Experimental Studies of the High-Temperature Starter-Generator for Aircraft Engine

Flur Ismagilov, Vacheslav Vavilov, Ruslan Karimov, Ilnar Yamalov, Nikolay Tarasov

***Abstract*—This paper provides basic characteristics, structural scheme and experimental research of the scalable prototype of electric starter-generator integrated in the electrified aircraft engine. The studies have shown that short circuit current value depends on starter–generator temperature (when the temperature of the starter–generator active elements increases by 5 times, short circuit current decreases by 25%). General recommendation on the calculation and short circuit currents determination for high-temperature starter-generator integrated to aircraft engine were also made.**

***Keywords*—Starter-generator; permanent magnets; high-temperature generator.**

I. INTRODUCTION

One of the trends in development of modern aircraft is the electric starter–generator (SG) placement inside an aircraft engine (AE) on a high-pressure shaft (HPS). The implementation of this concept allows to achieve a significant advantages for aircraft [1]:

– electric start-up of the AE instead of the currently used energy-consuming pneumatic start-up;

– transmission removal between the AD shaft and the SG, which simplifies the AD and nacelle assembly, increases reliability and simplifies the maintenance of the AE;

– the SG integration on the HPS reduce the size of the nacelle and improve the AE aerodynamic and fuel efficiency.

Having all the advantages this concept also has some drawbacks preventing the SG integration on the HPS. The main one is the aggressive environmental conditions on the HPS, figure 1.

Has following drawbacks there are a number of problems that impeded the integration of the SG on HPS shaft. The main of which are corrosive environmental conditions on HPS shaft, figure 1. The ambient temperature of the HPS depends on the integration point of the SG and varies from 150 °C (the SG integrated on the compressor side) and up to 350 °C (the SG integrated in front of the combustion chamber). The most effective point of the SG integration in the AE determined by the structural features of the engine. Therefore, such SG should be created in close cooperation between the electric machines and aircraft engines experts.

The integrated SG concept implementation has a number of solutions. Initial research on the integrated SG creation carried out by NASA in 1970 [1].

In these studies, the efficiency of integrated SG with rotating rectifiers on the HPS of the AE (on the compressor side of HPS, cold zone) was estimated. As a result, on the aircraft engine with a propulsion of 140 kN was proved that the use of the SG on the HPS improves the fuel efficiency of the aircraft and simplifies the maintenance of the AE. It should be noted that the AE with a propulsion of 140 kN is similar in energy characteristics to PD-14 engines.

In Politecnico di Torino, a multi-phase asynchronous electric machine (6-phase induction machine (IM)) [2, 3] integrated on the HPS is developed. IM HPS is intended only for electric start-up of the AE, but the board electricity is provided by the generator installed on low-pressure shaft (LPS).

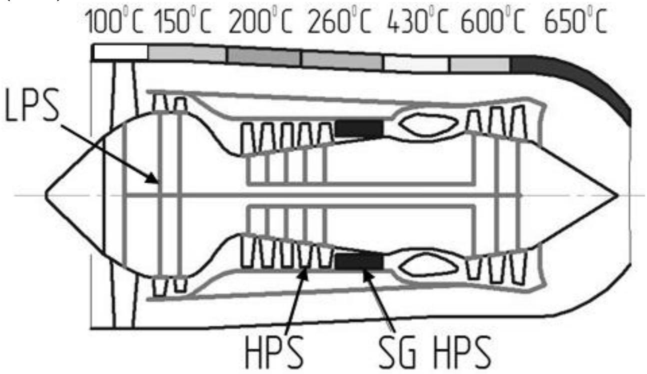

Fig. 1. Sketch of a double-shaft AE with integrated SG

University of Sheffield developed two integrated in the AE electric machines (High temperature embedded electrical machines) [4, 5]. One of them is the reluctance SG installed on HPS in front of the combustion chamber, and the another electrical machine installed on the LPS. The SG mounted on the HPS is designed for the rotation speed of 13,500 rpm and a power of 100-150 kW. This development is performed for Rolls-Royce. As AE considered an aircraft engines Trent 500 for implementing the University of Sheffield conception. It's known from the general theory of electrical machines that reluctance SG have high dimensions and weight, so their use as the SG installed on the HPS is less effective than the use of SG with permanent magnets.

