ELEKTROTEHNIŠKI VESTNIK 84(4): 181-188, 2017
ORIGINAL SCIENTIFIC PAPER

Magnetic-System Topology Selection for the High-Speed Electrical Machine with Interior Permanent Magnets

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Abstract. The paper presents a method enabling an optimal selection of the rotor magnetic-system topology. Using this method, the optimal magnetic-system topology of a 120 kW three-phase electrical machine (EM) aviation with a high-coercivity permanent magnet, 24,000-rpm rotational speed and 400 Hz output voltage frequency is determined. The developed bipolar magnetic rotor system allows achieving a maximum EM efficiency. To evaluate the computer modeling results, an experimental research on a full-size EM is carried out. The numerical difference between the experimental and simulation data is below 5 %.

Keywords: magnetic system topology, high-speed electrical machine, permanent magnets

Izbira topologije magnetov pri hitrem električnem stroju z notranjimi trajnimi magneti

V članku predstavljamo metodo za optimalno topologijo magnetov. Na podlagi predlagane metode smo določili optimalno postavitev magnetov v trifaznem letalskem električnem motorju z močjo 120 kW, ki se vrti s hitrostjo 24.000 v/min in frekvenco izhodne napetosti 400 Hz. Razvili smo nov bipolarni magnetni rotorski sistem, ki omogoča večjo učinkovitost električnega motorja. Rezultate, pridobljene z računalniškim modeliranjem, smo preverili eksperimentalno z električnim motorjem. Odstopanje med eksperimentalnimi rezultati in rezultati simulacij je manj kot 5-odstotno.

1 INTRODUCTION

Electrical machines (EMs) of the power supply systems are important in the modern transport industry. Ground vehicles have migrated to the hybrid technology direction [1-5]. The essence of these technologies is that the vehicle internal combustion engine is only used to rotate the electric generator which feeds the electric motors associated with wheels. Thus, the vehicle move is provided by converting the electrical energy into the mechanical energy, and the primary source for the electrical energy generation is the internal combustion engine. The vehicle fuel consumption is thus significantly reduced as the internal combustion engine works in one mode, which is optimal in terms of fuel consumption and efficiency. This reduces the environmental emissions and minimizes the vehicle noise. Obviously, the EM effectiveness depends on the entire vehicle efficiency.

All these prerequisites form a significant market of high-efficiency EMs for the transport industry. Its need increases annually and so does also the competition between the EM manufacturers.

Therefore, to meet customer requirements and to achieve a sustainable position in the market, the EM manufacturers should increase the EM power supply system effectiveness by decreasing the loss, increasing the power, reducing the mass and volume, and minimizing the cost.

A solution to this problem is the use of high-speed EMs with a high-coercivity permanent magnet (HCPM).

A significant number of articles and books is devoted to research these EMs [6-18]. Loss-reduction methods [6-9], design selection and calculation tasks of EM with HCPM and optimization solution task [10-12], selection of appropriate EM active materials, bearings [13-15] and cooling systems [16] are considered in literature.

In [17, 18], the focus is on use of concentrated winding in EM with HCPM, to shorten the EM axial length. However, this increases the eddy-current losses in HCPM due to the EM spatial harmonics.

In this paper, a method is proposed to solve the topology-selection problem of the EM bipolar rotor magnetic system with interior HCPM. The rotor magnetic system largely determines the EM effectiveness. This problem is not fully solved in literature [6-18], and it is interesting for EM manufacturers.

The main focus of our paper is on the selection of an optimal bipolar magnetic-system topology selection of EM with HCPM.

To solve the issue, a specific numerical example is used: a three-phase 120 kW 24 000 rpm EM with HCPM and 400 Hz output voltage frequency.

Received 19 May 2017
Accepted 10 July 2017

The developed methodology can be applied in different industries using EMs with HCPM. To achieve the maximum EM efficiency, a new two-pole rotor magnetic system is proposed. In contrast to known works [6-18], the optimal topology is determined by using the transient analysis, i.e. the magnetic field in the air gap is calculated by taking into account the demagnetizing field and distortions created by currents of the stator windings at different loads. This distinguishes our methodology from those defining the topology effectiveness by using the magneto-static analysis which may not be effective for the EM operation in the load mode.

The paper also presents the results of our study of transient processes in EM and the impact of the magnetic system on them.

