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High-speed Electrical Machine with Radial Magnetic Flux and Stator Core Made of Amorphous Magnetic Material. Technologies, Trends and Perspective of Development

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Abstract—This paper presents an analysis of the manufacturing technologies for the high-speed electrical machine with stator core made of amorphous magnetic material, their trends and perspective of development. The most efficient technology is determined. A design technology of sectional stator cores made of amorphous magnetic material is proposed. In addition, the paper shows the design methodology of the high-speed electrical machine with stator core made of amorphous magnetic material. A distinctive feature of the proposed technology is the implementation of the stator core made of amorphous magnetic material and laminated in the axial and radial directions. The fill factor for magnetic cores realized by this technology reaches 75%. The design methodology was tested on three prototypes of the high-speed electrical machine including the 120-kW prototype. The prototype experimental research is also presented in the paper. The main contribution is the loss minimization in the stator core made of amorphous magnetic material by 200%.

1. INTRODUCTION

Increasing the energy efficiency of electrical machines (EMs) is one of the effective ways to reduce greenhouse gas emissions and to improve environmental conditions, because EMs produce almost 90% of all electrical energy in the world and consume about 60%. Therefore, an increase in the efficiency of all EM used in the world by 0.1% will lead to savings of 35 billion kW per hour in the first approximation. These results were obtained with the world's total power generation of 24097.7 billion kW per hour. In addition, it will reduce the total carbon dioxide emissions into the atmosphere by at least 70 million tons per year, and it will also lead to a great economic benefit. Of course, an increase in the efficiency of all EMs is an impossible task. However, if the efficiency increases by 1% in 0.1% of the used EMs, the savings will be up to 0.35 billion kW per hour. Thus, new technical solutions and technologies, which make it possible to increase the EM efficiency, are economically viable and allow a significant increase in the developing trend in improving the environmental situation [1].

One way to increase the EM efficiency is using amorphous magnetic material (AMM). This method is particularly effective for high-speed and ultra-high-speed EMs (HSEMs). Due to the high magnetization reversal frequency of the stator magnetic core, the hysteresis and eddy-current losses reach up to 30% of the total losses. They constitute 2–2.5% of the HSEM efficiency. Reducing losses in the stator magnetic core by 100% will lead to an increase in the HSEM efficiency by 1–1.25%.

In this paper, the current and future technologies for manufacturing the AMM stator cores for the radial HSEMs were analyzed. Advantages and disadvantages are revealed, and development prospects

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are determined. In particular, such technologies as manufacturing stator cores made of AMM by pressing the powder and using wire from AMM are considered. In addition, three HSEMs with the AMM stator core were designed and tested:

1) 5-kW HSEM with a 60 000-rpm rotational speed;
2) 300-W slotless HSEM with a 60 000-rpm rotational speed;
3) 120-kW HSEM with a 60 000-rpm rotational speed.

Such HSEMs were created for the first time in practice, although LE declares the creation of a 170-kW EM. However, the rotational speed of this EM is 4 000 rpm. All samples presented in this paper were experimentally investigated.

The work is structured as follows. Section 2 presents an overview of different design technologies of the radial HSEM with the AMM stator core. In Section 3, an algorithm for designing the HSEM with the sectional AMM stator core is proposed, and three HSEM designs with an AMM stator core were calculated. The created HSEM experimental samples with the magnetic core made of AMM and the test results are shown in Section 4. Conclusions, as well as a brief overview of the planned future studies of the HSEM with AMM, are in Section 5.

2. DESIGN TECHNOLOGIES OF THE RADIAL HSEM WITH THE AMM STATOR CORE

The main problem for using the AMM in HSEMs is the lack of an economically and technologically efficient technology for manufacturing the stator magnetic core. Traditional stator manufacturing techniques such as stamping, laser or electroerosion cutting are ineffective to create the AMM stator cores due to a number of technical peculiarities that define the entire process of designing the EM with AMM:

– The AMM tape thickness is below 25–30 microns, and AMM layers in the stator core are not isolated from each other. The fill factor does not exceed 0.8 due to various technological defects and impurities in the AMM.
– The AMM produced by industry has a low saturation magnetic flux density, which varies from 1.3 to 1.55 T. This is lower than that of various cobalt alloys by 60%. The alloying of AMM with Co makes it possible to increase the magnetic flux density to 1.8 T. However, this also increases the specific losses due to the increase in electrical conductivity. Therefore, in the design of the EM with AMM, it is necessary to limit magnetic flux density in the air gap.
– The AMM tape has a high rigidity, which can exceed 1 000 N/m^2. This does not allow the effective use of punching to create the magnetic cores from AMM.
– AMM magnetic cores have a high magnetostriction with the magnetostriction coefficient of $26 \cdot 10^{-6}$. Therefore, the AMM magnetic cores produce more noise during operation than magnetic cores made of electrical steel.
– Mechanical and temperature effects can significantly change the magnetic properties of AMM.

These features lead to local overheating of the AMM tape during laser cutting, closing between AMM sheets in the stator core and, as a result, to an increase in the eddy-current losses.

