Progress In Electromagnetics Research M, Vol. 59, 123–133, 2017

Transients in Ultra-High-Speed Generators of Micro-Sized Gas Turbines

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Abstract—The article presents a research of the effect of different types of short circuits (SC) on the performance of the gas turbine and ultra-high-speed microgenerator (MG) in a wide rotational speed range (from 200,000 rpm to 1,000,000 rpm) at a power from 10 W to 1 kW. The studies are carried out on a specific two-pole 100 W 500,000 rpm microgenerator with permanent magnets with a toroidal winding. The research is carried out by finite element method using Ansys Maxwell software. Numerical study by the finite element method is performed at the rated operation mode and various types of short circuits: single-phase, two-phase, three-phase circuits coil inside MG. By the results of these studies, we estimate a negative impact of different types of faults on the parameters of MG and the mechanical characteristics of the gas turbine. Also various options MG with SC for various types of bearings were considered. Then, using the full-sized 100 W sample we carried out experimental studies of the MG operation in nominal operation mode at the 500,000 rpm. That allows to verify the developed computer model and confirm the results of our practice research. The obtained results can be used in the aerospace industry for design the high reliability complexes such as new energy systems for satellite power supply, unmanned aerial vehicles and microturbines. In addition, it can be used to design the ultra-high-voltage electric machines with a high fault tolerance for the compressor plants, air supply systems of hydrogen fuel cells, new medical tools and machine tools.

1. INTRODUCTION

The needs of different industries in portable sources of energy lead to the research, development and creation of micro-sized 100–150 W power systems. These systems are actively used in the creation of unmanned aerial vehicles, satellites power supply systems, portable devices power systems, in robotics and other applications [1-7].

As shown in work [8], the storage batteries are inferior to the converting fuel energy complexes according to the energy density in this power range, with the requirements to the minimum dimensions of the power supply system. Therefore, international research groups and industrial corporations [8–14] is engaged in research and development of micro-sized power systems, representing the gas turbine shaft which is a high-speed micro-generator (MG) with permanent magnets (PM) connected with the control system (Figure 1). To achieve maximum energy density rotational speed of the gas turbine and MG should be as high as possible. Therefore, all international teams working in this field aimed at creating 400,000–1,100,000 rpm MG and gas turbines. The rotational speed limit in 1,100,000 rpm in the world practice is not yet surpassed.

Celeroton company and ETH Zurich company together are developing such systems with rotational speed 400,000–1,000,000 rpm with power up to 1 kW [8–11]. IHI Corporation is developing a system with the rotational speed of 490,000 rpm and a power of 400 W [12]. Similar work is carried out by the

Received 6 June 2017, Accepted 4 August 2017, Scheduled 14 August 2017
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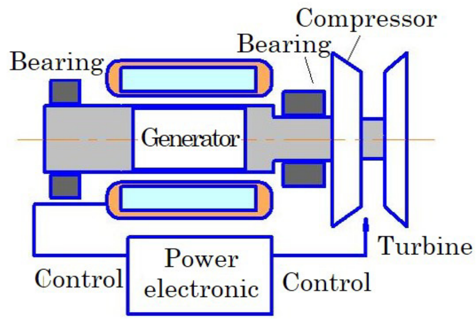

Figure 1. Micro-sized power system with ultrahigh speed generator.

Onera research center. They are developing a system with a power of 55 W [13]. NASA research center uses kinetic energy storage with 300,000 rpm MG [14]. Robot/Mechatronics Research Center carried out research aimed at the creation of a micro-turbine with 500 W 400,000 rpm MG to provide power to unmanned aerial vehicles and robots [15].

In publications dedicated to creation of portable power supply systems with gas turbines and MG, the main attention is paid to the design of a gas turbine, bearings, cooling system and power electronics [16–21]. Transient study MG, such as symmetrical and asymmetrical short circuits at terminals and inside MG in known publications [8–21], is not held. However, these issues have significant practical value as they allow assessing the performance of micro-sized power supply systems in all range of working modes, including emergency mode.