2 A METHODOLOGY TO DETERMINE THE MAGNETIC SYSTEM OPTIMAL TOPOLOGY

Our determination of the magnetic-system optimal topology is based on the weight coefficient method. The effectiveness of any magnetic-system topology is determined by two functions:

$$Q_{\min} = \sum_{m=1}^{m} k_n F_m^* \quad (1)$$

$$Q_{\max} = \sum_{n=1}^{n} k_n F_n^* \quad (2)$$

where Q is the topology estimation; k_n is the weight coefficient of the EM optimality criterion; F_n^* is the relative optimality criterion with the maximum value; F_m^* is the relative optimality criterion with the minimum value.

The most efficient magnetic-system topology is with $Q_{\min}$ lower and $Q_{\max}$ higher than for a competing variant.

Therefore, the main minimal effectiveness criteria for the transport industry are:

– the mass and overall dimensions for the cars, spaceships and aircrafts with a limited space in which EMs are installed;

– the permanent-magnet mass and rotor bandage thickness providing the rotor mechanical strength, air-gap value and EM efficiency;

– the permanent-magnet losses studied separately from the total losses;

– the total harmonic distortion (THD) coefficient under no-load conditions;

– THD coefficient under load conditions;

– the EM thermal factor (a product of the linear current load and the current density in the EM windings);

– the EM losses with the exception of the rotor losses;

– rigidity of the EM external characteristics (the ratio of the voltage to current); the mass of the EM control system depends on this criterion; rigidity is measured as a percentage of the voltage drop from the no-load condition to the 1.5 overload;

– the cost and manufacturability.

The most important criterion is the EM reliability.

Each criterion is considered in relative units because of the different measurement units:

$$F_n^* = \frac{F_n}{F_y}, \quad (3)$$

where F_n is the calculated criterion in dimensional units for a specific topology and F_y is the desired value of the criterion established in the technical task.

The optimal magnetic system with interior permanent magnets for a 120 kW EM aviation with an output phase voltage of 115 V is considered. Table 1 presents desired criteria values (3) for a given EM. The values of these criteria are selected specifically for each EM type.

Table 1. The EM criteria.

Criteria	Desired value
EM mass, [kg]	24
EM power, [kW]	120
Total losses, [W]	1700
Output phase voltage, [V]	115
Rotor-bandage material	Carbon
Rotor-bandage thickness, [mm]	2
THD under no-load conditions	3 %
THD under load conditions	5 %
Rigidity of the external characteristic	15 %
Rotor mass, [kg]	6
Rotor losses, [W]	80
Thermal factor, [$A/mm^2 \cdot A/sm$]	6000
Rotor cost, [$]	1000

3 INVESTIGATED TOPOLOGIES

For the high-speed EM with HCPM, the use of a bipolar magnetic system is the optimal variant. This allows the minimum magnetization reversal frequency of the stator and hence the minimum stator-core losses and also meets special requirements for the output frequency of the EM voltage. For example, for some space applications, a generator of a 1000 Hz output-voltage frequency and a 60,000-rpm rotational speed is used. For some aviation EMs, the rotational speed of 24000 rpm and the output-voltage frequency of 400 Hz are required.

The disadvantage of the bipolar magnetic system is the increased height of the stator back compared to other designs due to the magnetic-field line length.

The following most applicable magnetic-system topologies of the high-speed bipolar EM with HCPM are investigated:

3.1 Solid cylindrical bipolar magnetic systems (topology A)

The solid cylindrical magnetic systems (Fig. 1) can be effectively used in EMs with the rotor diameter below 60 mm. The higher rotor diameter values make the use of these magnetic systems ineffective due to the HCPM mechanical fragility and the complex provision of the rotor mechanical strength. Such magnetic systems are used in EMs with HCPMs at the rotational speeds of 30,000–1,000,000 rpm [19, 20-22].

