An Electromagnetic Moment in Short Circuits in Electrical Rotating Machines with High-Coercivity Permanent Magnets

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Abstract

This paper presents a computer model of an electrical rotating machine with high-coercivity permanent magnets and research of various short-circuit types in the electrical rotating machine with high-coercivity permanent magnets, including turn-to-turn short circuit. Diagnostic criteria of short circuits are revealed. There are the electromagnetic moment and the magnetic flux density in the stator core back. With comparison the experiment and computer modeling results, it was found that the created computer model is highly accurate and completely repeats the experiment results. The numerical discrepancy between the experimental data and the simulation data is below 5%. The obtained results can be used in practice in the design of the electrical rotating machine with high-coercivity permanent magnets.

Keywords: electrical rotating machine, high-coercitivity permanent magnet, electromagnetic moment, short circuit

1. Introduction

Electrical rotating machines (ERMs) with high-coercivity permanent magnets (HCPM) are promising for aerospace engineering, transport, robotics and autonomous energy [1-3]. The most papers [4-9] devoted to the research of such ERM mainly consider ways to minimize mass-dimensions, to improve efficiency, to develop control systems and to optimize parameters. However, the diagnostic problem research of the ERM with HCPM are practically not represented in the literature. This is partly because many technical problems of the ERM with HCPM such as rotor eccentricity or bearing failure can be diagnosed by using the well-known methods and work results [10-12]. At the same time, short circuits in ERM with HCPM are often very difficult to diagnose by the available diagnostic criteria. The short circuit in the ERM with HCPM is the most dangerous mode, which can lead not only to a malfunction of the entire system, but also to creating a hazard to the life and health of service personnel.

In the ERM with HCPM, the permanent magnet excitation field cannot be turned off, unlike electric machines with electromagnetic excitation, in which the magnetic field damping and the exclusion of the rotor excitation are used in the case of short circuit. To prevent the negative consequences from the short circuit in the ERM with HCPM, either mechanical disconnectors or semiconductor elements are used, which disconnect the damaged circuit section from the main winding [13-15].

For some applications, high-inductance ERMs are used. For these machines, the short-circuit current slightly exceeds the rated current, usually by 20-25% more. Accordingly, it does not create any significant disturbances in the ERM operation [16]). Each described method will be effective for some specific short-circuit types and be practically useless for others. For the effective use all these methods, it is necessary to know exactly which type of short circuit is in the ERM with HCPM. This is impossible to determine without the diagnostic criteria characterizing one or another short-circuit type.

In [17], authors presented studies of three-phase symmetric short-circuits and its dependences. Analytical solutions of other short-circuit types in the ERM with HCPM are difficult to obtain. It is also difficult and economically inexpedient to determine a diagnostic criteria and characteristic curves for various short-circuit types of ERM with HCPM experimentally.

Taking into account the accuracy and economic costs, the most effective variant is the computer simulation methods for various short-circuit types and the formation of diagnostic criteria based on these methods.Therefore, a computer model of the ERM with HCPM should be developed and verified experimentally in one or two operation modes, for example in the nominal mode and three-phase short circuits. With a sufficient accuracy, it can be argued that the obtained diagnostic criteria of other short-circuit types will correspond to the experiment.

The purpose of this work was to develop a computer model of the ERM with HCPM and to study the processes in the ERM for various short-circuit types. Based on the research data, a list of diagnostic criteria was developed for identification of various short-circuit types in the ERM with HCPM. The obtained computer model was verified experimentally at idling and at rated load.

2. Computer Simulation

In the Ansys Maxwell software package, a two-dimensional computer model of the ERM with HCPM was created. Parameters of the ERM with HCPM are presented in Table 1. In this work, each turn was modeled by a separate geometric figure unlike the models given in [4-8]. This greatly complicates the model, but allows simulation not only short circuits on the generator terminals, but also short-circuits inside the generator, including a turnshort-circuit.To ensure the interrelation between the electrical part characterized the winding parameters and their connection scheme and the magnetic part, the Maxwell Circuit software package was used.

