technical parameters of the stator: outer diameter of the stator – D_a=191 mm; stator inner diameter – D_i =132 mm; number of stator slots – Z=48; slot height – h_{slot}=18.1 mm; axial length of the stator package – L=130 mm.

In a standard asynchronous motor, the squirrel-cage rotor was replaced with a rotor with permanent magnets, which consists of a non-magnetic shaft *1*, ferromagnetic poles *2*, in which bevels are carried out to reduce the gear moment (cogging). Permanent magnets *3* and poles *2* are fixed on the shaft with the help of two cups *4*, which are made of non-magnetic material (Fig. 1, *a*). In this figure, for convenience, one of the ferromagnetic poles is not shown.

The calculation of the magnetic field and the characteristics of the electric machine was carried out in the software package Simcentr MotorSolve and Simcentr Magnet [4]. On Fig. 1, *b* shows the cross section of the magnetic system and the distribution of the magnetic flux density at rated current for an electric machine with neodymium magnets (N40SH) and ferrite magnets (C10).



a ***b***

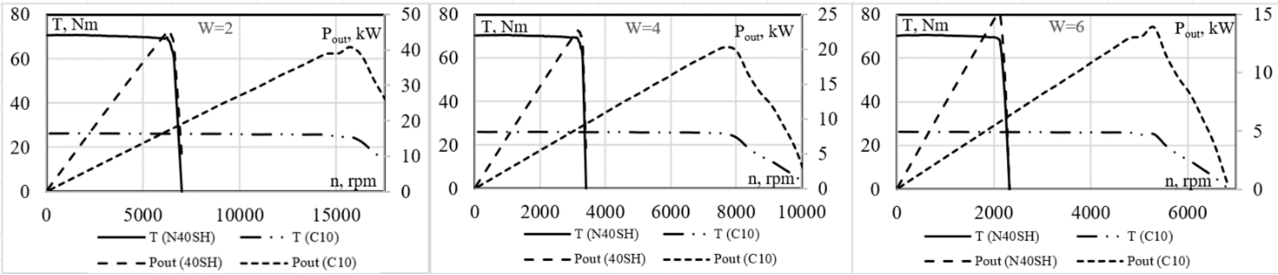
Fig. 1

As it is known, in contrast to asynchronous motors, in motors with permanent magnets, the dependence of the electromagnetic torque on the rotor speed has an almost constant value up to a certain rotor speed, after which the torque and power of the electric motor have a sharply falling character. This is explained by the fact that after a certain rotation frequency, the induced back EMF, proportional to the number of turns of the stator windings, becomes comparable with the supply voltage of the stator phases, which leads to a decrease in the phase current in the windings and a sharp drop in the torque and power of the electric motor.

The article investigates the characteristics of a motor with permanent magnets, the number of turns in the stator coils of which is chosen equal to: W = 2; W=2; W = 6 and it is shown that by varying these parameters and the type of permanent magnets, it is possible to design the optimal configuration of the magnetic system for the given characteristics of the electric machine.

When studying the characteristics of electrical machines, the stator phases were connected in a "star", and the four coils of each phase were connected in series. In all calculations, the current density in the stator windings is assumed to be the same and equal to J=7.2 A/mm^2, coil fill factor – k=40%. The rated currents for each value of the number of turns are as follows: W=2 – I_n=97.8 A; W=4 – I_n=48.9 A; W=6 – I_n=32.6 A.

On Fig. 2, *a* shows the operating characteristics of an electric machine in the motor mode with neodymium (N40SH) and ferrite magnets (C10) with the number of turns of the stator winding W = 2. It should be noted that with neodymium magnets, the rotational speed and power begin to decrease sharply after the rotational speed equal to n = 6500 rpm, with ferrite magnets, respectively, after the rotational speed – n = 15750 rpm. This is explained by the fact that ferrite magnets have a residual induction approximately three times less than neodymium magnets. Although the electromagnetic torque of a machine with ferrite magnets is less than that of a machine with neodymium magnets, due to the ability to operate at a higher speed, the power of both machines is approximately equal. On the other hand, the cost of ferrite magnets is significantly less than neodymium ones, and therefore they can have a competitive advantage in applications where high electromagnetic torque is not needed.