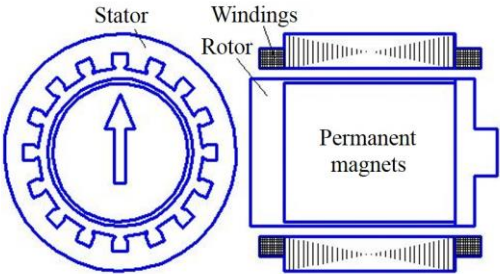


Figure 1. EM with a solid cylindrical magnetic system

3.2 Assembled bipolar magnetic systems (topology B)

The assembled bipolar magnet systems (Fig. 2) are used in EMs with the rotor diameter above 50 mm and mainly with the sectors magnetized radially or diametrically. For the bipolar magnetic system manufacturing technology, the magnetic field in the air gap can be inhomogeneous, leading to a significant high-harmonic manifestation and sinusoidal voltage distortion. The assembled bipolar magnet systems are effectively used only with the ferromagnetic rotor.

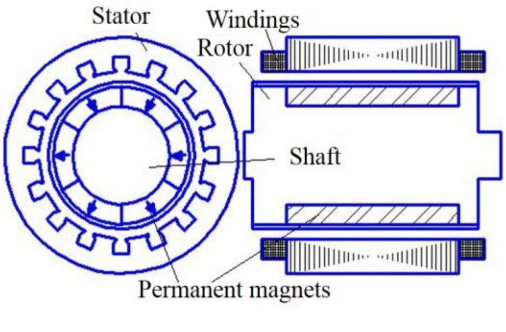


Figure 2. EM with assembled bipolar magnetic systems

3.3 Assembled bipolar magnetic systems with an optimal magnetization (topology C)

Because of the disadvantages of the assembled magnetic systems with radial magnetization, another configuration of the rotor bipolar magnet system of the magneto-electric generator for aerospace applications is proposed (Fig. 3).

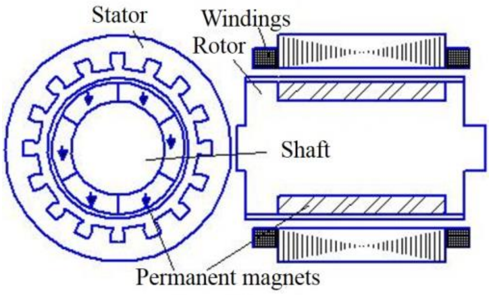


Figure 3. EM with an assembled bipolar magnetic system and an optimal magnetization.

In this case, the magnetization direction is simulated similarly to the entire cylindrical system (topology A), but the rotor is assembled. This minimizes the system cost and consequently the EM. Also the rotor mechanical stress is much smaller than in the solid cylindrical magnetic system. Thus, this magnetic system combines the advantages of the cylindrical and assembled magnetic system. Technologically, the magnetic system can be accomplished in two ways:

– the permanent-magnet magnetization in the rotor on a magnetic shaft;

– the desired permanent-magnet configuration is obtained from the magnetized prismatic HCPM by machining it.

Using two these technologies solves the problem of setting up the proposed magnetic system to be used in practical implementations.

4 COMPUTER SIMULATION OF THE BIPOLAR MAGNETIC-SYSTEM TOPOLOGY

To determine the optimal magnetic-system topology and to evaluate the proposed magnetic-system efficiency using the finite-element method, an EM computer model for each of the three topologies is created in the Ansys Maxwell software package.

For the B and C topology, the external rotor diameter of the 120 kW EM is 100 mm. The number of the turns of the EM phase winding is 6.

Based on calculations, at a diameter of 100 mm, the rotor mechanical strength for the A topology is practically impossible. Therefore, for this topology, the EM rotor diameter is reduced to 60 mm in order to maintain the same power for each topology, and the number of the turns is increased to 12.

For each topology, the liquid is cooled. To allow for a comparison, the current density for each topology is 15 A/mm^2. Table 2 shows the parameters for each EM topology.

In the computer simulation, the distribution patterns of the magnetic field and the HCPM eddy-current losses are obtained for each of the studied topologies (Figs. 4–6). Fig. 7 shows results of the magnetic-field calculation and of the permanent-magnet loss analysis in EM.