Considering the large air gap between the stator and rotor and the small mass of the MG rotor in these systems at high speeds, the transient processes will have a different characteristic compared to electric machines with permanent magnets with a rotational speed not higher than 60,000 rpm whose transients are well described in publications [22, 23]. That is, it is not possible to make full use of known articles on transient processes in electric machines with permanent magnets [22, 23] to assess the performance of MG in emergency operation modes. Therefore, the aim of this work is to study transient processes in the ultra-high-speed (500,000 rpm) 1000 W MG. This goal is new and not considered in the literature.

The main contribution of this work is the analysis of influence of different types of short circuits on the performance of the gas turbine and MG in a wide rotational speed range from 200,000 rpm to 1,000,000 rpm at a power from 10 W to 1 kW. Research is conducted on the 500,000 rpm 100 W two-pole MG with permanent magnets and toroidal winding. Initially the research is carried out by finite element method using Ansys Maxwell software. Numerical study by the finite element method is performed at the rated operation mode and various types of short circuits in the MG windings: single-phase, two-phase and three-phase. A negative impact of different types of fault on the MG parameters and mechanical characteristics of the gas turbine was estimated. We considered various options MG at SC for various types of bearings. Using the 100 W MG, experimental studies in the rated operation mode at 500,000 rpm were carried out. This allows us to verify the developed computer model and confirm the results of our research in practice.

The research results of processes in ultrahigh-speed MGs in the case of short circuits allow the workability evaluation of the system, in which they are installed, and the selection of the high effective methods to protect system with MG from short circuits. Thereby, the maximum reliability is ensured. These results are especially important for designing high reliability complexes such as new energy systems for satellite power supply, unmanned aerial vehicles and microturbines. In addition, the results can be used in the design of the ultra-high-voltage electric machines with a high fault tolerance for the compressor plants, air supply systems of hydrogen fuel cells, new medical tools and machine tools. The results of this research have already allowed the development recommendations for the power supply system protection of the unmanned aerial vehicle with an ultra-high-speed 100 W MG.

2. COMPUTER SIMULATION OF TRANSIENTS AND RATED MODES OF THE MG

A two-dimensional finite element model of the MG in the Ansys Maxwell software was created by settlement scheme (Figure 2). Table 1 shows the parameters of the investigated MG and properties of materials used in it.

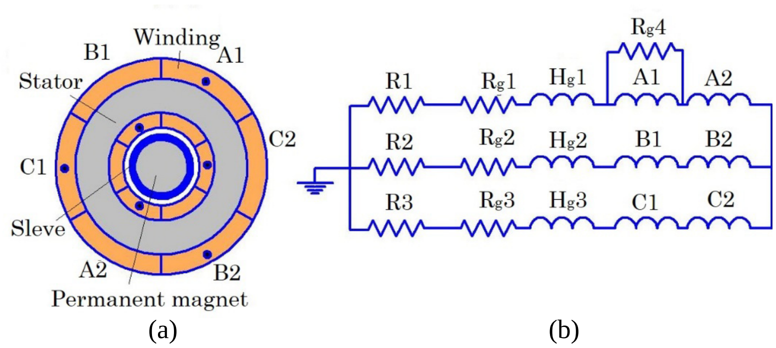

Figure 2. The electrical part of the model (a) equivalent circuit of MG (b).

Table 1. MG properties.

Power, W	100
Rotational speed, rpm	500,000
Number of phases	3
Number of poles	2
Outer diameter of stator, mm	16
Number of turns in the phase	30
Phase resistance, Ohm	0,15
Phase inductance, H	9,3 10^{-6}
Active length, mm	15
The phase voltage amplitude, V	19
Full length of the rotor, mm	20
Rotor diameter, mm	6
Rotor moment of inertia kg m^2	$1,95 * 10^{-8}$
Permanent magnets type	$Sm_2Co_{17}/Br = 1.08\,T/H = 850\,kA/m$
Rotor mass, g	4,5
Rotor damping ratio Nms/rad	8.49766e-014
Current density, A/mm^2	8
Stator core material	Amorphous alloy
Stator core type	Wound
Wire type	60-strand Litz with a strand diameter of 0.071 mm

To achieve this goal, it is necessary to provide interconnection between the electrical (representing the windings parameters and their connections) and magnetic parts of the model. To solve this problem Maxwell Circuit software was used. The electrical part of the MG model is given in Figure 2.