Table 1. Parameters of the ERM with HCPM

| Parameter	Value
Power, [kW]	100
Rotor rotational speed, [rpm]	24,000
Phase number	3
Poles number	2
Outer stator diameter ($D1$), [mm]	190
Turn number in phase	9
Phase resistance, [Ohm]	0.0063
Phase inductance, [H]	$7.93 \cdot 10^{-6}$
Active length (l), [mm]	120
Air gap (δ), [mm]	3
Phase voltage amplitude, [V]	175
Total rotor length, [mm]	120
Rotor diameter ($D2$), [mm]	100
Type of permanent magnets / residual magnetic flux density / coercive force	Sm_2Co_{17} / 1.08 T / 850 kA/m
Current density, [A/mm²]	15
Stator core material	Amorphous alloy
Stator core type	wound
Wire type	Litz with a core diameter of 0.071 mm; number of conductor is 60
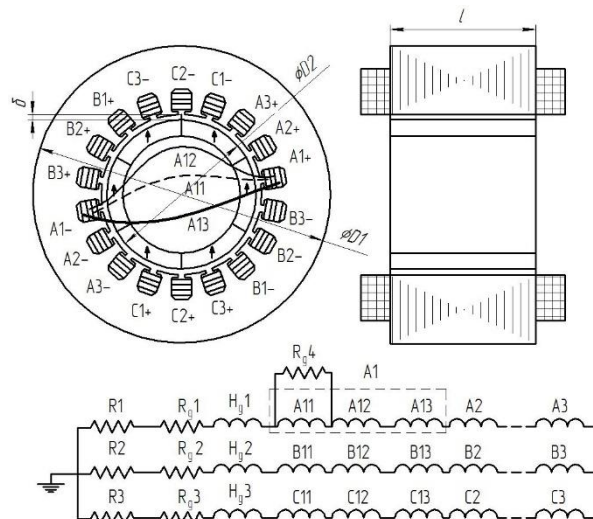
Figure 1. Design of the ERM with HCMP (upstairs) and the electric part of the model (downstairs)

The design of the ERM with HCPM and the electrical part of the model are shown in Figure 1. R1-R3 are loads; Rg1-Rg3 are the internal resistances of the ERM with HCPM (winding resistances). Hg1-Hg3 are the winding inductances. Rg4 is the resistance to simulate the turnshort-circuit inside the ERM with HCPM. A1, A2, A3, B1, B2, B3, C1, C2, C3 windings of the electric model (Figure 1, downstairs) correspond to the phases of the design scheme (Figure 1, upstairs). Each winding consists of three turns. For convenience, only the A1, B1 and C1 windings are exposed on the model electrical part.

All the research results were obtained for specific numerical parameters given in Table 1. The generality of the physical processes in the ERM with HCPM makes it possible to use results in a wide range of design parameters and features of the ERM with HCPM. The proof of this assertion is below.To study different operating modes, R1-R3, Rg4 parameters were changed, thereby simulation various short-circuit types, including various combinations of turn-to-turn and phase-to-phase short circuits, were made.

3. ERM Computer Simulation in the Different Modes

As a computer simulation result, electromagnetic moments, currents and magnetic field distribution in various stator elements were determined at the idling, rated load and various short-circuits types.