a *b* *c*

Fig. 2

Table 1

Parameter	n, rpm	P_{out}, kW	$P_{loss\Sigma}$, W	η, %	$\frac{P_{PM}}{P_{IM}}$	$\frac{\eta_{PM}}{\eta_{IM}}$, %
N40SH	710	5.25	0.45	92.0	1.75	15.0
C10	710	1.94	0.44	81.6	0.65	2.0
IM(2p=4)	710	3	-	80	-	-
N40SH	1500	11.1	0.63	94.7	2.02	10.5
C10	1500	4.11	0.45	90.3	0.75	5.3
IM(2p=2)	1500	5.5	-	85.7	-	-
N40SH	3000	22.1	0.97	95.8	2.95	10.1
C10	3000	8.22	0.59	93.4	1.10	7.3
IM(2p=1)	3000	7.5	-	87	-	-

Table 1 shows the results of comparing the power and efficiency of electric machines with permanent magnets and standard induction motors, as well as the total losses ($P_{Loss\Sigma}$) of machines with permanent magnets. Comparison of the power of an induction motor with the number of pole pairs equal to $2p = 4$, the rotational speed of which is $n = 710$ rpm, with the corresponding electric motor based on permanent magnets shows that with neodymium magnets the power in 1.75 times greater, with ferrite magnets the power is 0.65 of the power of the asynchronous motor. The same trend persists when comparing the power of a standard induction motor with the number of pole pairs $2p = 2$. Comparison with an asynchronous motor with the number of pole pairs $2p = 1$ showed that the power of the machine with neodymium magnets in 2.95 times greater, and with ferrite magnets more 1.1 times.

Table 2 shows the values of the rotor speed at which the maximum values of power and electromagnetic torque of machines with neodymium and ferrite magnets are observed for various values of the number of turns of the stator windings.

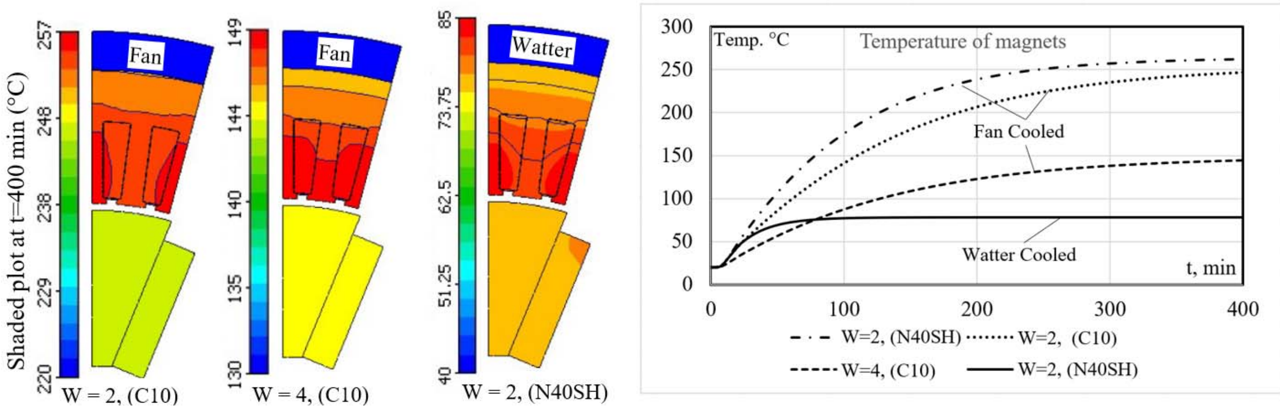
Table 2

Parameter	$W = 2$		$W = 4$		$W = 6$	
	n_{max}, rpm	P_{max}, kW	n_{max}, rpm	P_{max}, kW	n_{max}, rpm	P_{max}, kW
N40SH	6500	45.40	3200	22.50	2120	15.47
C10	15750	40.78	7650	20.29	5300	13.9

Thus, if in a standard asynchronous motor with a rotation axis height of 112 mm and the number of pole pairs $2p = 4$, we replace the squirrel-cage rotor with a rotor with permanent neodymium magnets, then we can get an approximately 15-fold increase in power ($P_{PM}/P_{IM} = 45.4/3 = 15.1$). Naturally, for neodymium magnets, the rotational speed compared to an asynchronous motor should be approximately 9.2 times higher, for ferrite magnets, approximately 22 times higher. It should be noted that a significant increase in the power of an electric machine also leads to a proportional increase in losses in structural elements, which means that a thorough study of the heating of structural elements is required.

The calculation of the temperature of the structural elements of the electrical machines under study (windings, magnets, iron of the stator and rotor, shaft, housing, end shields) was carried out in the Simcentre MotorSolve package, taking into account the cooling system. The thermal calculation was carried out for the operating mode ($S1$), which provides for a long and uninterrupted operating period during which the motor is heated to a steady temperature. Fig. 3 shows pictures of the thermal field of electrical machines with neodymium and ferrite magnets, as well as graphs of heating of permanent magnets for different values of the number of turns, type of cooling (air, liquid), and different values of the number of turns, and hence the rated current in the windings.