In different studies [2–12], one of the manufacturing technologies for the AMM stator core is investigated, and no analysis of all the technological features of the AMM application has been given. In addition, a comparison of different manufacturing technologies of the AMM stator cores is not shown. It is obvious that the technological features of the EMs with AMM require the use of other approaches to design such EMs. The lack of the design approaches of the EMs with AMM is also one of the problems hampering their industrial development.

An overview of the wound AMM stator cores obtained by laser cutting is given in [8]. However, powder technologies are not considered, and the EM research with a power more than 15 kW is not presented.

One of the promising areas of the AMM is the design of the sectional stator cores from the AMM individual elements. It is important to notice that these technologies are common for both slotless and slotted EMs. The AMM stator core elements of the HSEM sectional structures are made separately from simple geometric shapes, which are then assembled. This technology has been widely used for the axial EMs [13, 14]. The sectional stator magnetic core technology is also used for the radial EMs [15, 16]. In the sectional AMM magnetic cores, the stator core elements are wound. They are made of the AMM type with the subsequent element gluing into a single magnetic core. Such a technology allows achieving the fill factor of the AMM stator core of 0.8. This technology has a number of drawbacks due to the presence of additional air gaps and the difficulty of providing reliable fastenings of the stator core elements.

The authors carried out detailed studies of this technology. As a result, one of its significant disadvantages was revealed. For the radial EM, made according to this technology with an axial stator core length more than 10 mm, the eddy-current contours in the stator core become quite significant. This leads to the opposite effect: the stator core losses did not decrease but increase. Therefore, the sectional design is proposed in the axial and radial directions of the AMM magnetic cores with a maximum axial sector length of 5 mm.

This approach is analogous to the stator-core sheet lamination in the traditional EMs. In the EMs with AMM, this leads to a decrease in the fill factor of the AMM stator core to 70–75%. In this case, the eddy-current and hysteresis losses are reduced by 200%. This approach is effective both in creating slotless EMs with the AMM stator core and in slotted EMs. The technology allowed the design of the 120-kW 60 000-rpm HSEM with AMM.

Occasionally, to design the HSEM with AMM, individual geometric figures can be performed not wound, but by typing from plates. Further, these sets are inserted into the stator. According to this technology, Radam created the radial EM [6]. Special advantages of this technology for EMs are in the tooth-coil windings, since the winding can be laid on each individual tooth with the maximal slot fill factor. The disadvantage of this technology is the complexity of manufacturing the stator cores. The stator fill factor is 70%.

An important problem of the EM with tooth-coil windings is the loss in the end plates of the stator core caused by currents in the winding ends of the tooth coil [17]. To solve this problem and generally to increase the efficiency of using AMM in the EM, the manufacturing technology of the stator core not from AMM tape but from the wire can be effective. Features of this technology are disclosed by the authors in the patent of the Russian Federation [18].

According to [19], the stator-core losses will be much lower than in the EMs realized by using other technologies. At the same time, the fill factor of the stator core made of the AMM wire will be significantly lower than other technologies. Estimations show that it will not be above 0.5–0.65. Technologically, the stator core made of the AMM wire can be made by two methods.

- From the AMM wire together with an adhesive binder, a cylinder is formed according to the technology similar to the formation of cylinders from a carbon fiber. By electroerosion processing, slots for windings are formed. For this technology, the fill factor of the AMM stator core can reach 0.65.
- From the AMM wire, the sectional stator core elements are formed. The HSEM stator core is assembled similarly to the technology of the sectional magnetic core formation. In this case, the stator core fill factor is below 50%.

Both technologies are promising, and their implementation requires additional studies, which are planned to implement in the future.

Another promising technology for creating AMM stator cores is the powder metallurgy. This technology was investigated together with the industrial partner. Fig. 1 shows the powder obtained from the AMM tape and AMM particle forms.

As a research result, it was found that the magnetic permeability of the AMM powder reached up to 40 units. Fig. 1 shows that the powder particles have a scales shape, which leads to a low fill factor of the stator core. In the experiment result of the AMM stator core manufacture, the fill factor of the stator core is below 40%.

In the future, with the increase in the fill factor of the stator core, this technology can find wide application in the industry and can be used to ensure the serial production of the EM with AMM similar to Somalloy 500 P stator cores of the EM. Nevertheless, at this stage of development, the powder

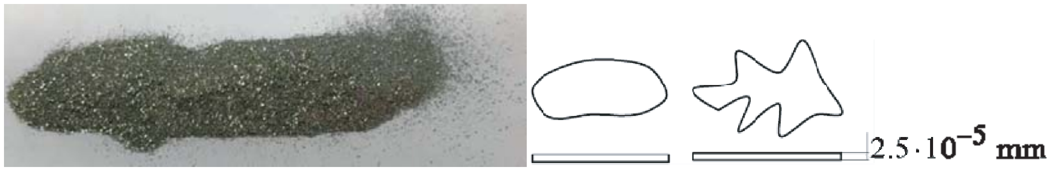


Figure 1. The AMM powder.

technology for creating magnetic cores may be considered as promising, but not competitive, because of the low fill factor.

Table 1 lists all the manufacturing technologies for the AMM stator cores. It is shown that the AMM sectional stator core technology is the sectional stator core technology, although promising areas are AMM powder or wire stator core technologies.

Table 1. Comparison of different AMM stator core technologies for radial HSEM.