Table 2. The EM parameters for the A, B and C topology

Parameter	Topology A	Topology B	Topology C
EM mass, [kg]	22	25.1	24
EM power, [kW]	120	120	120
Rotor diameter, [mm]	60	100	100
Outer stator diameter, [mm]	180	195	195
Active length, [mm]	125	120	120
Slot number	18	18	18
Output phase voltage, [V]	115	115	115
Number of the turns	12	6	6
RMS current, [A]	349	359	347
THD under no-load conditions, [%]	3	7	3
THD under load conditions, [%]	4	10	4
The current density j, [A/mm^2]	15	15	15
Linear AC current load, [A/sm]	106700	38829	37531
Thermal factor $j \cdot AC$, [A/mm^2 $\cdot$ A/sm]	16005	5820	5625
Rotor mass, [kg]	3	6	6
Rotor losses, [W]	154	17	15
Stator-core losses, [W]	350	518	510
Stator-winding losses, [W]	2096	1109	1036
Total losses, [W]	2600	1644	1561

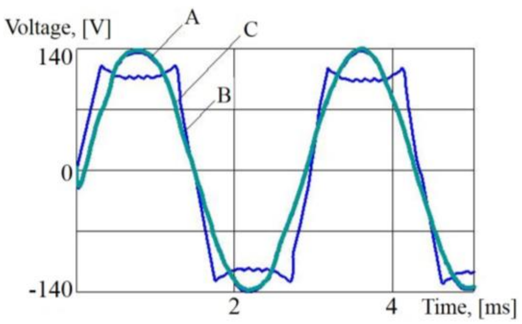


Figure 4. Idling voltage for the investigated topologies.

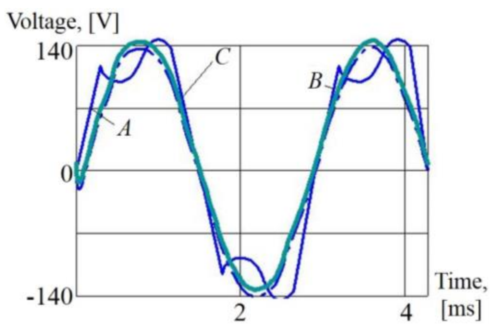


Figure 5. Voltage at the rated load for the investigated topologies.

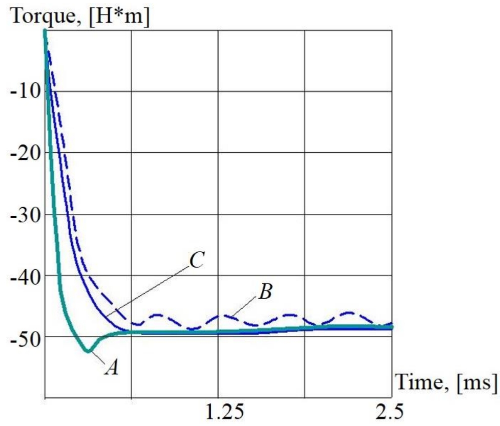


Figure 6. Torque dependencies for the investigated topologies.

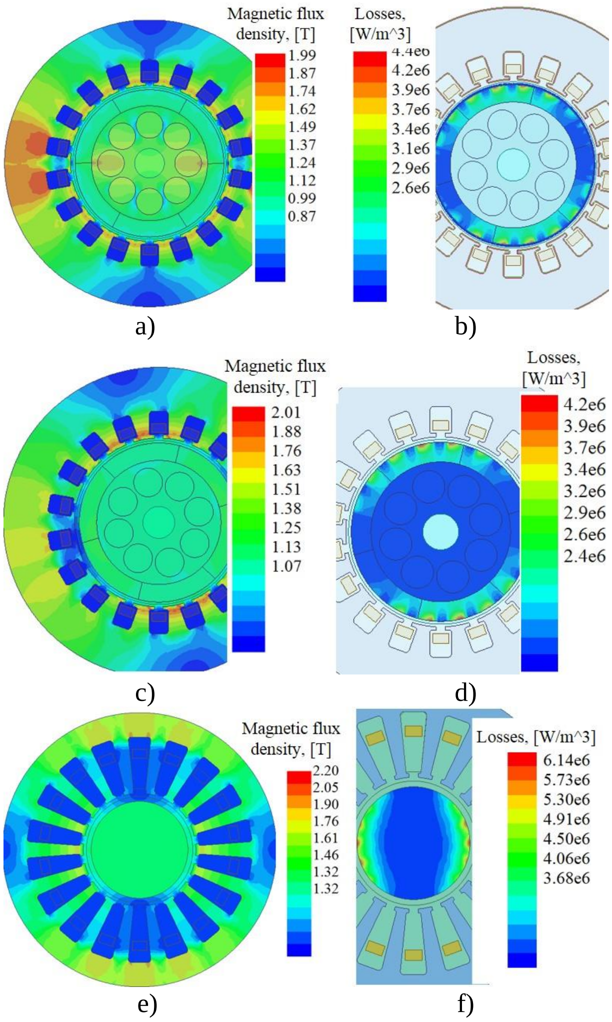


Figure 7. Distribution of the magnetic field and the permanent-magnet losses for various topologies: a) the magnetic-flux density for the B topology; b) the permanent-magnet losses for the B topology; c) the magnetic-flux density for the C topology; d) the permanent-magnet losses for the C topology; e) the magnetic-flux density for the A topology; f) the permanent-magnet losses for the A topology.