Thales AES also develops a SG installed on the HPS (in front of the combustion chamber) based on an electric machine with high-coercivity permanent magnets [6]. Thales SG is designed for the rotation speed of 9 000 – 13 500 rpm and a power of 150 kW in generator mode, in the starter mode it provides a torque of 350 Nm at the rotation speed of 4800 rpm. This SG has oil cooling and a duplicated winding. The weight of the stator and rotor of this SG is 88 kg. Thales SG has been tested on the stands Hispano-Suiza

Manuscript received May 12, 2017; Research carried out by the grant (project №8.1277.2017/PP).

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(Advance online publication: 10 February 2018)

Aircraft Systems Validation Rig (ASVR).

Disadvantages of Thales SG are its significant weight and dimensions, as well as the complexity of providing SG oil cooling.

II. STATEMENT OF RESEARCH PROBLEMS

As can be seen from the overview, most of the current concepts of integrated SG propose the SG integration in front of the combustion chamber, i.e. in the high temperature zone of HPS. Therefore, in this paper the research of the SG integrated in the high temperature zone of AE (in front of the combustion chamber) is carried out.

In [7] we have proved that the optimal design (by the Pareto method and genetic algorithm) of the SG installed on the HPS with power of 150-200 kW is the SG integrated in front of combustion chamber with permanent magnets, tooth-coil winding and external rotor. This SG has minimal weight and overall dimensions with a maximum efficiency and power characteristics in comparison with other competing options.

The research of electric machine with external rotor and tooth-coil winding discussed in a number of papers [8-12]. There are works aimed to the transient processes study in the SG with a tooth-coil winding [13]. At the same time, there are almost no papers aimed to the study of electromagnetic nominal and abnormal (including transient) modes of SG operation with tooth-coil winding and external rotor taking into account the temperature effect.

The importance of carrying out similar researches for asynchronous and synchronous electric machines with direct start noted in [14-16]. The problem of ultrahigh-speed SG optimization taking into account thermal and electromagnetic processes is solved in [17]. At the same time, joint studies of transient electromagnetic and thermal processes for high-temperature integrated SG on the high-pressure shaft are not present in the papers. This problem solution makes a significant contribution to the SG HPS creation, because it allows to increase the SG reliability and develop SG protection system. That is, the present paper makes a practical contribution to the electrical machines design for an electrified AE.

This paper aimed to experimental studies of nominal and transient processes in high-temperature SG with external rotor and tooth-coil winding taking into account temperature and electromagnetic processes, as well as evaluation of transient processes duration and permanent magnet properties changes and winding wires at short circuit at high ambient temperatures. The resulting empirical data will be further used to build a complex of mathematical and computer models describing transients in high-temperature SG taking into account temperature and electromagnetic interdependence.

III. PROTOTYPE DESCRIPTION

The object of research is a low-power scalable experimental prototype (300 W) of high-temperature SG with an external rotor and tooth-coil winding. Designed low-power SG prototype with permanent magnets and an external rotor is suitable for integration on the HPS of AE. In figure 2 the appearance and winding connection diagram of SG are shown. To achieve the minimum distortions of the harmonic voltage spectrum the number of slots per pole and phase was 2/5 [3]. Designed SG has three phases. To improve reliability we provide six-phase, double-module electrical machines installation on HPS in future, figure 3. Each of the modules is an electrical machine corresponding to the investigated experimental prototype. Therefore, to simplify laboratory studies only one module can be explored. The geometrical dimensions and weight properties of double-module SG should be less than Thales SG or University of Sheffield SG with equivalent power and rotor speed. In our solution each module rotors are connected with the HPS rim of AE and mounted with an offset of 60 degrees relative to each other (to form a six-phase system). The stator windings of both modules are connected to a common 12-pulse rectifier with the ability to disconnect each phase from rectifier. The Fireproof lining is mounted between the front parts of each module stator windings.

Since the rotation speed of HPS of AE depends on the aircraft flight task mode and varies from 9000 to 15000 rpm, then SG works on the rectifier.

TABLE I

PARAMETERS OF THE SCALABLE EXPERIMENTAL SAMPLE

Power at rotor speed of 9,000 rpm, W	300
Power at the speed of 2000 rpm	66
The number of turns in the phase	32
The number of poles / slots	10/12
The type of PMs / operating temperature	SmCo (T 550), operating temperature 550 °C
Residual flux density/coercive force of the PMs (Br/HcB)	0,92 T; 720 kA/m
Type of wire	Nickel heat-resistant NVS wire;
Core material	Nickel
Insulation material	silicone coated
Operating temperature	fiberglass
Peak temperature	60 to 450 °C
Operating voltage	+550 °C
Specific resistivity	300/500 V
	0.091 Ohm/m
Active phase resistance, Oh	0.38
Phase inductivity, H	0.000024

The prototype characteristics are given in Table 1. Figure 4 presents the stator, the rotor and the experimental prototype assembled.