3.1. Nominal ERM Operating Mode

The study of the nominal mode was not the main task of the work. However, this analysis is necessary for the model verification, since experimental research of this mode do not have any negative consequences in contrast to the short-circuit modes. The simulations were performed with an active load; the load power factor was 1. R1-R3 resistances were 0.25 and 0.35 Ohm. The resistance Rg4 was 1,000,000 Ohm. A computer simulation in this mode allowed the determination of the nominal electromagnetic moment, voltages at rated load, various overloads and idling. Figure 2 shows the electromagnetic moment at the nominal operation mode and various loads. The obtained electromagnetic moment of 55-60 Nm has no pulsations. Its value corresponds to the rated power.
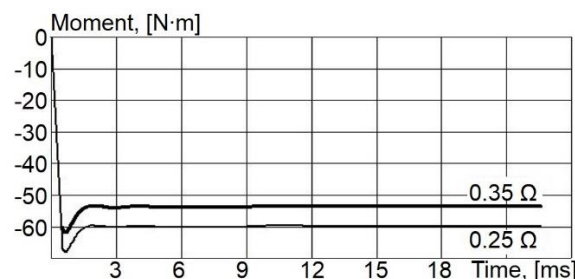

Figure 2. Electromagnetic moment at the nominal operation mode and various loads

3.2. Three-Phase Symmetric Short Circuit of the ERM with HCPM and a Sudden Three-Phase Short Circuit Simultaneously with a Turn Short Circuit

The next research stage was computer modelling of the ERM with HCPM in the three-phase short-circuit mode. For studies of this operation mode, R1-R3 were set equal to $1 \cdot 10^{-6}$ Ohm. Rg4 was 1,000,000 Ohm. Rg1-Rg3 were 0.0063 Ohm. The phase inductance was exhibited in accordance with Table 1.

As a result, currents in the ERM windings were obtained at the sudden three-phase short-circuit, and an electromagnetic moment dependence of time is presented in Figure 3, which shows that in the case of a symmetric three-phase short-circuit in the ERM with HCPM and studied numerical parameters, an almost two-fold throw of the electromagnetic moment occurs. Therefore, the ERM drive should withstand double overloads in the generator mode. The electromagnetic moment has a decaying character and after a period of 20 ms, it decreases by 200 % more. The electromagnetic moment has an alternating character. The obtained result agrees with the results of [17], as well as with other scientific papers of the three-phase short-circuit study. This confirms the adequacy of the obtained results.
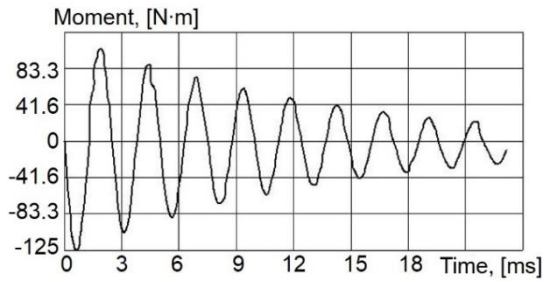
Figure 3. Electromagnetic moment at a sudden three-phase short-circuit
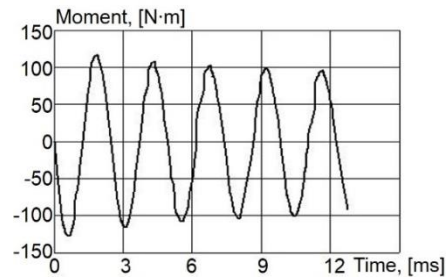

Figure 4. Electromagnetic moment with three-phase short-circuit fault simultaneously with a turn-to-turn short-circuit

Figure 3 shows that the pulse duration of the maximum currents and, correspondingly, of the maximum moment does not exceed 3-6 ms. At 7 ms, the electromagnetic moment is almost equal to the nominal electromagnetic moment.Thus, due to the influence of such currents in a short time period, the ERM winding temperature will change insignificantly. The main negative effect of three-phase short-circuit currents for the ERM with HCPM is a significant increase in the electrodynamic forces in windings and the torque overload.

It is obvious that with the arising electrodynamic forces acting on the winding, an insulation breakdown can occur. Simultaneously with a three-phase closure, there is also a turn-to-turn short circuit in the ERM with HCPM.For the analysis of these processes, the computer simulations of a three-phase short-circuit and a turn-to-turn short-circuit were also carried out.