The analysis result shows that the C (the proposed design) and A topology have the required THD coefficient and the magnetic-flux density in the stator core is below 2 T. The value of the magnetic-flux density is ensured by using the Vacoflux cobalt alloy enabling the stator core to remain unsaturated.

It should be noticed that the magnetic-system topology insignificantly affects the permanent-magnet losses. They are the same for the B and C topology, although the primary magnetic field in the air gap is significantly distorted for the B topology, and it is sinusoidal for the C topology.

The reason for the equal permanent-magnet losses for these topologies are the unchanged zone of these topologies and the winding data. In the A topology, the slotted zone and the winding data are changed resulting in a 30 % permanent-magnet loss increase.

Thus, the A topology is a perspective variant for EMs with the power below 30–40 kW and the rotor diameter below 60 mm. For more powerful EM, the use of such magnetic system is inefficient because of the high thermal load. A reason is the small rotor diameter limited by the rotor-bandage mechanical strength and the necessity of a significant linear current-load increase. This leads to an increase in the number of the turns of the stator windings, to a higher thermal load and lower low external characteristic rigidity (Table 2) and to increased winding losses. The THD coefficient of this topology is the same as for the C topology. The character of the magnetic field in the air gap is a sinusoidal.

Therefore, it is recommended to use the A topology for EMs with the power below 30 kW and with the rotor diameter below 50 mm. For EMs with a higher power, the C topology is the most effective.

Besides evaluating the effectiveness of various magnetic-system topologies under the rated operation mode, the magnetic-system topology impact on the transient processes is considered, too. The single-phase and three-phase short circuits in EMs are investigated. Fig. 8 shows the torque characteristics of EMs with a three-phase symmetrical short circuit. A single-phase short circuit is presented in Fig. 9.

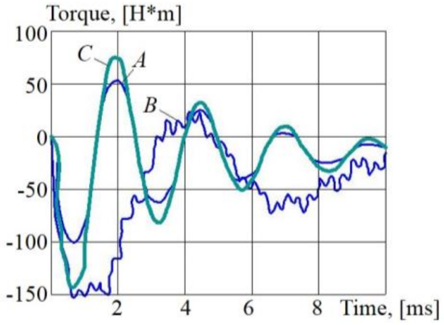


Figure 8. Torque characteristics of EM with a three-phase symmetrical short circuit

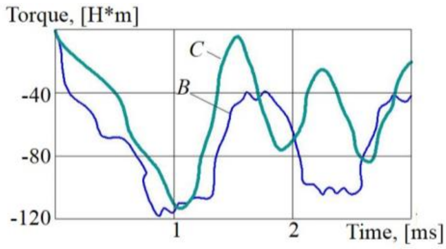


Figure 9. Torque characteristics of EM with a single-phase symmetrical short circuit

The dependency analysis (Figs. 8, 9) shows that the A topology has the minimum current of the three-phase short circuit. The A and C topology have a minimal time of the transient process. In the B topology, the transient process is protracted. This negatively affects the EM performance at a sudden three-phase and single-phase short circuit.

In the case of a sudden three-phase short circuit, EMs are subjected to a two-fold overload at the torque due to 2 ms. Therefore, engagement of a mechanical drive and EMs should be calculated for a short-term mechanical overload with a safety factor of 2.

Based on the transient-process analysis, the B topology has the most negative effect on EMs in case of a short circuit. Its maximum short-circuit current is 1814 A, whereas it is 885.7 A for the A topology and 1272 A for the C topology. The transient process is protracted.

Thus, the A and C topology are the most effective to ensure operability in a sudden short circuit and single-phase short circuit. This confirms the conclusion that for EMs with the power below 30–40 kW and the rotor diameter below 60 mm, the use of the A topology is the most effective.