AMM stator core technology	Fill factor	The specific loss ratio of the AMM to the electrical steel, [%]	Complexity and economic cost level	Possibility for serial use
Laser cutting	0.8	90	High	No
Electroerosive cutting	0.8	50	High	No
Sectional stator core	0.75	40	Low	Yes
Radam technology	0.75	30	Average	Yes
AMM powder	0.4	35	Low	Yes
AMM wire	0.5	25	Average	Yes
Proposed technology	0.75	35	Low	Yes

Since 2014, our team has been exploring the technologies for creating radial HSEMs with AMM and developing them. A number of investigations are given in [20, 21], in which the main technology is the AMM sectional stator core.

The following approach is used. Several triangular magnetic cores are formed from the AMM tape. The number of triangular magnetic cores corresponds to the number of HSEM stator slots. To reduce economic costs in production, the number of these slots should be minimal.

The formation of triangular magnetic cores occurs by installing annular AMM magnetic cores into the technological mandrel with triangular shape slots (Fig. 2). Then they are poured with epoxy resin with special binders and exposed to temperature. In this mandrel, the annular AMM magnetic cores take a triangular shape and the necessary mechanical strength. The axial length of one AMM stator core is below 5 mm. One of the corners of the triangular magnetic cores is cut off, and the slot part of the HSEM is formed by installing triangular stator core in the annular, which simultaneously serves as a fastener of the stator core and back. After installation of the triangular stator cores in the annular ones, refill with epoxy resin, and the heat treatment is made.

In this technology, it is possible to effectively use a tooth-coil winding, which can be located on several triangular stator cores, prior to mounting them into a single common ring. The main problems that all HSEM developers face are the provision of the rotor mechanical strength, the selection of the winding type and bearings. These aspects of the HSEM design are considered in [22–24] and are not given here.

In the next section, the design features of the HSEM with the AMM stator core realized by the proposed technology are noted.

(a) (b)

Figure 2. (a) AMM magnetic core created by the proposed technology and (b) magnetic cores of triangular shape in the technological mandrel.

3. MACHINE DESIGN

The HSEM research analysis shows that the most applicable type of HSEM is EMs with permanent magnets (PMs) due to their high reliability, implementation simplicity and the possibility of achieving maximum efficiency with minimum mass-and-size parameters. The current research is also devoted to the EMs with PMs.

Taking into account the technological features of using AMM, in the design of the HSEM with the sectional AMM stator core, an algorithm is proposed (Fig. 3).

Step 1. The number of stator slots is determined from the technological possibilities for manufacturing the AMM magnetic core, i.e., at the first design steps; the number of stator slots is a fixed value. The most effective number of stator slots is 6, since its manufacture requires minimal costs.

For the selected number, rotor materials are selected. Preliminary electromagnetic calculations are performed for all possible variants of the rotor pole number. The low saturation magnetic flux density of the AMM magnetic cores should be taken into account. Thus, the frequency in this design methodology is a variable.

In the HSEM with the cobalt or silicon alloy stator core, the minimum number of poles is selected based on the value of the hysteresis and eddy-current losses. In the AMM stator cores, due to the low losses, the rotor pole number is selected to achieve the maximum power-to-mass ratio in the HSEM. At this step, the winding and rotor mechanical calculations are performed. Several topologies are compared, and the optimal rotor pole number is determined. Electromagnetic calculations are carried out by using the known analytical methods and finite element method (FEM). During electromagnetic calculations by FEM methods, it is necessary to take into account the fill factor of the AMM stator core. Thus, the results of FEM calculations for voltage, magnetic flux must be multiplied by a factor of 0.7–0.8, depending on the stator core type and its implementation technology. At the end of this stage, the number of poles is fixed. The number of poles is selected based on two criteria: the power-to-mass ratio and efficiency of HSEM.

Step 2. Various bearings for HSEM are considered and selected. Recommendations are given in [22–24]. The most effective ones are gas or magnetic bearings, since they allow the high efficiency of the HSEM.

Step 3. Several variants with different numbers of poles are calculated. The rotor geometric dimensions and the number of stator teeth remain fixed. The further analysis of the HSEM rotor dynamics is performed in conjunction with the turbine shaft, on which it is mounted. If results are unsatisfactory, step 2 is repeated and other bearings are selected. If this does not help, it is needed to return to step 1 and select new geometric dimensions of the rotor. Otherwise, the HSEM design is continued.

Step 4. Optimization of the HSEM slot zone is performed by the criterion of minimum losses