High-temperature PMs and the AVS winding wire with operating temperature up to 550 °C were used in modeling. The nickel wire was used for this prototype (its drawbacks are significant specific resistivity and its magnetic properties). Therefore, experimental studies of short circuits on this prototype allowed estimating the features of the nickel wires use.

To simplify the manufacturing process of the experimental prototype the stator was not laminated.

To solve these objectives all studies were performed in two modes: nominal mode and short-circuit mode.

IV. EXPERIMENTAL STUDIES OF THE SCALABLE PROTOTYPE IN THE NOMINAL MODE

In experimental studies the developed prototype rotated at 2,000 rpm. The prototype was studied at load and at idles in two temperature modes:

- experimental studies of the prototype at 25 °C;
- experimental studies of the prototype at ambient temperature of 217 °C for 5 minutes;
- experimental studies of the prototype at ambient temperature of 217 °C for 1 hour.

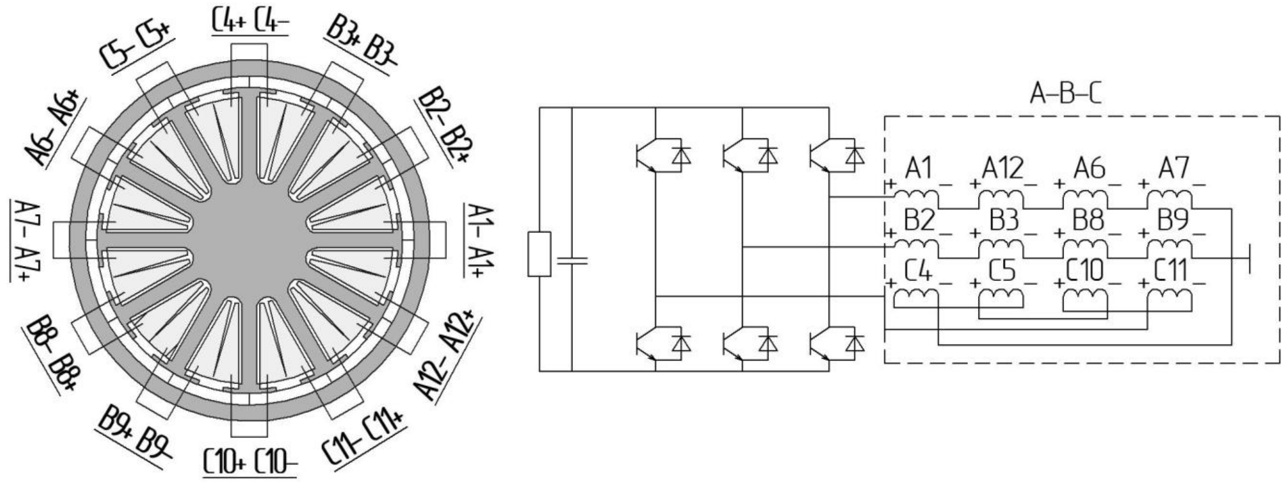


Fig. 2. High-temperature SG with external rotor and tooth-coil winding