In Figure 2, the winding ends are marked as a point. Resistances R1–R3 are load resistances. Resistances Rg1–Rg3 are internal generator resistances (winding resistance). Hg1–Hg3 are inductances of the MG windings. Resistance Rg4 is designed to simulate short circuit of one coil inside MG.

Windings A1, A2, B1, B2, C1, C2 of the electric model (Figure 2(a)) correspond to phases of the equivalent MG circuit (Figure 2(b)). The parameters of the resistances R1–R3 and Rg4 are changed to simulate different types of short circuits. The mechanical actuator characteristics describe constant load torque of 2 mNm.

3. THE RATED MODE OF MG

The first stage of our research is the computer simulation of the MG in the rated mode. Studies of this mode were performed at resistive load (power factor of load equal 1). The resistances R1–R3 equal 2.8 Ohms, and resistance Rg4 equal 1 MOhms.

Computer simulation in this mode allowed determining the nominal electromagnetic torque of MG, the voltage at rated load and the voltage at various loads.

Figure 3 shows the rated torque, rated voltage and the three-phase and single-phase short-circuit voltages in the MG.

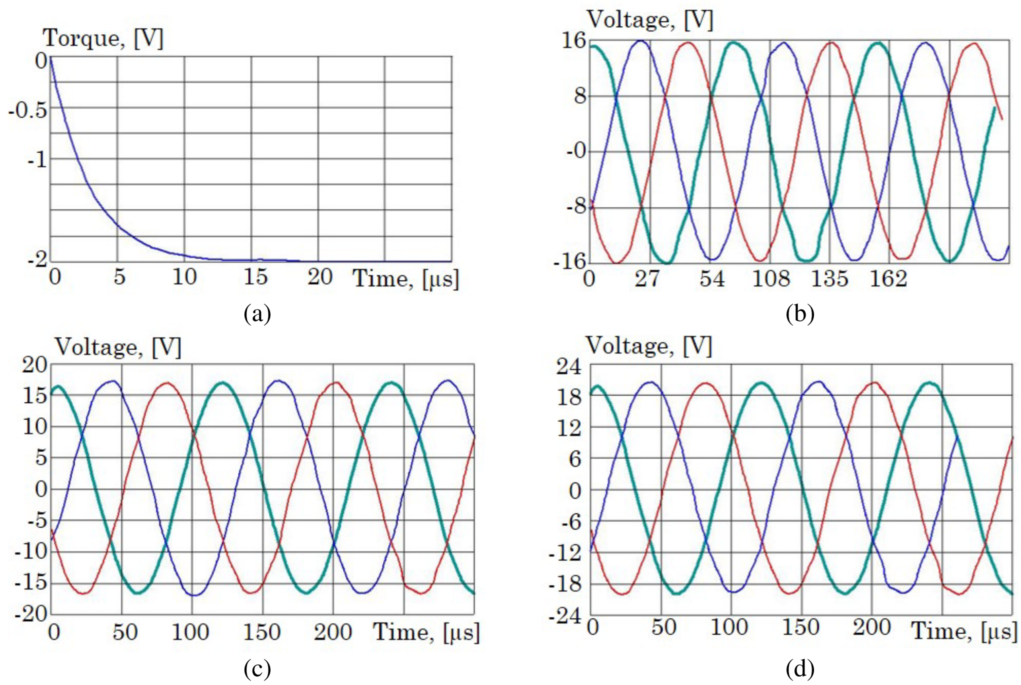

Figure 3. (a) Electromagnetic torque at the rated mode; (b) MG voltage at three-phase short circuit (phase A, B, C); (c) MG voltage with single phase short circuit (phase A); (d) MG voltage at the rated mode (phase A, B, C).

As a result, it was established that the electromagnetic moment of the MG was 2 mNm at a load of 2.8 Ohms (amplitude of the phase current of 4 A). The dependence of the torque from the time does not contain any ripple or deviations. The nominal moment MG is gaining for 5 μs.