5 THE EM ROTOR OPTIMAL TOPOLOGY SELECTION

Table 3 shows the magnetic-system optimality criteria for each topology calculated using the proposed method. The EM rotor cost is determined based on the cost of the permanent magnet and manufacture.

To simplify the analysis, the weight coefficients are assumed to be 1. According to the proposed optimization method, the most effective variant is the C topology, because of the significant disadvantages of the other two topologies for this power. Due to the rotor mechanical strength, A topology has a small diameter and, consequently, a high linear-current load and a low efficiency.

B topology has a significant harmonic voltage distortion, which is unacceptable for the aircrafts, cars and spacecrafts. Moreover, the B topology is not effective in a short circuit.

As seen, for a 120 kW EM with a 24,000 rpm rotational speed, the C topology is the optimal.

Table 3. Relative criterion values for the investigated topologies

Criterion	**A topology**	**B topology**	**C topology**
EM mass	0.916	1.04	1
EM power	1	1	1
Total losses	1	1	1
Output phase voltage	1	2.3	1
THD under no-load conditions	0.8	2	0.8
THD under load conditions	2.6	1.03	1.06
Thermal factor	0.5	1	1
Rotor mass	1.925	0.21	0.18
Rotor losses	1.2	0.7	1.04
Rotor cost	1.52	0.96	0.918
Rigidity of the external characteristic	1.3	2.2	1.27
EM reliability	0.95	0.99	0.99
$\sum_{m=1}^{m} k_n F_m^*$, where k_n =1 for any m	13.761	13.44	11.258
$\sum_{n=1}^{n} k_n F_n^*$, where k_n =1 for any n	0.95	0.99	0.99

6 EXPERIMENTAL RESEARCH

To evaluate the obtained results, an experimental research is made of the magnetic-system topology impact on the EM characteristics with PM. The evaluation results confirm the computer simulation data presented above.

To reduce the experimental costs, only the B topology, being the cheapest, is studied and realized in a full-size 120 kW EM with a 24,000 rpm rotational speed. To simplify the laboratory studies, the experiments are conducted at a 6000-rpm rotational speed (Table 4).

Table 4. The parameters of the used full-size experimental model

Parameter	**Value**
Steel type of active parts	CoFe
Sheet thickness, [mm]	0.18
Magnet system type	Topology B
Phase-current frequency, [Hz]	400
Phase voltage, [V]	120
RMS-phase current, [A]	306.22
Current density in winding, [A/mm^2]	15
Linear load, [A/m]	33104
Thermal factor, [A/mm^2 · A/sm]	3972
Generator power, [kW]	120
Active and leakage resistances, [Omh]	0.965
Inductive resistance of the phase axis d-q, [Omh]	0.957

Fig. 10 shows the full-size experimental EM model and the main EM elements, such as the carbon-fiber rotor, stator core, and cooling jacket. Fig. 11 demonstrates the EM test set-up.

In the experimental research, the active load is connected to the EM output terminals. The EM current and, consequently, the load value are limited to 80–85 A. Fig. 12 shows experimentally obtained current and voltage oscillograms recorded at various loads.

The results of experiments and computer modeling (Figs. 4-6) show that the developed computer model is highly accurate and completely repeats the experimental results. The numerical difference between the experimental data and the simulation data is below 5 %. This experimentally confirms our conclusion, since there is only one general computer model used in our investigation.

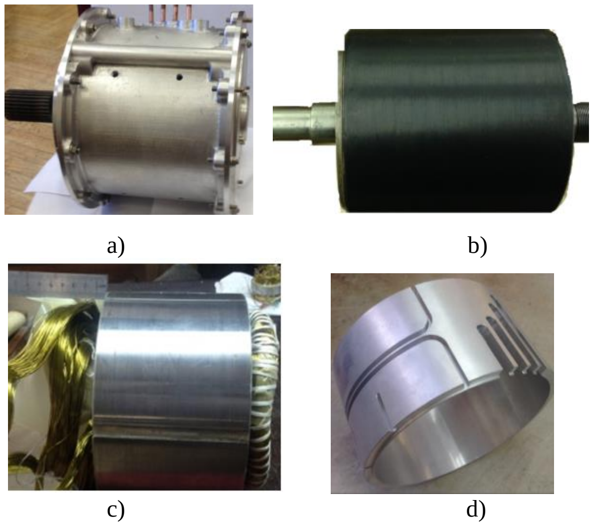


Figure 10. Full-size experimental EM model (a), carbon-fiber rotor (b), stator core (c) and cooling jacket (d)