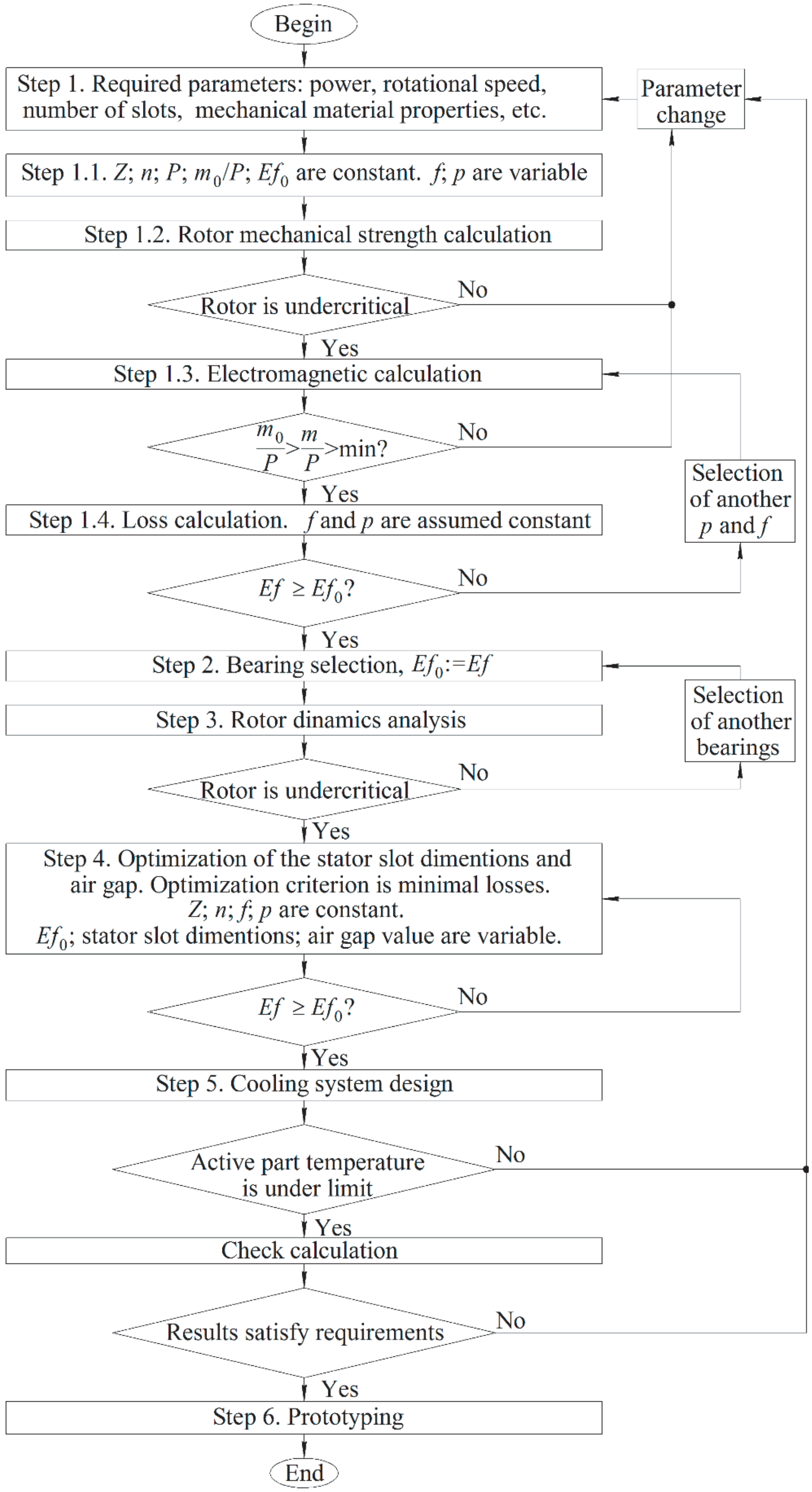


Figure 3. The proposed design algorithm: Z is the number of slots; n is the rotational speed; P is the HSEM power; $m0$ and m are the initial and final masses of the HSEM respectively; E_{f0} and E_f are the initial and final efficiency of the HSEM respectively; f is the frequency; p is a number of poles.

and maximum power-to-mass ratio. Optimization tasks are solved by using the genetic algorithms implemented in commercial software products. At this step, losses in the active elements of the HSEM are also determined. Optimization is carried out with a fixed number of slots and poles, and the variable values are only the geometric dimensions of slots and the air gap. The optimality criterion is the maximum efficiency of HSEM.

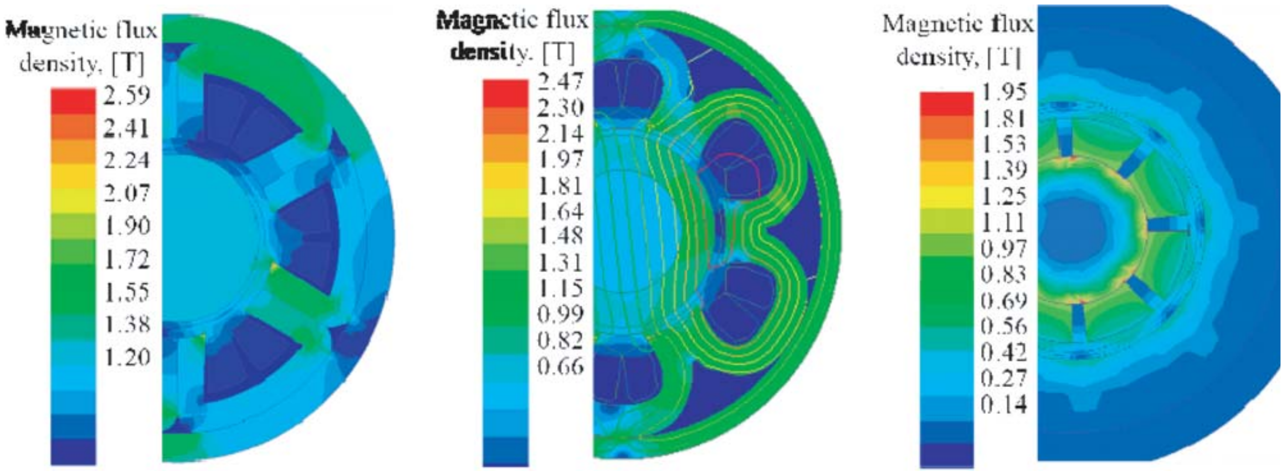
Step 5. Thermal calculations of the HSEM. If results are unsatisfactory, the correction is performed in step 1, and the cooling system is optimized. Otherwise, a prototype is created. The proposed algorithm differs from the existing methodology for the HSEM design. The main difference is the selection and fixing of the slot number, as well as the cooling system and the absence of limits on the pole number. In addition, this algorithm differs from the recently proposed HSEM design approach based on a fixed volume of PMs [25] due to the technological features of the AMM and their low saturation magnetic flux density.