4. SUDDEN THREE-PHASE SYMMETRICAL SHORT CIRCUIT OF MG

The next stage of research was computer modelling of MG in the three-phase short circuit mode. The resistances of R1–R3 are equal to $1 \cdot 10^{-6}$ Ohm. The resistance of Rg4 is equal to 1 MOhm. The resistances of Rg1–Rg3 are equal to 0.15 Ohm. The inductance of phases is shown in Table 1. As a result, the currents in the MG windings during a sudden three-phase short circuit and changes of the electromagnetic of the gas turbine were measured. The results are shown in Figure 3 and Figure 4.

Figure 3 shows oscillograms of voltages in rated mode and at a three-phase short circuit and single-phase short-circuit. From these waveforms, the output voltage of the MG is seen to decrease, in comparison with rated mode, by only 3–3.5 V, that is, no more than 5% of the rated value. This is due to the structural location of the MG windings (toroidal), a significant air gap and significant phase resistance in the three-phase short circuit. Therefore, in the case of a short circuit the MG generates considerable energy.

This conclusion is confirmed from the analysis of Figure 4. Maximum currents for sudden three-phase short-circuit in MG are 30–32 A (8 times higher than rated values). Maximum current pulse length does not exceed 20 µs. That is, due to the influence of such currents in such a short period, the temperature of MG windings will change insignificantly. Therefore, the major adverse effect of SC currents on the windings is a significant increase in the electrodynamic forces in the winding. Since the MG in question does not have slots, the conductors of its winding are affected by a significant tangential force tending to displace the winding. In three-phase short circuit mode, as seen from the simulation results, the power increases 8 times. And that could lead to winding displacement. In addition, the conductors are also affected by the radial force tending to press the conductor to the magnetic core of the stator. This force depends on the square of the current and in three-phase short circuit mode increased to 64 times. The joint action of these forces will lead to a breakdown in the insulation of the conductors and cause simultaneously a sudden three-phase short circuit and a short-circuit. So, obviously, to ensure the reliability of the MG winding at the design stage, it is necessary to put a significant margin of safety in electrodynamic efforts.

At the three-phase short circuit, the MG voltage is reduced significantly compared to the rated mode, and the resistance of the winding is large enough. The MG has a significant electromagnetic torque. Peak electromagnetic torque occurs in the first 20–30 µs of SC and equal 10 mNm. That is 5 times higher than rated. Obviously, if the gas turbine is not designed for such an overload, it will cause mechanical breaking of the connection of the turbine and MG. This will lead to significant mechanical vibrations of the rotor. If the MG rotor is mounted on magnetic or gas bearings, the MG rotor can run out of them. This will lead to MG destruction. It is possible to avoid this by using mechanical bearings. In this case, after breaking the connection between the rotor and the gas turbine, the rotor, under the action of substantial retarding torque, will stop.

The greatest danger for MG at three-phase short circuit is the skew of the windings. As you know, the bevel of the windings leads to the appearance of axial forces in electric machines, which act on the rotor and depend on the current. When the three-phase short-circuit axial forces caused by the bevel increase 8 times, they can lead to freewheeling of the rotor, possessing a significant kinetic energy.

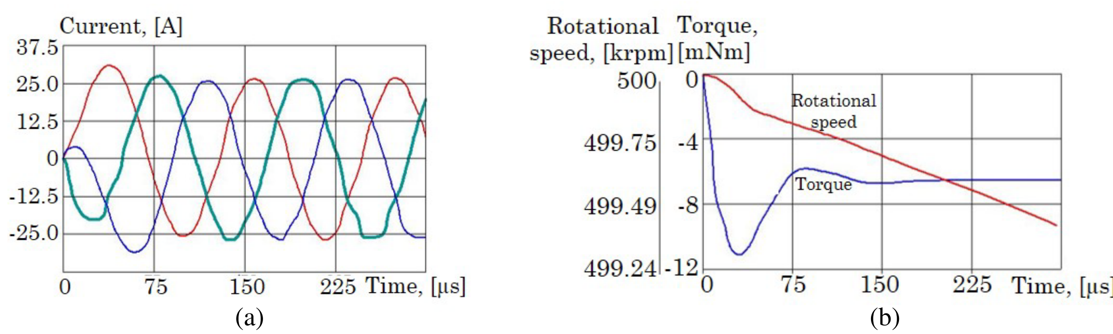

Figure 4. (a) Currents, (b) electromagnetic torque and rotational speed of the gas turbine at three-phase short circuits.