To investigate this perationmode, resistances R1-R3, Rg4 were set equal to $1 \cdot 10^{-6}$ Ohm. Resistances Rg1-Rg3 were 0.0063 Ohm. Phase inductances was set according to Table. 1. As a computer simulation result, the electromagnetic moment of this emergency was obtained. It is presented in Figure 4, which shows that in the case of a symmetric three-phase short-circuit simultaneously with a turn-to-turn short-circuit in the ERM with HCPM and numerical parameters, a double throw of the electromagnetic moment occurs. The electromagnetic moment has a weak fading character. It decreases below 10 % after 20 ms. The electromagnetic moment has an alternating character. The destructive effect of a short circuit on the drive and the system, in which ERM with HCPM is installed, are significant at a three-phase short-circuit simultaneously with a turn-to-turn short-circuit. In this case, the current in the short-circuited coil increases by 3-5 times and can lead to burnout of the coil, as it is aperiodic in nature and also fades weakly in time.

To minimize the effects of this mode, the decision of the protection method selection should be taken at the first milliseconds. The diagnostic criterion in this case may be an alternating magnetic moment, which fades weakly in time unlike to three-phase short circuits. Also a diagnostic criterion of this mode may be the magnetic field change in the stator core. These criteria will be described later.

3.3. Two-Phase Symmetrical Short Circuit of the ERM with HCPM and Two-Phase Short-Circuit Simultaneously with a Turn-to-Turn Short Circuit

To investigate these operating modes, resistances R1, R2 and Rg4 were set equal to $1 \cdot 10^{-6}$ Ohm, the resistance R3 was 0.25 Ohm. Resistances Rg1-Rg3 were 0.0063 Ohm. Phase inductances were also exhibited in accordance with Table. 1. Currents in the ERM windings at a two-phase short-circuit, as well as the electromagnetic moment dependence in time were obtained. Results are presented in Figure 5, which showthat for a two-phase short-circuit in the ERM with HCPM with the numerical parameters, a throw of the electromagnetic moment exceeding the nominal almost in 2.5 times occurs. The electromagnetic moment has a fading character. After a period of 20 ms, it decreases by more than 1.5 times. In addition, it has an alternating character and differs in form from the electromagnetic moment characteristics obtained for the three-phase short-circuits, since the even harmonics in the current appears at the two-phase short-circuits.
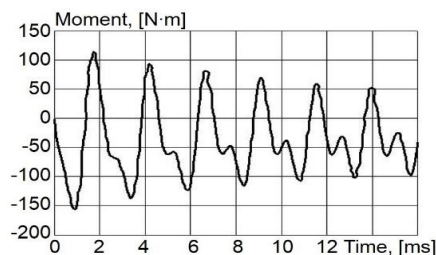
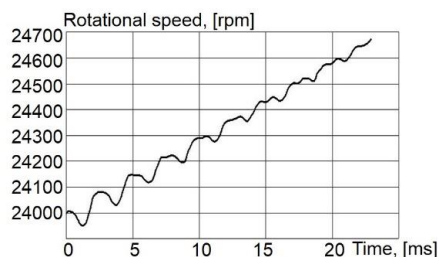Figure 5. Electromagnetic moment
at a two-phase short circuit

Figure 6. Velocity characteristic of the drive
at a two-phase short-circuit

To estimate this mode with the theoretical results given in other works such as [16], the acceleration characteristics of the drive were also investigated for a two-phase short-circuit and presented in Figure 6. The obtained results are consistent with results of [18], which also confirms the adequacy of the obtained curves. Figure 7 shows that in the case of a two-phase short-circuit simultaneously with a turn-to-turn short-circuit in the ERM with HCPM, the electromagnetic moment is thrown 2.5 times.The electromagnetic moment has a weak fading character, which is similar to the three-phase short-circuit simultaneously with the turn-to-turn short circuit. After 20 ms, it decreases by below 10%. It has an alternating character and exceeds the electromagnetic moment that takes place during a three-phase short-circuit simultaneously with the turn-to-turn short circuit. Therefore, this mode is more negative for the ERM with HCPM.
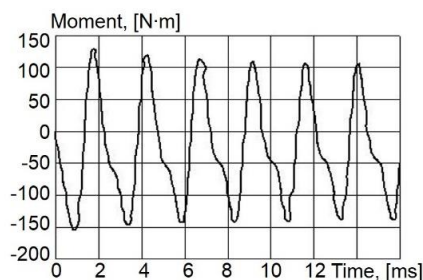