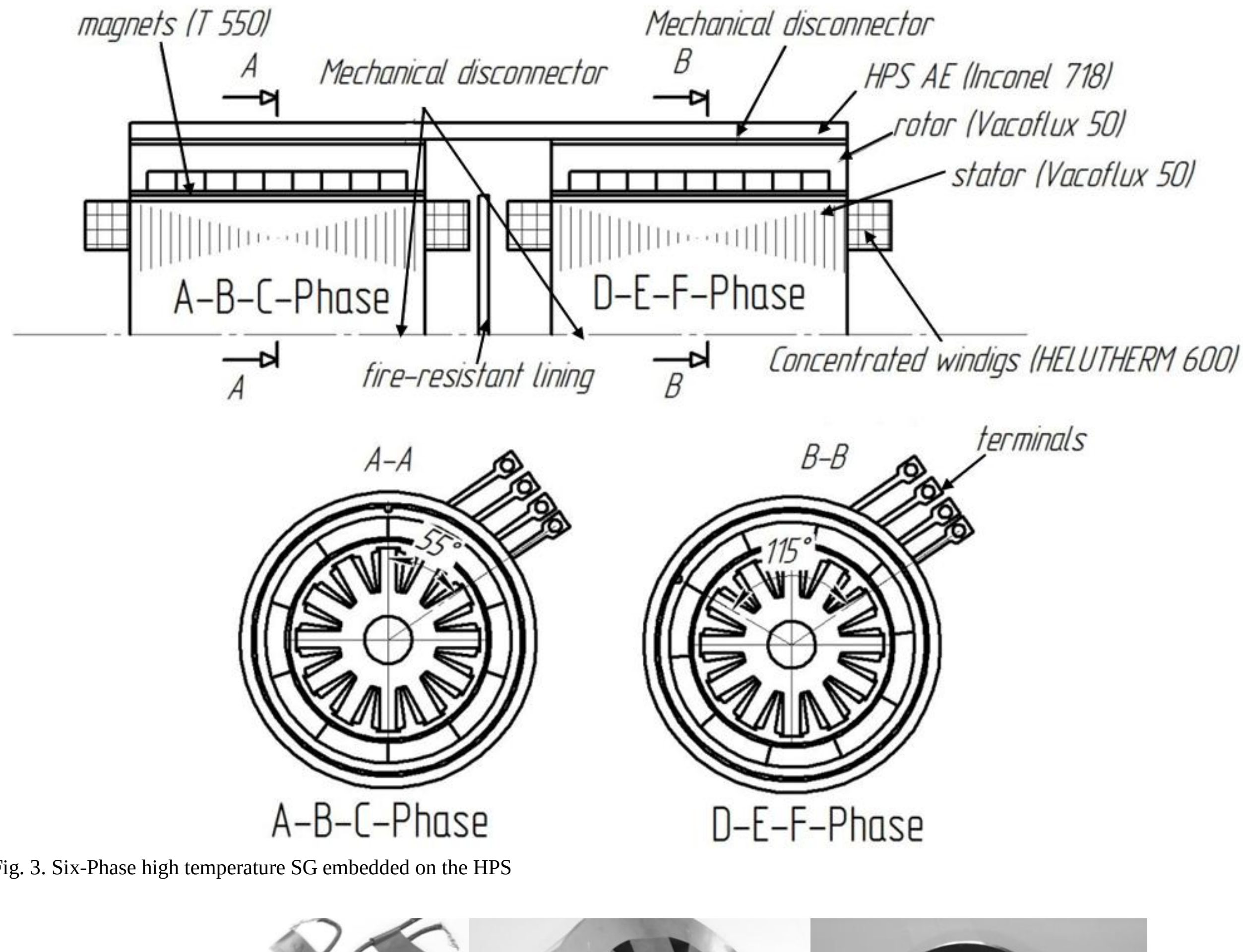
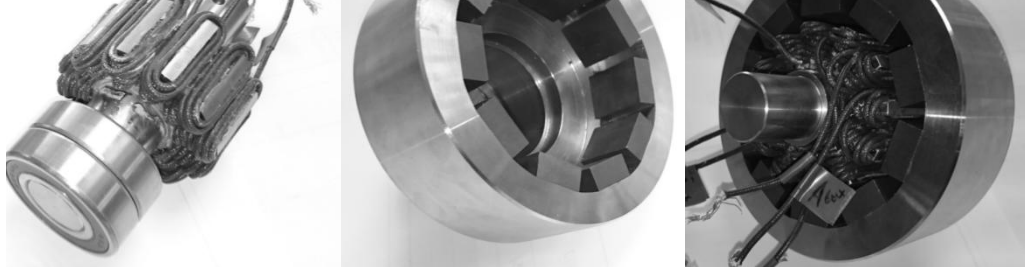


Fig. 3. Six-Phase high temperature SG embedded on the HPS



(a) (b) (c)

Fig. 4. (a) – stator of the experimental model; (b) – rotor of the experimental model; (c) – assembled experimental model

Experimental studies at high temperatures were performed as follows: the prototype were placed for a specified period of time in the oven with a temperature of 217 °C, after which it was removed from the oven and tested under load. A set of resistors was the load of the prototype in all studies.

Waveforms of voltage and current in each phase were obtained and dependencies of voltage from current at different temperatures were built. A harmonic spectrum of current and voltage waveforms was estimated using a spectrum analyzer.

Figure 5 shows voltage waveforms in all three SG phases. Figure 6 shows the voltage waveforms of the experimental prototype at a different current. Figure 7 shows the dependencies of current and voltage at ambient temperature of 25 °C and at 217 °C for 1 hour.