Typically, high-speed EMs use 2 poles to minimize losses in the stator core. However, the AMM already has low eddy-current and hysteresis losses. Therefore, in the proposed topology, a large number of poles can be used, which is limited by the number of stator slots, i.e., the possibility of implementing a winding circuit for a certain number of slots in pole and phase.

The proposed design algorithm of the HSEM with AMM has been tested for 3 different HSEMs with different powers. The parameters of these HSEMs are shown in Table 2. Fig. 4 shows the FEM results for the HSEMs. Electromagnetic calculations were performed in the Ansys Maxwell software package. The rotor mechanical strength was calculated in Solid Works. Thermal calculations were performed in Ansys IcePack.

Table 2. Parameters of the designed HSEM.

Parameter	A-Type	B-Type	C-Type
Power, [kW]	120	5	0.3
EM type	slotted	slotted	slotless
Winding type	Distributed	Tooth-coil	Distributed
Pole number of the rotor	2	2	10
Slot number of the stator	6	6	–
Rotational speed, [rpm]	60 000	60 000	12 000
Voltage frequency, [Hz]	1 000	1 000	1 000
No-load phase voltage, [V]	125	115	12
Current density, [A/mm^2]	10	12	6
Turn number in phase	4	58	208
Outer stator diameter, [mm]	160	68	56
PM diameter, [mm]	60	28	28
Rotor sleeve diameter, [mm]	68	31	31
Active stator length, [mm]	150	48	52
Stator length with end winding, [mm]	220	60	60
AMM thickness, [µm]	25	25	25
Saturation magnetic flux density, [T]	1.35	1.35	1.35
PM, B_r [T]/H_c [kA/m]	SmCo, 1.07/756	SmCo, 1.07/756	SmCo, 1.07/756
Rotor sleeve thickness, [mm]	4	3	3
Rotor sleeve material	Inconel 718	Carbon	Carbon
Mass of active parts, [kg]	18	1	0.7
Refrigerant	Air	Air	Air



(a) (b) (c)

Figure 4. FEM results for the HSEMs: (a) A-Type; (b) B-Type; (c) C-Type.

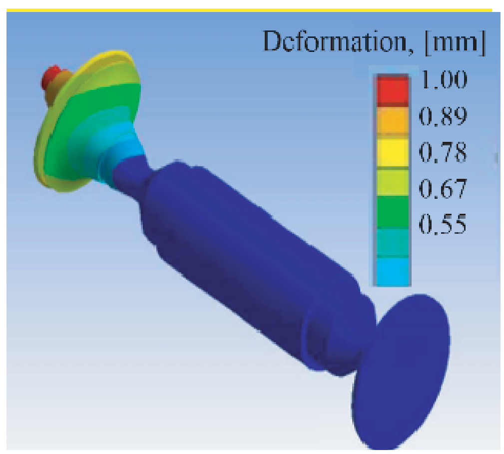


Figure 5. Rotor dynamics at the first critical speed taking into account the turbine parameters for prototype A-Type.

Rotor dynamics analysis was performed for the HSEM rotor together with the turbine on which it was installed and manufactured in the Ansys Maxwell software package. It is important to notice that the rotors for B-Type and C-Type differ only in the pole number. The geometric dimensions of both rotors are fixed. Fig. 5 presents the rotor dynamics analysis for prototype A-Type.

To simplify the design, all prototypes use mechanical bearings. In the future, it is planned to use magnetic bearings in order to maximize the HSEM efficiency. It is established from Fig. 5 that for the A-Type prototype the critical speed is 69 000 rpm taking into account the turbine parameters, and for the B-Type prototype it is 70 600 rpm. The experimental prototypes and their experimental research results are described below.

Thus, using the proposed methodology, three HSEM designs with an AMM stator core were developed. The A-Type prototype was created for each design.

4. PROTOTYPES AND MEASUREMENTS

The proposed design algorithm has been tested on three HSEM prototypes.