Figure 7. The electromagnetic moment at a two-phase short-circuit simultaneously
with a turn-to-turn short circuit

It should be noticed that with the turn-to-turn short circuit appearance, the diagnostic criteria for the magnetic field and electromagnetic moment are the same qualitatively, i.e. in the form and nature of the changes, and they are differ only in magnitude. Therefore, for the case under consideration, it is difficult to separate these two types of short-circuit.

3.4. A Single-Phase Symmetric Short Circuit of the ERM with HCPM and a Single-Phase Short-Circuit Simultaneously with the Turn-to-Turn Short Circuit

To research these operating modes, the resistance R1 was equal to $1 \cdot 10^{-6}$ Ohm. The resistance Rg4 was 1 000 000 Ohm, resistances R2, R3 were 0.25 Ohm. The resistances Rg1-Rg3 were 0.0063 Ohm. The phase inductances were also exhibited in accordance with Table 1.

Currents in windings of the ERM with HCPM and changes in the electromagnetic moment in time were obtained at a single-phase short-circuit. Results are presented in Figure 8, which shows that for a single-phase short-circuit, the current amplitude in the short-circuited phase increases twofold, while the current in the operable phases increases by 10-15 %. The ERM electromagnetic moment has a pulsating character with a pulsation amplitude of 40 Nm and a constant component of 20 Nm. The maximum electromagnetic moment is 80 Nm. The electromagnetic moment character is undamped. The constant component of the

electromagnetic moment is created by working phases. Figure 9 presents the electromagnetic moment for the single-phase short-circuit simultaneously with the turn-to-turn short circuit.

During a single-phase short-circuit simultaneously with the turn-to-turn short circuit in the ERM with HCPM and with the studied numerical parameters, the electromagnetic moment throw in 2.3 times happens. The electromagnetic moment has a non-damped, alternating character.Changes in the electromagnetic moment in the positive region and in the negative region are asymmetric. In this case, there are curves analogous to the two- and three-phase short-circuit simultaneously with the turn-to-turn short circuit considered above.Thus, the diagnostic criteria of the turn-to-turn short circuit predominate over other types, in combination with which they can appeared. At the same time, in the case of the single-phase short-circuit simultaneously with the turn-to-turn short circuit, there is an electromagnetic moment asymmetry with respect to the abscissa axis. This criterion in a number of cases allows a separation the single-phase short-circuit simultaneously with the turn-to-turn short circuit, in contrast to the other variants considered. To confirm this conclusion, it also carried out a research of only turn-to-turn short circuit. The results are presented in Figure 10, which shows that in the case of a turn-to-turn short circuit, the electromagnetic moment characteristic has a character similar to considered above. It is weakly damped, alternating and exceeds the rated torque by above 2 times.