5. SINGLE-PHASE SHORT CIRCUIT OF MG

For research of single-phase short circuits, the resistance of R1 was $1 \cdot 10^{-6}$ Ohms; resistances of R2, R3 were 2.8 Ohms; resistance of Rg4 equal 1 MOhms; resistances of Rg1–Rg3 were 0.15 Ohm. In the result,

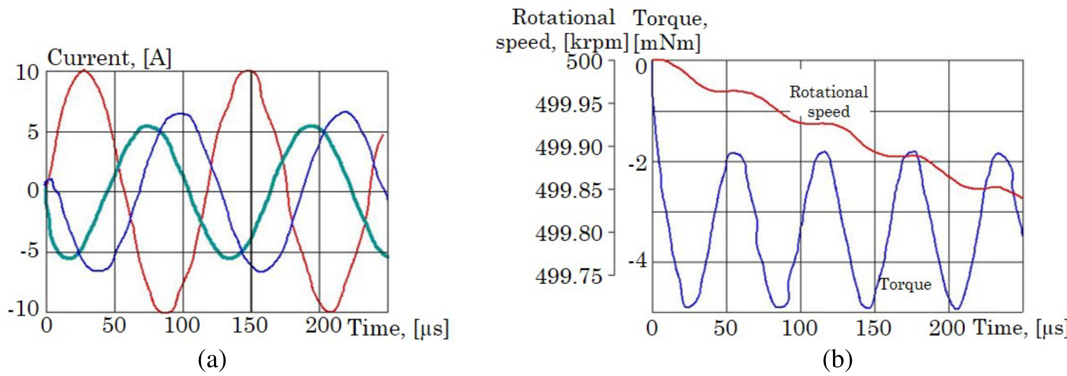

Figure 5. (a) Currents, (b) electromagnetic torque and rotational speed of the gas turbine at single-phase short-circuit.

we get the values of the currents in the MG windings at single-phase short-circuit and the dependence of electromagnetic torque from time and rotational speed of the gas turbine (Figure 5).

Analysis of Figure 5 shows that the amplitude current in the shorted phase increases twice at the single-phase short circuit, while in normal phase, current is increased by 10–15%. Electromagnetic torque MG has a pulsating nature with a ripple amplitude 4 of the CMA and constant part 2 of the CMA. That is, the maximum electromagnetic torque is 6 CMA. For 250 μs, the electromagnetic torque has 4–5 oscillations. The constant component of the electromagnetic torque is created in workable phases. That is, in the mode of single-phase short-circuit, gas turbine experiences three times of the overcharge, which have a pulsating characteristic. This leads to that the rotational speed of the gas turbine is reduced and also decreases with a pulsating characteristic.

Electrodynamic efforts at single-phase short-circuit change accordingly in 2 times for the tangential force acting on the coil and 4 times for radial forces. Therefore, compared with the three-phase short circuit, the electrodynamic stress and mechanical overload acting on the gas turbine during single-phase short-circuit generate less negative impacts on system portable power supply and MG. After operating in this mode, there is a possibility of no MG destruction.

6. TWO-PHASE SHORT CIRCUIT MG

For research of a two-phase short circuit, the resistances of R1, R2 exhibited equal $1 \cdot 10^{-6}$ Ohms; resistance of R3 was 2.8 Ohms; resistance of Rg4 equaled 1 MOhms; resistances of Rg1–Rg3 were 0.15 Ohm. As a result of computer simulation, currents in the MG windings at two-phase short-circuit and the dependence of electromagnetic torque from time and rotational speed of the gas turbine were