4.1. 120-kW HSEM with a 60 000-rpm Rotational Speed

This HSEM is designed for decentralized power plants and in advanced aircrafts. The rotor of the prototype was made of 6 cylindrical SmCo magnets ($B_r = 1.07\,\text{T}$, $H_c = 756\,\text{kA/m}$) with a 60 mm diameter and 25 mm axial length. PMs were laminated to reduce the eddy-current losses, which appear due to spatial and temporal harmonics. The rotor sleeve thickness was 4 mm. The stator windings were distributed. The end winding axial protrusion length was 35 mm. The HSEM winding was made of Litz with a strand diameter of 1.6 mm. The strand diameter was selected from the magnetic field penetration depth into the stator conductor to minimize the eddy-current losses between the stator conductors. The wire insulation was polyamide with the temperature index of 220°C. The number of slots per pole and phase for a distributed winding was 1. The current density was $10\,\text{A/mm}^2$. Fig. 6 shows the AMM stator core created by the proposed technology without winding and with it after impregnation.

(a) (b)

Figure 6. The AMM stator core created by the proposed technology (a) without winding and (b) with it after impregnation.

Figure 6(b) shows that the stator core is assembled from a number of sections laminated in the axial direction. The axial length of the sector is 5 mm. This complicates the assembly technology of the stator core, and it was performed manually for the experimental sample. In the future, it is planned to automate this technology. Fig. 7 shows the rotor and experimental prototype of the HSEMPM. The total mass of the 120-kW HSEMPM is 28 kg with masses of housing and bearing shields. The obtained power-to-mass ratio for the prototype is 4.29 kW/kg. It is obvious that this ratio will be improved during mass production. The HSEMPM installed on the test bench is shown in Fig. 7.

Initially, the phase voltage was measured at no-load mode during the rotor acceleration. The no-load voltage differs by 25% from the FEM results. This indicates that the fill factor is 0.75. The main issue in the HSEM design was the efficiency evaluation. For this purpose, the mechanical power consumed by the generator was estimated at the no-load mode.

All magnetic, mechanical and additional losses in the generator are estimated excluding the electrical losses in the winding. Electrical losses in the winding were estimated at the load mode. The data were taken from a torque sensor mounted on the shaft of the measuring stand. To ensure the measurement accuracy, the data were taken at three time points after 10, 40 and 60 minutes of operation. It was found that the stator core losses were below 10 W at 400 Hz, i.e., the specific stator core losses were 1.11 W/kg at a 400 Hz frequency and a 1.2 T magnetic flux density. At a 1000 Hz frequency and 1.25 T magnetic flux density, the specific losses measured experimentally were 8 W/kg, i.e., the stator core losses were 72–80 W at nominal rotational speeds. These values are less than that for electrical steels by 200–400%.

Figure 8 shows the comparison of the experimental and simulated data obtained by using the proposed method. Tests of this prototype showed the effectiveness of the proposed methodology for the HSEM design.

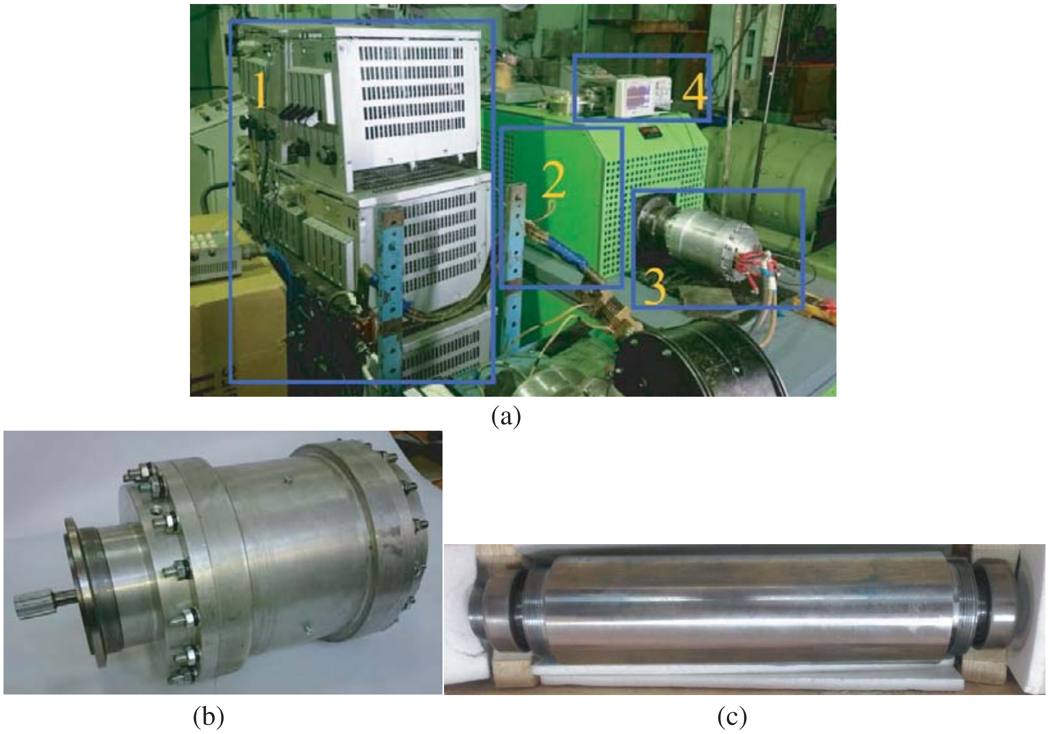


Figure 7. (a) HSEMPM installed on the test bench, (b) experimental prototype of the HSEMPM, (c) rotor: 1 — load; 2 — test bench; 3 — HSEM; 4 — oscilloscope.