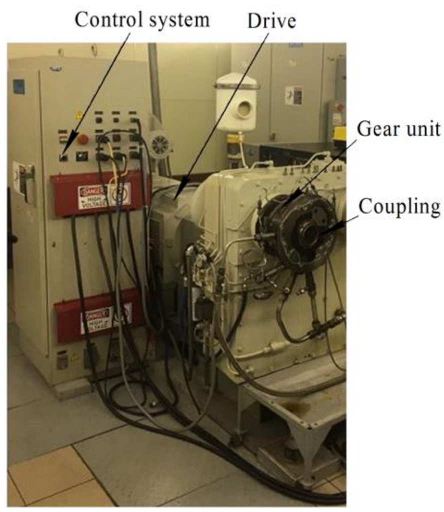
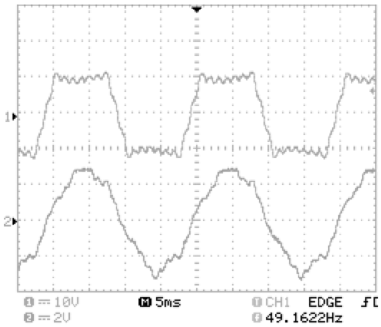
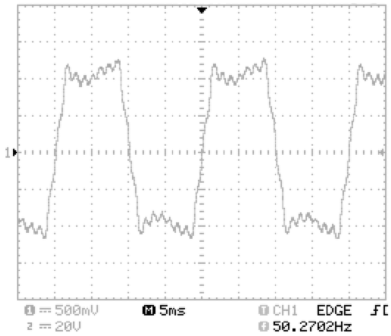


Figure 11. EM test set-up



a)



b)

Figure 12. The EM test results: a) under load of 50A; b) under load of 80 A

7 CONCLUSION

The paper presents a method to determine the rotor optimal magnetic-system topology. Using this method, the optimal magnetic-system topology of a 120 kW three-phase EM aviation with HCPM, 24,000-rpm rotational speed and 400 Hz output voltage frequency is calculated. A new bipolar magnetic-rotor system is developed enabling the maximum EM efficiency.

To evaluate the computer modeling results, an experimental research on a full-size EM is carried out. The numerical difference between the experimental and simulation data is below 5 %.

The disadvantages of the A and B topology for the 120 kW EM with a 100 mm rotor diameter are significant. Due to the rotor mechanical strength, the A topology has a small diameter and, consequently, a high linear-current load and a low efficiency. The B topology has a significant harmonic-voltage distortion, this being unacceptable for the aircrafts, cars and spacecrafts. Moreover, this topology is ineffective in a short circuit.

To sum up the optimal magnetic system for these parameters is the C topology, here proposed as a new technology. The next choice is the A topology. The B topology is the most inefficient solution compared to the investigated topologies.

ACKNOWLEDGEMENT

The work was supported by the Ministry of Education and Science of the Russian Federation (project 8.1277.2017/PCH).

REFERENCES

[1] E. Ganev "High-Performance Electric Drives for Aerospace More Electric Architectures", *IEEE Power Engineering Society Meeting*, str. 1-8, 2007.

[2] A. Nagorny, N. Dravid, R. Jansen, B. Kenny "Design Aspects of a High Speed Permanent Magnet Synchronous Motor/Generator for Flywheel Applications", *NASA/TM-2005-213651*, str. 1-7, 2005.

[3] A. A. Bobtsov, A. A. Pyrkin, R. Ortega et. all. "A robust globally convergent position observer for the permanent magnet synchronous motor", *Automatica*, 61, str. 47-54, 2015.

[4] Z. Q. Zhu, David Howe. "Electrical Machines and Drives for Electric, Hybrid, and Fuel Cell Vehicles", *Proceedings of the IEEE*, 95(4), str. 746-765, 2007.

[5] Y. K. Chin, J. Soulard. "A Permanent Magnet Synchronous Motor for Traction Application of Electric Vehicle", *Electric Machines and Drive Conference. IEEE int.*, 2, str. 1035–1041, 2003.