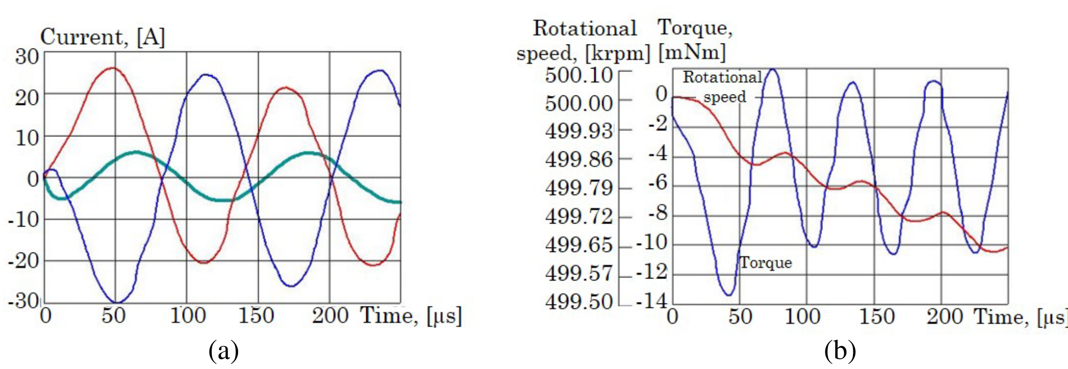

Figure 6. (a) currents, (b) electromagnetic torque and rotational speed of the gas turbine at two-phase short-circuit.

obtained and presented in Figure 6, which shows that for a two-phase SC, the electromagnetic torque alternates in nature and equals 13 mNm (peak value). It should be noted that the positive component of the electromagnetic torque is much smaller than the negative one. Currents in short-circuited phases increase to 30 A. This leads to the electrodynamic forces changing commensurably with the three-phase short circuit mode.

Based on the fact that the electromagnetic torque and currents are commensurable with the three-phase short circuit mode, it is obvious that in a two-phase short-circuit the negative effects will be similar to that described above in three-phase short circuits.

7. SHORT CIRCUIT OF COIL INSIDE MG

For research of short circuit of coil inside MG, the resistances of R1–R3 were 2.8 Ohms; resistance of Rg4 equaled $1 \cdot 10^{-6}$ Ohm; resistances of Rg1–Rg3 were 0.15 Ohm. As a result of computer simulation, currents in the MG windings at short-circuit inside MG and the dependence of electromagnetic torque from time and rotational speed of the gas turbine were obtained (Figure 7).

The analysis of Figure 7 shows that in this mode overload of electromagnetic torque does not exceed two rated values. The current in the closed loop is increased to 30 A and has not sinusoidal characteristic. Because of this the impact on gas turbine protracts in time, but the gas turbine, unlike all other modes considered, accelerates.

In general, this mode is gentle for the gas turbine load. In addition, the act on the short-circuited coil can lead to the winding ignition. This mode is difficult to diagnose during operation because of the small changes in the electromagnetic torque.

Figure 8 shows the results of computer simulation of the magnetic field in the MG to estimate the distribution of the magnetic field at the short-circuit winding inside the MG.

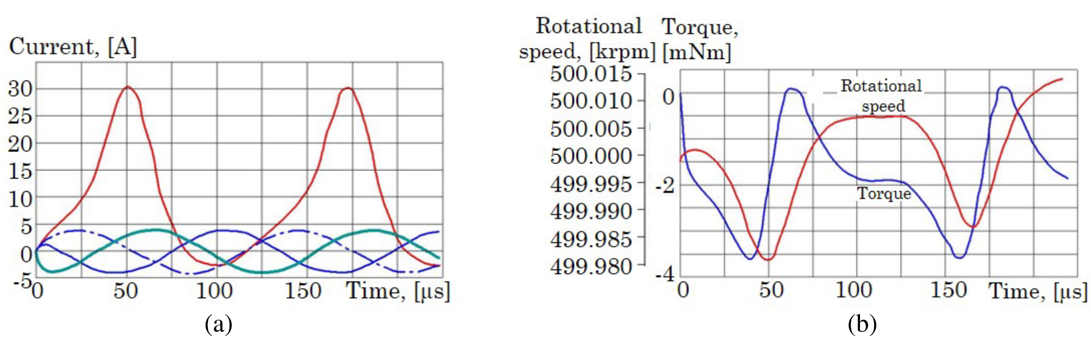

Figure 7. (a) Currents, (b) electromagnetic torque and rotational speed of the gas turbine at short-circuit inside the MG.