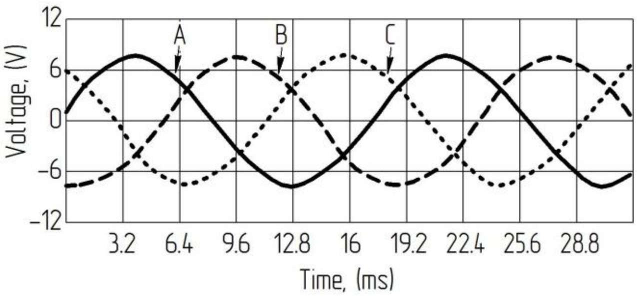


Fig. 5. Output voltage waveforms of the experimental prototype at idle and an ambient temperature of 25 °C

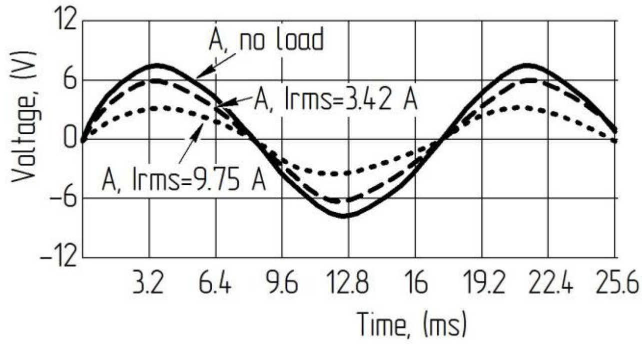


Fig. 6. Output voltage waveforms of the experimental prototype at various loads and an ambient temperature of 25 °C

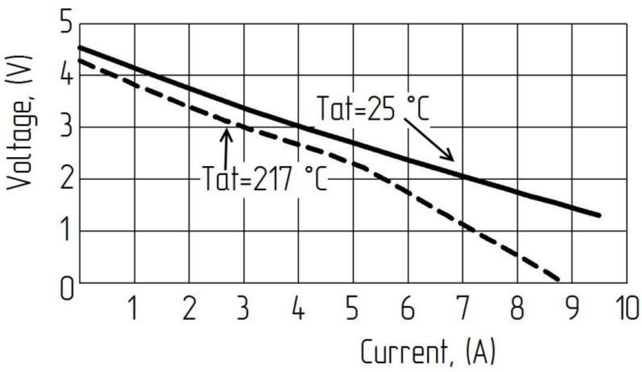


Fig. 7. Voltage and current dependencies at ambient temperature of 25 °C and at 217 °C for 1 hour

When the prototype is in the oven for 5 minutes at ambient temperature of 217 °C a power and energy characteristics of SG are almost unchanged. This is due to the fact that for a given period of time the prototype does not have time to heat up because of the high thermal time constant. The time constants of the experimental magnet will be evaluated further.

When the prototype was in an oven at an ambient temperature of 217 °C for 1 hour its power decreased by 15-17%. The magnets temperature was 113 °C and the winding temperature was 130 °C. When the prototype was tested under load, the cooling was not provided. It is important to note that with increasing load the VI-characteristics of the prototype (dependence of voltage from current) has become less rigid compared to the tests at 25 °C. When the SG load changes from idling to 1.5 times the nominal current overload the VI-characteristic decreases by 15 % (the prototype is in oven for 1 hour at a 217 °C). When the SG load changes from 1.5 times to 3 times the nominal current overload the VI-characteristic decreases from 50% (overcurrent was 2.2 In) to 90% (overcurrent was 3 In), Figure 7.

The obtained data also show the fact that the SG power and torque will be 20-25% higher in starter mode than in generator mode. This is due to the fact that the HPS temperature is less than 50 °C when AE starts and SG does not have time to warm up (start time is 60 sec.). This fact shows that the calculations of SG characteristics in a generator and starter mode should be taken at different temperatures. At the same time, it is necessary to take into account that it's often require to start AE in the air and in this case the SG will be in heated condition. The dependence of power and voltage from flight time in the generator mode of the high-temperature SG will have longer transient process compared to SG, not integrated into AE. The transient process depends not only on the SG electromagnetic properties but also on temperature processes (the time of the SG heating to the environment temperature and SG achieving steady thermal conditions). Figure 8 shows power characteristics curves of the experimental SG prototype. It was assumed that HPS temperature varies from 25 °C to 217 °C for no more than 3 minutes and kept at this level throughout the remaining time. SG load is constant during the study for each characteristic.