Thermal calculation was performed for two cooling systems, air and liquid. In an air-to-air cooling system, air is driven by a fan along the outer casing of the electric machine. The initial data for air cooling are as follows: machine orientation – horizontal; forced convection direction – axial; coolant flow speed – V_{flow}=2 m/s; initial temperature – T=20 °C.



a *b* *c* *d*

Fig. 3

The liquid cooling system consists of channels evenly spaced inside the outer casing of the electric machine and oriented along the axis of rotation of the rotor. The initial data for thermal calculation are as follows: type of channels built into the body – spiral; the number of cooling channels – n_k=100; the shape of the cooling channels is round; diameter of cooling channels d_k = 3 mm; productivity of the circulation pump Q=2 l/min; the initial temperature at the inlet to the cooling channels is 20 °C.

When calculating the temperature of structural elements, it is first necessary to control the heating of permanent magnets. From the heating graphs of the magnets shown in Fig. 3, *d* it follows that with air cooling for a rated current I_n=97.8 A (*W*=2), the magnets heat up to a temperature of 255°C, which is unacceptable and will lead to their demagnetization. For a machine with ferrite magnets at *W*=2, the magnets do not heat up above 300°C, but the maximum temperature of the windings is 250°C, which is also not acceptable. For *W*=4 and *W*=6, an air-cooled machine with ferrite windings will be capable of continuous operation. For a machine with neodymium magnets, it is necessary to use liquid cooling, which can significantly reduce the heating of structural elements. As can be seen from the heating graph of magnets with liquid cooling, even for *W*=2, their temperature does not exceed 75°C.

Thus, when designing a permanent magnet motor based on the stator of a standard asynchronous motor, should consider the method of cooling it, taking into account the type of magnets used and its operating mode. Let's show this on the example of designing an electric motor for an electric car.

When designing electric motors for electric vehicles, one should take into account the driving cycle, which describes the movement of the vehicle in the city and outside the city [5, 6]. In Europe, the so-called new European driving cycle, referred to as NEDC, has recently been applied, consisting of accelerations, decelerations and steps at a constant speed for 20 minutes.

In the MotorSolve software package, it is possible to calculate the required speed and torque for almost any driving cycle, given the basic parameters of the vehicle [4]. As the initial data for calculating the electric motor, the parameters of a mini-class car are taken: the total mass of the electric car is *m*=1500 kg; air resistance coefficient for the chassis body – C_x=0.33; frontal area of the chassis body – *S*=1.9 m^2; drive wheel diameter – *d*=0.546 m; gear ratio of the main gearbox U_{mg}=5.33; rolling friction coefficient – *f*=0.018.

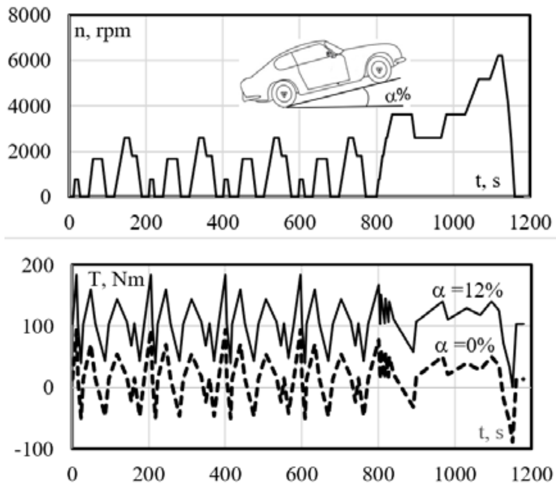
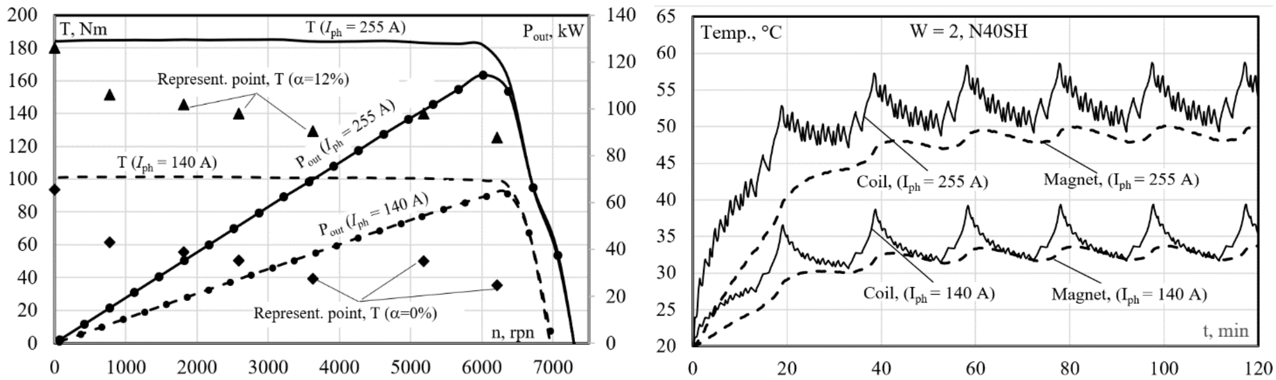