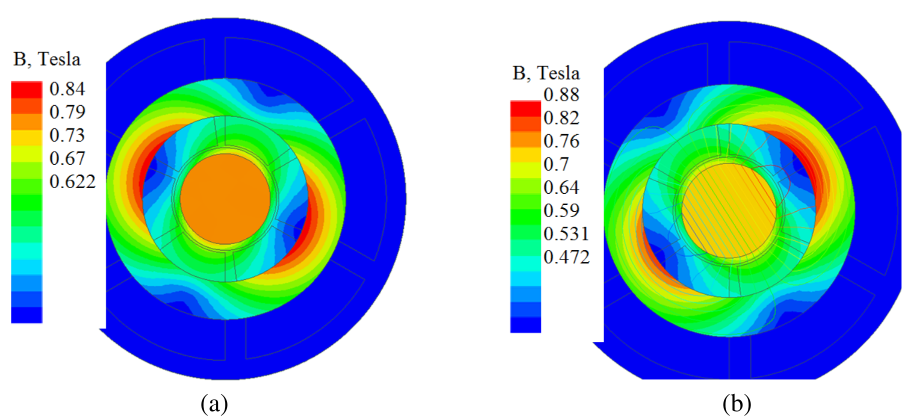

Figure 8. (a) Short-circuit inside the MG and (b) magnetic field distribution at three-phase fault.

The analysis of Figure 8 shows asymmetry of the magnetic field in the magnetic core of the stator under short-circuit inside the MG. Assessment of that magnetic field asymmetry can be a diagnostic criterion of inter-winding SC.

Thus, it is obvious that all considered SC modes will cause harm and can cause MG damage. This applies particularly to the circuits inside MG, three-phase and two-phase short-circuits. This is due to a significant air gap MG, significant phase resistance, as well as a very high rate of transients, which practically does not allow to prevent short-circuit in MG. The only possible effective technical solution is the mechanical decoupling of the MG rotor and the gas turbine shaft by the magnitude of the electromagnetic torque overload.

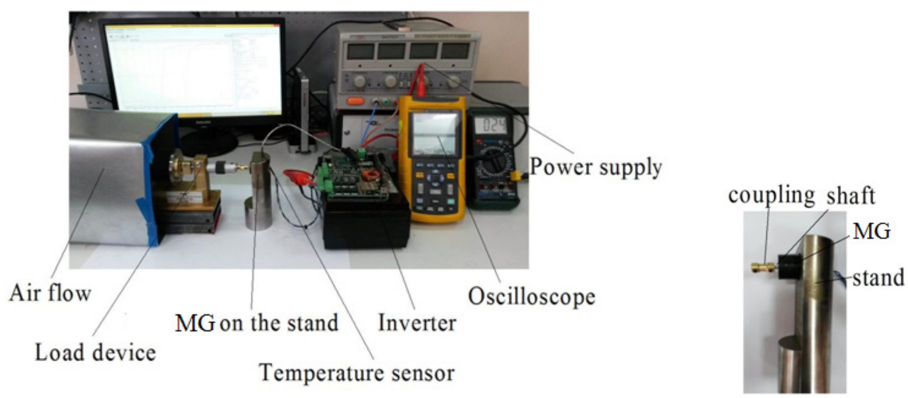

Figure 9. The investigated MG.