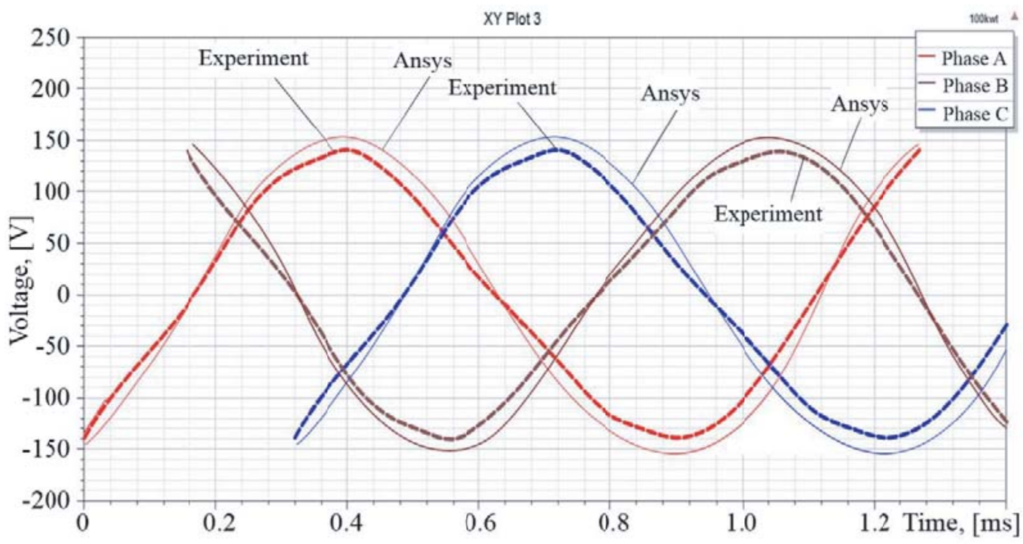


Figure 8. The comparison of the experimental data and simulation results.

4.2. 5-kW HSEM with a 60 000-rpm Rotational Speed

This EM is designed for the use in unmanned aerial vehicles. Its characteristics are described in [20]. This prototype is shown in Fig. 9. Its test bench is presented in Fig. 10. The stator core losses for this prototype are 11.25 W/kg taking into account the stator core mass. Losses were measured in the same way as for the previous one. This prototype was made sectional only in the radial direction. Its axial length is 48 mm. This caused increased stator core losses. Based on the FEM analysis and experimental

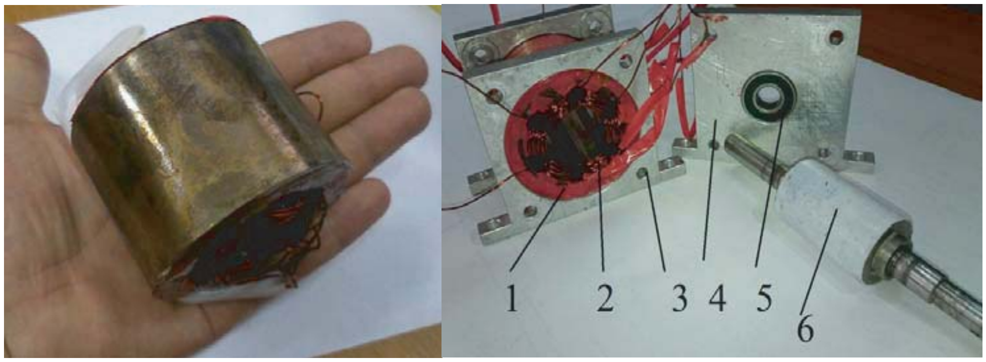


Figure 9. The HSEM prototype with AMM for an unmanned aerial vehicle: 1 — stator core; 2 — stator winding; 3 — housing; 4 — shield; 5 — bearing; 6 — rotor.

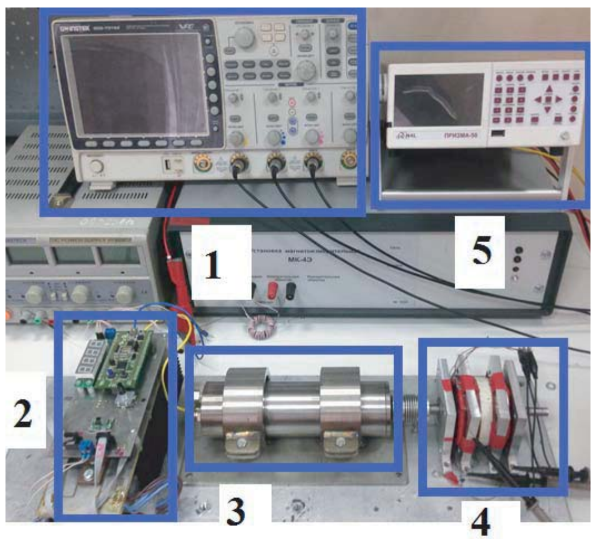


Figure 10. The test bench (a): 1 — oscillograph; 2 — an inverter with a 1 000 Hz frequency; 3 — the "GDZ-62" electrical spindle; 4 — the HSPMG; 5 — the "Prisma-50" spectrum analyzer.