Thus, it can be concluded that in the ERM with HCPM, the turn-to-turn short circuit can lead to the most negative consequences, since they have an undamped character. To minimize the consequences of the turn-to-turn short circuit, it is effective to break the conductor into a coreplurality.
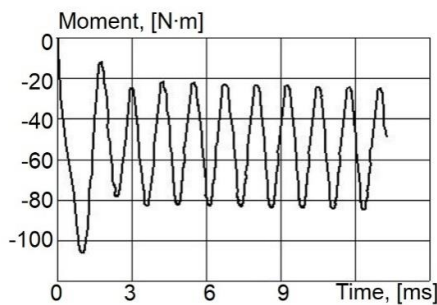

Figure 8. Electromagnetic moment
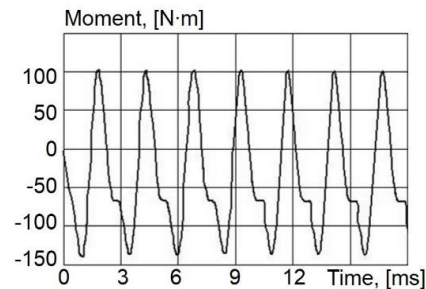at a single-phase short-circuit

Figure 9. The electromagnetic moment for a single-phase short-circuit simultaneously with the turn-to-turn short circuit
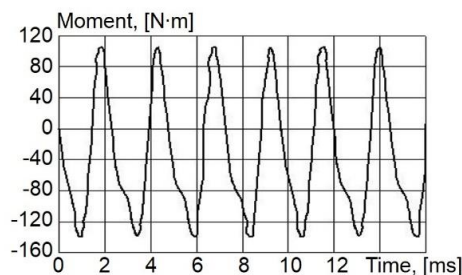

Figure 10. The turn-to-turn short circuit

4. Magnetic Fields in the Stator Core Back at the Various Short Circuit Types

It is obvious that the electromagnetic moment can not always be the main criterion of the short circuit particular type. Therefore, in addition to the electromagnetic moment analysis, the magnetic field changes in the stator core back were investigated and the various short-circuit types influence on the magnitude and the magnetic field distribution was estimated. The

results of these studies are summarized in the general graph in Figure 11, which shows that various short-circuit types have a significant effect on the magnetic field distribution in the stator core back. And this influence can be traced both qualitatively and quantitatively. The magnetic field use as a diagnostic criterion makes it possible to separate various combinations of phase and interfacial short-circuits in the ERM with HCPM.

It should be noticed that the studies were carried out for the magnetic field in the stator core. External magnetic fields, due to the smallness of their values, do not allow the estimation the defects investigated sufficiently accurately.

Thus, using the two diagnostic criteria obtained allows the various short-circuit types determination in the ERM with HCPM with sufficient accuracy at minimal time intervals.
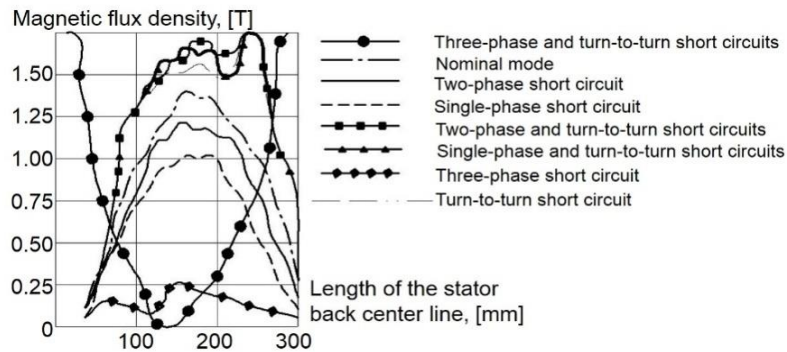

Figure 11. The magnetic field distribution in the stator core back at various short-circuit types