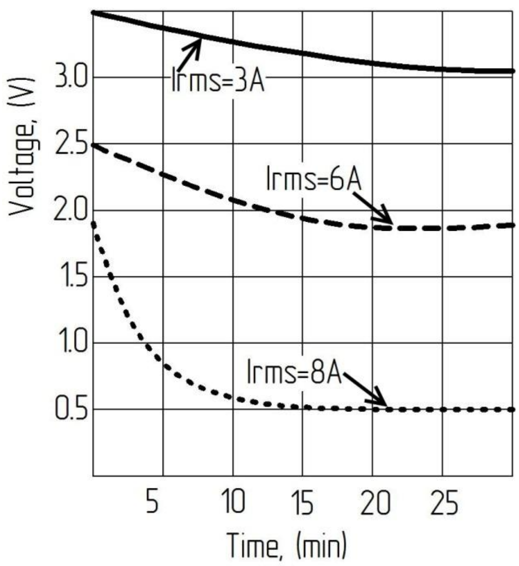


Fig. 8. Power characteristics curves of the experimental SG prototype

The curves show that the SG HPS energy characteristics are largely determined by its thermal time constant, the impact of which was particularly evident after the launch of the AE and within 15-20 minutes of the flight task. At this point, high-temperature SG has excess power and excess voltage which decrease as it is heated as part of AE. The time of this decrease is determined by load value (by demagnetizing magnetic field of the armature reaction, by losses in winding) and the SG thermal inertia. Therefore, transients in high-temperature SG should be studied by combined solving of equations describing transition thermal process and transition electromagnetic process which considerably complicates the research task (transients at sudden short circuit in SG will be very different at transient thermal condition of SG and in steady thermal condition) in contrast to aircraft SG not integrated to AE. This is evident from the difference between the VI-characteristics at different temperatures (figure 7) and the experimental curves (figure 8). In addition, the above dependencies of the transients on temperature must be considered when a voltage stabilization system for such SG is developed. Therefore, the next step of this work includes the experimental studies of transients in SG.

V. Experimental studies of transients in high-temperature SG

To solve the set tasks the experimental SG prototype was artificially studied with the asymmetric mode (one and two-phase short circuits) and symmetric three-phase short circuit from different modes of operation (idling and rated load). In this case, short circuits were studied at different temperatures of 25 °C and 217 °C, without SG cooling. Were studied not only electromagnetic processes in SG but also its thermal state by using a thermal imager.

Figure 9 shows current and voltage waveforms in the phase of scalable SG under three-phase symmetrical short circuit. Windings short circuit was provided by closing the relay contacts. From figure 9 it is seen that the transient time is not more than 0.05-0.1 ms. During this time, at the sudden three-phase short circuit current abruptly surges from 0 to 13.46 A, and phase (amplitude) voltage reduces from 5.8 V to 0.4 V. It is important to note, since the inductive resistance of SG winding is less than active winding resistance (due to the use of a nickel wire) mechanical moment of SG increases by 0.6 Nm under short circuit.

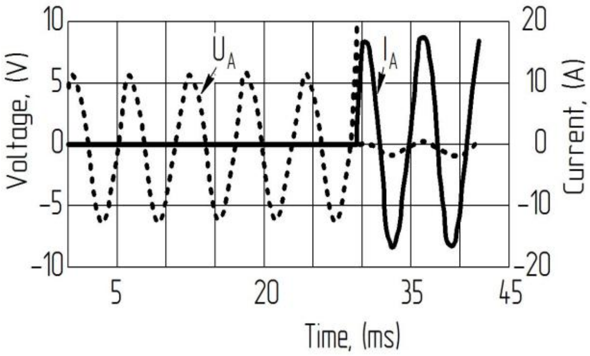


Fig. 9 Waveforms of currents and voltages at the sudden three-phase short circuit in SG

After carrying out these experimental studies SG was placed in an oven at a 217 °C for 1 hour. The SG was studied again with a symmetric three-phase short circuit after removing from the oven. Figure 10 shows waveforms of currents at three-phase short circuit of SG at different SG winding temperatures (25 °C and 120 °C).

Figure 10 shows that when the winding temperature was increased by 5 times the current of sudden three-phase short circuit decreased by 25%. In conventional methods of short circuit current calculation [18, 19] this reduction in short circuit current due to temperature is not considered, which leads to an incorrect SG short circuit protection system design.