Fig. 4

Fig. 4 shows the dependence of the rotor speed and torque on the electric motor shaft on time for the NEDC driving cycle, calculated when the electric vehicle is moving uphill (road inclination angle α=12%) and on a straight road section (α=0%). Analyzing these dependencies, it should be noted that at α=0%, the maximum value of the moment is T_{max}=98 Nm, at α=12% – T_{max}=180 Nm. Therefore, the electric motor for a given electric vehicle and a given driving cycle must be designed in such a way that its maximum electromagnetic torque is at least 180 Nm.

Fig. 5 shows the performance characteristics of electric motors calculated in the Infolytica MotorSolve package. This figure also shows representative (peak) torque points for the driving cycle at α=0% and α=12%. To obtain an electromagnetic torque value that exceeds the corresponding peak torque values at α=12%, the phase current of the electric motor must be equal to I_{ph}=255 A, the current density at this current is equal to J=18.4 A/mm^2. It should be noted that at this current density and speed n=3000 rpm, the power of the electric motor is P=60 kW, which is 8 times higher than the power of an asynchronous motor at the same speed. To obtain the value of the electromagnetic torque, slightly exceeding the value of T_{max}=98 Nm, the phase current must be equal to I_{ph}=140 A, which corresponds to the current density J=10.3 A/mm^2. Thus, the calculation results show that with an increased current density in the windings, it is possible to realize the specified value of the electromagnetic torque, which ensures the movement of the electric vehicle in accordance with the specified driving cycle and the maximum angle of inclination of the road.



a *b*

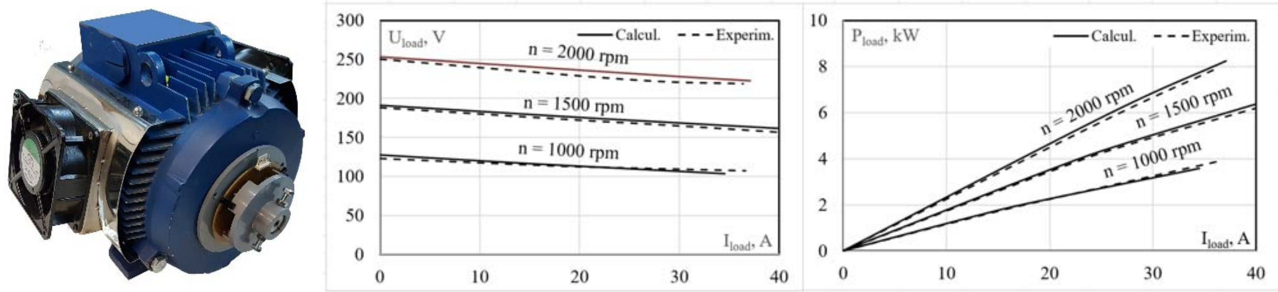
Fig. 5

The permanent magnet motor control system consists of the following elements: controller power section; microprocessor control system; controller blocks, blocking, indication; control panel; software.

Naturally, it is necessary to carry out a thermal calculation of the electric motor, taking into account the driving cycle and the increased current density. The input data for the thermal calculation for liquid cooling are the same as for the calculations shown upper. Fig. 5, *b* shows the temperature of the permanent magnets and motor windings as a function of time at a phase current value of I_{ph}=255 A and I_{ph}=140 A. With a liquid cooling system, with a circulation pump capacity of Q=2 l/min, the temperature of the stator windings at a current of I_{ph}=255 A does not exceed 58°C, which is significantly lower than the permissible temperature for class *H* insulation, and the temperature of the magnets does not exceed 50 °C, which is also acceptable for the operation of magnets. At current I_{ph}=140 A, the steady-state temperature of the windings does not exceed 39°C, and that of the magnets – 33°C. Thus, the calculation results show that the design of an electric motor for an electric vehicle should be carried out taking into account the driving cycle.