5. Rotor Design Influence on the Electromagnetic Moment at the Short Circuit

To estimate the obtained resultgenerality, it was studied the influence of the various rotor magnetic system design on the electromagnetic moment in the case of the short circuits. In the solution of this problem, it were considered the single-phase and three-phase short circuits in the ERM with HCPM and with three different magnetic systems: a single permanent magnet (A), a system recruited from sectors magnetized radially (B) and a system recruited from sectors magnetized parallel to each other (C). Figure 12 shows the ERM electromagnetic moment characteristics in a three-phase symmetrical short circuit. Figure 13 presents a single-phase symmetrical short circuit.Analysis of these dependencies shows that the rotor magnetic system design does not significantly affect the electromagnetic moment qualitatively. Thus, fluctuations in the electromagnetic moment curve change, its numerical values change, but the curve shape remains unchanged. This proves the fact that the obtained curves can be used to diagnose ERM with HCPM in a wide range of input parameters.
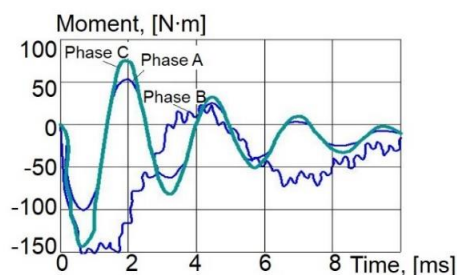

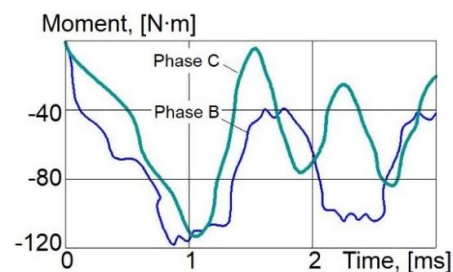Figure 12. The ERM electromagnetic moment characteristics at a three-phase symmetrical short circuit

Figure 13. The ERM electromagnetic moment characteristics at a single-phase symmetrical short circuit

6. Experimental Research

To verify the results obtained, experimental studies of a full-size 120-kW ERM prototype with rotational speed of 24,000 rpm were carried out. Parameters of the sample are presented in Table 2. Experimental research allow the confirmation of computer simulation data. To simplify the laboratory research, experiments were conducted at a frequency of 6000 rpm. Figure 14 shows the main ERM elements: rotor, stator core, cooling jacket, as well as the full-size experimental ERM model.
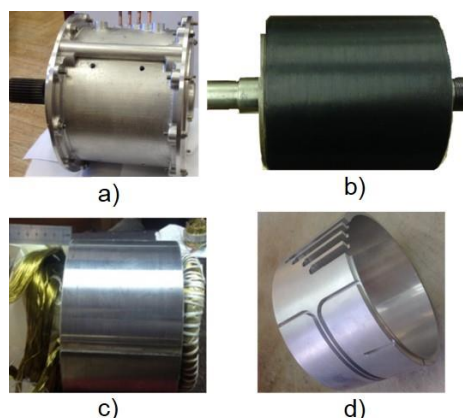

Figure 14. The full-size experimental ERM model (a); rotor (b), stator core (c), cooling jacket (d)

Table 2. Parameters of the sample

Parameter	Value
Steel grade of the active area	CoFe
Sheet thickness, [mm]	0.18
Phase current frequency, [Hz]	400
Phase voltage, [V]	120
Phase current, [A]	306.22
Current density in the winding, [A/mm^2]	15
Linear load, [A/m]	33104
The thermal factor, [A/m$^2 \cdot$ A/cm]	3972
Power, [kW]	120
Shortening coefficient	0.965
Distribution coefficient	0.957
Active resistance and scattering resistance, [Ohm]	0.00268 / 0.0255
Inductive phase resistances along the d and q axes, [Ohm]	0.099 / 0.099

The computer model verification took place in two ERM operation modes – rated load and idling. In the experimental research at the nominal mode, the active load was connected to the ERM output terminals. The ERM current and, consequently, the load magnitude were limited to a level of 80-85 A. With comparison the experiment and computer modeling results, it was found that the created computer model is highly accurate and completely repeats the experiment results. The numerical discrepancy between the experimental data and the simulation data is below 5%. Thus, conclusions are confirmed experimentally, since for all research, one general computer model was used.

7. Conclusion

The computer model of the ERM with HCPM is presented, research of various short circuit types in the ERM with HCPM, including turn-to-turn short circuit, was carried out. Diagnostic criteria of short circuits are revealed. There are the electromagnetic moment and the magnetic flux density in the stator core back. It is important to notice that the conducted research were verified experimentally. The obtained results can be used in practice in the design of the ERM with HCPM.