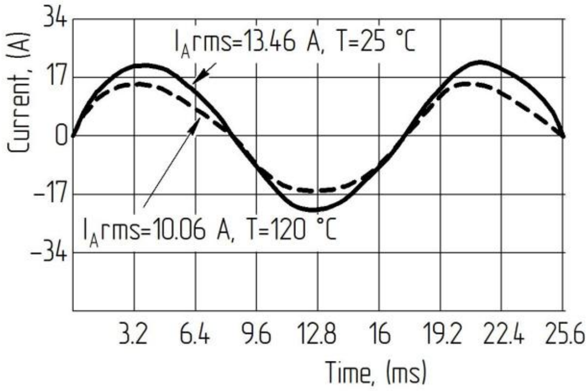


Fig. 10. Waveforms of sudden three-phase short circuit currents in SG at different temperatures

That is, from these results we can conclude that the values of the sudden short circuit currents in "cold" SG and SG at the operating temperature are significantly different (this proves the thesis about the need for a joint study of transient electromagnetic and thermal processes).

Similar results were obtained for asymmetrical single phase (Figure 11) and two-phase short circuits. As winding temperature increases by 5 times the sudden short circuit current decreases by 18-20%. For asymmetric two-phase short circuit a short circuit current decreases by 19% with a 5 times temperature increase.

After all studies the SG run in idle mode and waveforms of the voltage remained at the same level which indicates that PMs were not demagnetized under different types of short circuit (including significant temperature influence for up to 1 hour at 217 °C).

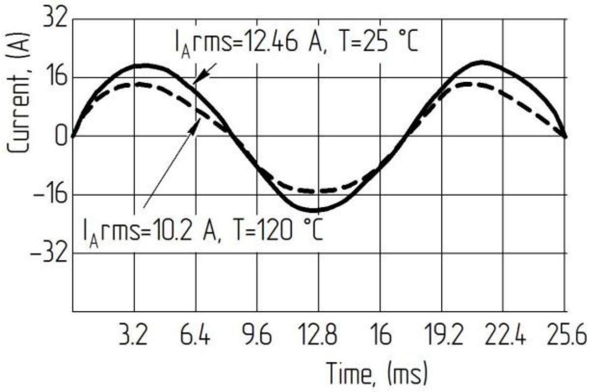


Fig. 11. Waveforms of sudden single-phase short circuit current in SG at different temperatures

Next, to evaluate the thermal condition of the SG at different ambient temperatures thermal images of the SG were made (figure 12) in various modes: after static heating in the oven and after SG operation within 40 seconds under a three-phase short circuit. From the resulting telegram it is seen that the winding temperature was 130 °C after SG heating for 1 hour in the oven and the temperature of PMs was 113 °C. That is, it is experimentally possible to determine the heating time constants of the SG active elements in the absence of losses (0.029 °C/sec for the winding).

After heating the SG was studied in a three-phase short circuit mode for 40 seconds. During this time, the winding temperature has changed by 20 °C and the temperature of PMs has changed only by 3 °C. It shows the fact that in transients (with single-, two- and three-phase short circuit) winding temperature has a slight effect on the magnets temperature. The ambient temperature has more significant effect on the temperature of magnets. At the same time, an increase in winding temperature by 20 °C had practically no effect on the magnitude of the short circuit current.

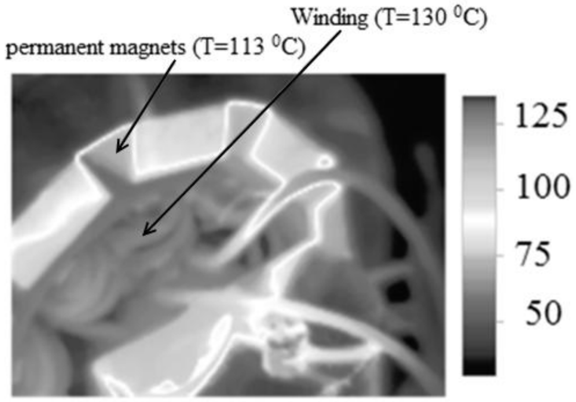
Therefore, in the studies of transient and nominal operating modes of high-temperature SG with similar geometrical dimensions and material properties only the temperature of SG active elements at the beginning of transition should be considered. The change of this temperature during the transient will significantly effect on SG parameters because SG heating time constants are not commensurate with time constants of electromagnetic processes. That is, to simplify SG calculations in transients it is enough to determine the temperature and properties of the materials at a given temperature at a given time. For aircraft this problem is solved based on the flight time. At the same time, the protection system against short circuiting of high-temperature SG should be designed for the duration of the flight time.