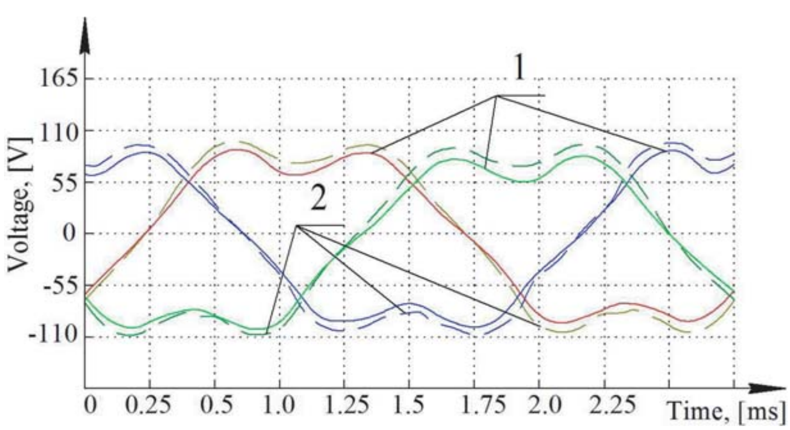
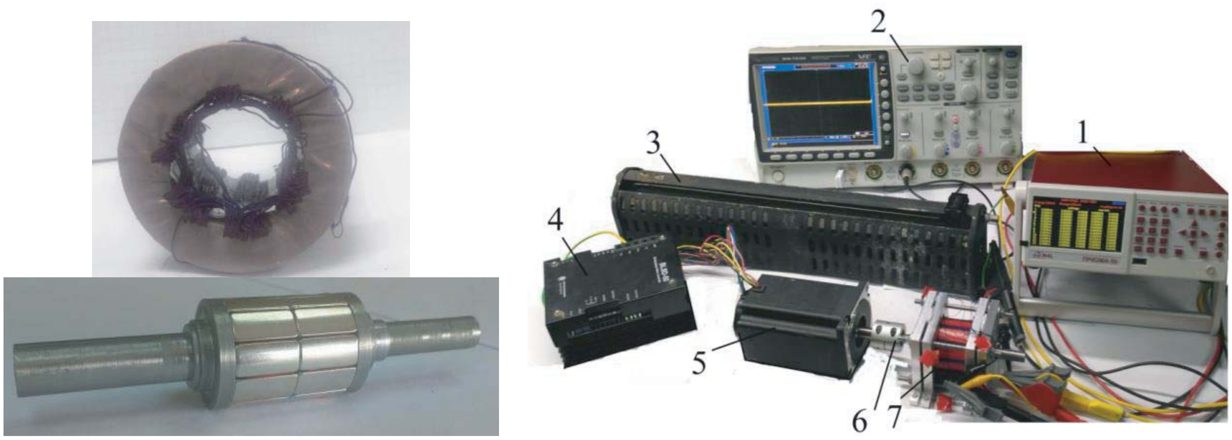


Figure 11. The comparison of the simulation (1) and experimental (2) results.

test data, the fill factor of the stator core is 0.8–0.85. This is a good result for HSEM with AMM. Fig. 11 shows the comparison of the experimental and simulated results. Thus, the HSEM design algorithm described above was confirmed on this prototype as well.

4.3. 0.3-kW HSEM with a 12 000-rpm Rotational Speed

This slotless HSEM is designed for the use in power supply systems of robotic complexes. The HSEM research is given in [21]. Fig. 12 shows the slotless HSEM prototype and the experimental setup for its research. In the test result, the efficiency of AMM and the proposed design methodology was also confirmed. Herewith, the power-to-mass ratio of the slotless HSEM is less than that of the slotted one.



(a) (b)

Figure 12. (a) Slotless HSEM prototype and (b) the experimental setup: 1 — spectrum analyzer; 2 — oscilloscope; 3 — adjustable resistive load; 4 — the control unit of the drive motor; 5 — drive motor; 6 — coupling; 7 — HSEM prototype.

5. CONCLUSION

The AMM application in HSEMs is a promising direction of their development, the implementation of which is able to solve a number of global economic and environmental problems. In this paper, the manufacturing technologies of the HSEM with AMM have been analyzed. It is proved that the most efficient technology is sectional magnetic cores. Nevertheless, significant prospects have powder and wire technologies, the improvement of which requires joint efforts of specialists in the field of materials science and electrical engineering. Some experimental researches of the AMM magnetic cores created by pressing the AMM powder are given.

In addition, the paper describes the proposed design technology of sectional AMM stator cores of the HSEM. A distinctive feature of the proposed technology is the implementation of the AMM stator core laminated in the axial and radial directions. The fill factor for magnetic cores realized by this technology reaches 75%. The paper shows the design methodology of the HSEM with AMM, which takes into account all the AMM technological features. The design methodology was tested on three prototypes of the HSEM with AMM including the 120-kW HSEM prototype. The prototype experimental research is also presented in the paper. The main contribution is the minimization of the stator core losses by 200%.

A further research direction will be the design of the HSEM with AMM by using the AMM powder and wire stator core technologies, as well as the development of the HSEM with the sectional AMM magnetic core and a power up to 300 kW. A separate direction will be testing already created samples for vibration resistance and under different temperature conditions. Similar experimental works in publications are not presented.

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