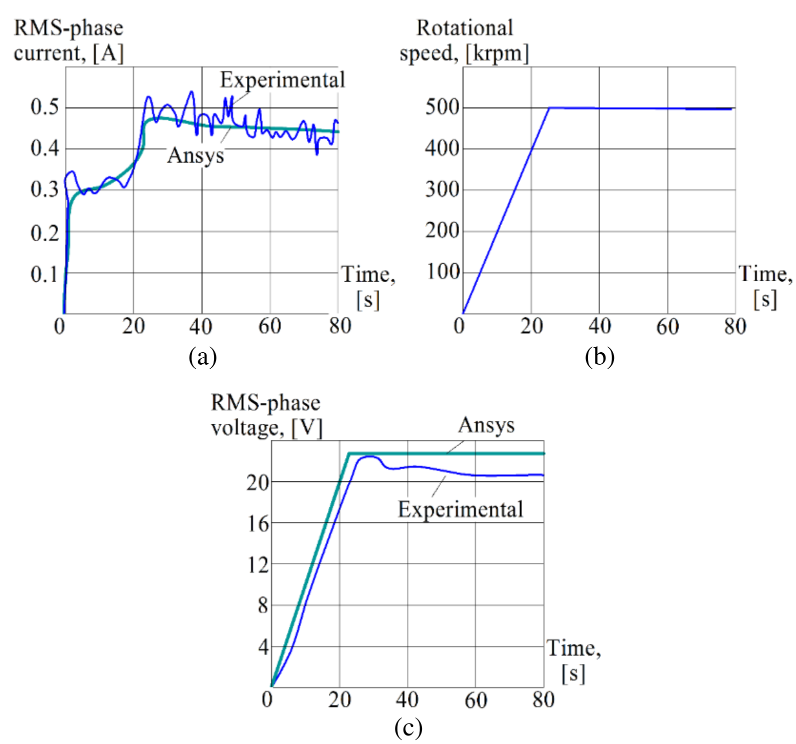

Figure 10. Experimental results of 100 W MG with a rotational speed of 500,000 rpm during acceleration: (a) time-dependence of the rms-phase-current; (b) time-dependence of the rotational speed; (c) time-dependence of the rms-phase-voltage.

8. EXPERIMENTAL STUDIES

To assess the effectiveness of the developed computer models, the authors carried out experimental studies of the Celeroton Company's MG in the rated mode. The short-circuit modes were not investigated due to high safety requirements for such experiments and probable MG destruction. Obviously, if our model provides good agreement with experiment at the rated modes, then the SC modes will also provide the same accuracy. The studied MG with rotor speed of 500,000 rpm and a power of 100 W with cooling-ventilation. Figure 9 shows the setup for experimental studies. The results of experimental studies and their comparison with the data of computer simulation are presented in Figure 10.

Figure 10 shows that the difference between the developed models and experimental data does not exceed 5–7%, which shows a sufficient accuracy of the models and adequacy of the results of the transient studies. The measured electromagnetic torque of the experimental model was 2 mNm.

It is important to notice that the current in experimental studies has peaks and is not linear in nature, in contrast to the simulation data. This is due to the switching of transistors. The characteristics of the MG with a speed of 500,000 rpm are experimentally investigated. Results are presented in Table 2.

Thus, experimental studies have confirmed the above theoretical arguments and allow us to recommend the results obtained by the transient analysis for practical use.

Table 2. Experimental research results.

Power, W	100
Rotational speed, rpm	500,000
Magnet type	Sm_2Co_{17}, $H = 765$ kA/m, $B_r = 1.06$ T
Flux linkage Vs	0.00075
Phase resistance, Ohm	0,15
Inductance, H	$9,3 * 10^{-6}$
Rotor moment of inertia, kg m^2	$1,95 * 10^{-8}$
Rotor diameter, mm	6
Rotor active length, mm	15
Aerodynamic losses, W	8
Temperature of the rotor, °C	50
Ohmic losses in the winding, W	8
Losses in the stator core, W	1,6

9. RESULTS AND CONCLUSIONS

The article presents studies of various types of short circuits in ultra-high-speed microgenerators. It is proved that practically all types of short-circuits in ultra-high-speed microgenerators lead to irreversible destructive consequences. This is due to a significant air gap of the MG, significant phase resistance, as well as a very high rate of transients, which practically do not allow to prevent short-circuits in MG. The only possible effective technical solutions are the mechanical decoupling of the MG rotor and the gas turbine shaft by the magnitude of the electromagnetic torque overload.

Numerical estimation of the overload moments arising at various short-circuits in MG and electrodynamic forces acting on the MG winding is carried out. Also, experimental studies of the nominal operating mode of the MG were performed, and their results verified computer simulation data.

The obtained results can be used in the aerospace industry for designing high reliability complexes such as new energy systems for satellite power supply, unmanned aerial vehicles and microturbines. In addition, the results can be used to design the ultra-high-voltage electric machines with a high fault tolerance for the compressor plants, air supply systems of hydrogen fuel cells, new medical tools and machine tools. It is important to notice that the results of this research have already allowed the development recommendations for the power supply system protection of the unmanned aerial vehicle with an ultra-high-speed 100 W MG.

ACKNOWLEDGMENT

The work was supported by the Russian Science Foundation, project 17-79-20027.

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