[6] J. F. Gieras. "High speed machines", *Advancements in Electric Machines (Power Systems)*, str. 81–113, 2008.

[7] Hans-Christian Lahne, Dieter Gerling. "Investigation of High-performance Materials in Design of a 50000 rpm High-speed Induction Generator for Use in Aircraft Applications", *Workshop on Aircraft System Technologies Conference (AST-2015)*, Hamburg, str. 1–10, 2015.

[8] C. Bailey, D. Saban, P. Guedes-Pinto. "Design of High-Speed Direct-Connected Permanent-Magnet Motors and Generators for the Petrochemical Industry", *IEEE Transactions on Industry Applications*, 45 (3), str. 1159–1165, 2009.

[9] A. Borisavljevic, H. Polinder, J. Ferreira. "On the Speed Limits of Permanent-Magnet Machines", *IEEE Transactions on Industrial Electronics*, 57(1), str. 220–227, 2010.

[10] B. Abdi, J. Milimonfared, J. Moghani "Simplified Design and Optimization of Slotless Synchronous PM Machine for Micro-Satellite Electro-Mechanical Batteries", *Advances in Electrical and Computer Engineering*, 9(3), str. 84–88, 2009.

[11] J. Microw. "Optimal design of a set of permanent magnet generators with the same cross-section", *Optoelectron. Electromagn. Appl.*, 12(2), str. 678–693, 2013.

[12] T. Zhang, Y. Xiaoting, Z. Huiping. "Strength Design on Permanent Magnet Rotor in High Speed Motor Using Finite Element Method", *Telkomnika Indonesian Journal of Electrical Engineering*, 12(3), str. 1758–1763, 2014.

[13] D. K. Hong, B. C. Woo, J. Y. Lee. "Ultra High Speed Motor Supported by Air Foil Bearings for Air Blower Cooling Fuel Cells", *IEEE Trans. Magn.*, 48, str. 871–874, 2012.

[14] D., M. Malengret. "High speed PM motor with hybrid magnetic bearing for kinetic energy storage", *Conference Record – IAS Annual Meeting (IEEE Industry Applications Society)*, 1, str. 57–63, 2001.

[15] F. Ismagilov, I. Khairullin, V. Vavilov, M. Gumerova. "Application of hybrid magnetic bearings in aviation starter-generators", *International Review of Electrical Engineering*, 9 (3), str. 506-510, 2014.

[16] A. Tuysuz, M. Steichen, C. Zwyssig, J. W. Kolar. "Advanced cooling concepts for ultra-high-speed machines", *9th International Conference on Power Electronics - ECCE Asia: "Green World with Power Electronics", ICPE 2015-ECCE Asia 7168081*, str. 2194-2202, 2015.

[17] Dieter Gerling, Mohammed Alnajjar. "Six-Phase Electrically Excited Synchronous Generator for More Electric Aircraft", *International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, str. 7–13, 2016.

[18] G. Dajaku, D. Gerling. "Magnetic Radial Force Density of the PM Machine with 12teeth/10-poles Winding Topology," *IEEE International Electric Machines and Drives Conference, IEMDC2009*, Florida, USA, str. 157-164, 2009.

[19] N. Uzhegov, E. Kurvinen, J. Nerg, J. T. Sopanen, S. Shirinskii. "Multidisciplinary Design Process of a 6-Slot 2-Pole High-Speed Permanent-Magnet Synchronous Machine", *IEEE Transactions on Industrial Electronics*, 63 (2), str. 784–795, 2016.

[20] K. Isomura, M. Murayama, S. Teramoto, K. Hikichi, Y. Endo, S. Togo, S. Tanaka. "Experimental Verification of the Feasibility of a 100W Class Micro-scale Gas Turbine at an Impeller Diameter of 10 mm", *J. Micromech. Microeng*, 16, str. 254–261, 2006.

[21] V. Vavilov, F. Ismagilov R., I. Khairullin, D. Gusakov. "High Efficiency Ultra-High Speed Microgenerator" *Industrial Electronics Society, IECON 2016 - 42nd Annual Conference of the IEEE*, 2016.

[22] Arda Tüysüz, Christof Zwyssig. "A novel motor topology for high-speed micro-machining applications", *IEEE Transactions on Industrial Electronics*, 61(6), str. 2960–2968, 2014.

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