References

[1] Nagorny A, Dravid N, Jansen R, Kenny B. *Design Aspects of a High Speed Permanent Magnet Synchronous Motor/Generator for Flywheel Application*. NASA/TM-2005-213651. 2005; 1: 1-7.
[2] Bobtsov AA, Pyrkin AA, Ortega R et. all. A robust globally convergent position observer for the permanent magnet synchronous motor. *Automatica*. 2015; 61: 47-54.
[3] Zhu ZQ, Howe David. Electrical Machines and Drives for Electric, Hybrid, and Fuel Cell Vehicles. *Proceedings of the IEEE*. 2007; 95(4): 746–765.

[4]   Ismagilov F, Vavilov V, Ayguzina V, Bekuzin V. New method of optimal design of electrical rotating machines. *Indonesian Journal of Electrical Engineering and Computer Science*. 2017; 5(3): 479-487.
[5]   Chin YK. A Permanent Magnet Synchronous Motor for Traction Application of Electric Vehicle. *Electric Machines and Drive Conference, IEEE int*. 2003; 2: 1035–1041.
[6]   Gieras JF. High speed machines. Advancements in Electric Machines (Power Systems), ed. by JF Gieras. Berlin: Springer. 2008: 81–113.
[7]   Bailey C, Saban D, Guedes-Pinto P. Design of High-Speed Direct-Connected Permanent-Magnet Motors and Generators for the Petrochemical Industry. *IEEE Transactions on Industry Applications*. 2009; 45 (3): 1159–1165.
[8]   Borisavljevic A, Polinder H, Ferreira J. On the Speed Limits of Permanent-Magnet Machines.*IEEE Transactions on Industrial Electronics*. 2010; 57(1): 220–227.
[9]   Pham Cong Thanh, Shen An Wen. A Comparative Study of Control Methods for Induction Motor and High Performance Z-source Inverter. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2013; 11(6): 2912-2925.
[10] Nikiyan NG, Yondem M Ye. Determination of the rotor eccentricity of asynchronous machines by the emf magnitude of higher harmonics (in Russian). *Izv. vuzov. Elektromekhanika*. 1991, 11.
[11] Geller B, Gamata V. High harmonics in asynchronous machines (in Russian). Moscow: Energiya. 1981.
[12] Gaydenko YUA, Vishnevskiy TS. Method of electromagnetic diagnostics of the static eccentricity of the rotor in a synchronous generator (in Russian). *Gidroenergetika Ukrainy*. 2011; 2: 52–57.
[13] Gerasin AA, Chuyanov GA, Ismagilov FR et. all. *The device for protection of the magnetoelectric generator against short-circuit (variants)* (in Russian). RU 2498473C1 (Patent). 2013.
[14] Bertinov AI. Aviation electrical generators (in Russian). Moscow: Oborongiz. 1959.
[15] Ismagilov FR, Khayrullin IKh, Farrakhov DR et all. The control and protection system of a magnetoelectric synchronous generator for autonomous objects (in Russian). 2015613868 (certificate of the computer program registration). 2015.
[16] Ganev E. *High-Performance Electric Drives for Aerospace More Electric Architectures*. IEEE Power Engineering Society Meeting. 2007; 1: 1-8.
[17] Farrakhov DR, Ismagilov FR, Murach VI, Vavilov VYe, Panteleyev SV. Analysis of the symmetrical short-circuit of a synchronous generator with excitation from permanent magnets, taking into account the change in rotor rotation frequency (in Russian). *Aviakosmicheskoye priborostroyeniye*. 2016; 9: 31-38.
[18] Gorev AA. Transient processes of a synchronous machine (in Russian). Moscow, Leningrad: Gosenergoizdat. 1950.