For low-power wind turbines, synchronous power generators are used, usually based on rare-earth permanent magnets. The frequency of rotation of the wind rotor depends on the diameter of the wind wheel, as well as on the wind speed, and for power up to P=10 kW is approximately n=100÷300 rpm. For such a speed, it is advisable to use a high-speed generator with a magnetic gear, the reduction factor of which can be, for example, equal to k_G=7.3. The use of an electric generator paired with a magnetic gearbox has a number of significant advantages. The magnetic gearbox, unlike mechanical gearboxes, does not create additional noise, does not require lubrication, its service life is higher, and operating costs are also significantly reduced [7]. In addition, a comparison of the characteristics of a generator with permanent magnets for wind turbines showed that, with equal power, a generator with a magnetic gearbox has at least 2 times less mass of active materials than a low-speed generator, the shaft of which is directly connected to the shaft of a wind turbine an approximately equal mass of magnets.

The article compares the calculated and experimental dependences for electric generators with permanent magnets. To achieve this goal, an electric generator with permanent magnets of the N40SH type was manufactured, while a stator from an asynchronous motor with a rotation axis height of 112 mm was used. Tests of an experimental sample of the generator, the photo of which is shown in figure 6a was carried out on an experimental stand. The coils of each phase are connected in parallel; the phases are connected in a "triangle" and connected to a rectifier bridge of six diodes, which is connected to an active variable resistor – R_{load}.



a ***b*** ***c***

Fig. 6

Fig. 6, *b* shows a comparison of the calculated and experimental dependences of the voltage in the load U_{load} on the current in the load I_{load} for three values of the generator rotor speed: n=2000 rpm, n=1500 rpm, n=1000 rpm and in Fig. 6, *c* – power in the load P_{load} on the current in the load I_{load} for the same three values of the rotor speed. The rated phase current at current density J=7.2 A/mm^2 corresponds to the load current I_{load}=31.5 A. The average discrepancy between the calculated and experimental values is less than 4%.

Conclusions. As a result of experimental and numerical studies, it has been established that replacing a squirrel-cage rotor with a rotor with permanent magnets makes it possible to obtain a significant increase in specific power. Compared to a standard asynchronous motor with an axis height of 112 mm and the number of pole pairs 2p=1, a machine with neodymium magnets has about three times the power density.

As a result of thermal calculations, taking into account the NEDC driving cycle, it was found that the use of liquid cooling makes it possible to cool neodymium magnets and windings to a temperature below the critical one at an increased current in the windings, which makes it possible, for example, at a rotation frequency of n=3000 rpm to increase the specific 8 times power compared to standard asynchronous motor.

The characteristics of the experimental samples of the generator and its computer model are compared. The discrepancy between the calculated and experimental dependences for several values of the rotor speed does not exceed 4%. Thus, the calculation model adequately describes the characteristics of an electric generator with permanent magnets and can be used in further studies with a variation in the type and main dimensions of the magnetic system.

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ПОРІВНЯЛЬНИЙ АНАЛІЗ ХАРАКТЕРИСТИК ЕЛЕКТРИЧНИХ МАШИНИ З ПОСТІЙНИМИ МАГНІТАМИ ДЛЯ ЕЛЕКТРОМОБІЛІВ І ВІТРОУСТАНОВОК

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Наведено результати чисельного та експериментального досліджень електричної машини з постійними магнітами циліндричного типу. Показано, якщо замінити в стандартному асинхронному двигуні короткозамкнутий ротор на ротор з постійними магнітами, можна отримати істотне збільшення питомої потужності електричної машини. Проведено чисельні дослідження та аналіз характеристик електричної машини з тангенціально намагніченими неодимовими та феритовими магнітами в двигунному режимі. Показано, що задля забезпечення максимальних питомих характеристик для застосування в електромобілях необхідно враховувати їздовий цикл та здійснювати рідинне охолодження електродвигуна. Також проведено порівняння характеристик, отриманих під час випробувань експериментального зразка в генераторному режимі, і характеристик, отриманих в розрахункових моделях. Показано, що розбіжність розрахункових та експериментальних залежностей для кількох значень частоти обертання ротора становить не більше 4%. Характеристики досліджуваних електричних машин розраховано в пакетах програм Simcenter MagNet і Simcenter MotorSolve. Бібл. 7, рис. 6, табл. 2.

Ключові слова: чисельне моделювання, електродвигун для електромобіля, постійні магніти, їздовий цикл, робочі характеристики, тепловий розрахунок, вітроенергетична установка.

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