Also from the obtained results it can be concluded that it is possible to determine the presence of short-circuit currents in a high-temperature SG and to distinguish these processes from overload modes since currents in these modes (as shown above) may be the same.

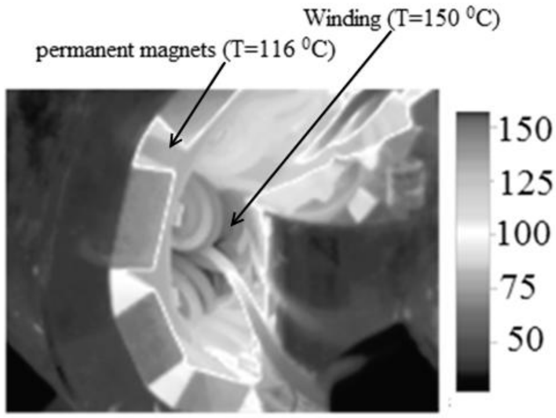
Thus, as a result of the experimental studies the main characteristics of the SG are determined in different modes (nominal and abnormal) and conclusions about the various design features of high-temperature SG are made. All studies were performed taking into account mutual influence of thermal and electromagnetic processes.

Thus, the obtained experimental results prove the possibility of high-temperature SG creation for integration into an AE. This allows us to propose a new architecture of the aircraft power supply system which contains two high-temperature SGs for the twin-engine aircraft (they are similar in design to the developed and described prototype and will be integrated into the HPS of the AE). These SGs will be installed one per each engine. The power of these SGs will be 100-150 kW. Also proposed architecture will include two electric generators (EG) (one per each engine) with the operating temperature of 50 °C mounted on a low-pressure shaft (LPS). The EG power will be 250 kW, rotor speed will be 12,000 rpm, operating temperature – 150 °C. The design will also include a generator integrated into an auxiliary power unit (APU) of an aircraft with a power of 450 kW.

The proposed design allows to provide 1.2-1.3 MW of a power in the aircraft which is commensurate with the installed capacity on board of Boeing 787 and allows to implement a concept of a more electric aircraft (MEA). The circuit functions as follows: SG of APU is started from the storage batteries and rotates the APU before reaching the required speed according to the diagram. After that, SG switches to the generator mode and supplies SG mounted directly on the HPS. The torque of these SGs should be 300-350 Nm. These SGs rotates the HPS and provides the AE launch. After that, the aircraft takes off and the power consumed from this APU and SG increases. After gaining altitude the EGs integrated on the LPS begin to rotate providing the installed capacity of power supply system.



SG thermal image after heating for 1 hour at 217 ^{0}C



SG thermal image after heating for 1 hour at 217 ^{0}C and 40 sec of operation in the short circuit mode

Fig. 12. SG thermal images in different operating modes

To assess the effectiveness of the proposed design it is reasonable to compare it with the Boeing 787 power supply system (the newest MEA).

The Boeing 787 power supply system has 4 main generators with a power of 250 kW installed through a gearbox on the HPS and two generators with a power of 225 kW installed through the gearbox in APU.

This system operates as follows: SG of APU (speed of 12,000 rpm) starts through the APU gearbox; then SG of APU (switching to the generator mode) supplies the main SGs (12,000 rpm) which start the AE through the gearbox.

The design of Boeing 787 contains 3 gearboxes, each per two SGs and SG of APU. The weight of these gearboxes can reach 30-40 kg. The weight of APU, generators, gearboxes and their control systems is 505-520 kg. The weight of each SG with a power of 250 kW (connected through the gearbox to the main engine), its control system and excitation system is 140 kg. That is, the weight of two SGs and the weight of the reducer are about 320 kg per AE. Then the total weight of the power-generating units of Boeing 787 (APU and 4 SGs of AE with their control systems) will be about 1,160 kg.

The weight of the components according to our design is defined as follows: 2 SGs (power of 150 kW with a speed of 12,000 rpm), their control system weigh is 75 kg each. The total weight of two EGs integrated on the LPS (EG with

PMs power of 250 kW weighing 70-75 kg each, and also the weight of their control system of 60-65 kg) will be 280 kg, the weight of APU with integrated high-speed EG (power of 450 kW) will be 477 kg. The total weight of the system will be 1,077 kg which is almost 100 kg less the weight of the Boeing 787 system. At the same time, the reduction in the weight-dimension indicators offered by the aircraft power supply system can be achieved by further reducing of the generator weight.

VI. Conclusion

This paper presents analytical and computer calculations of a high-temperature SG. Based on these calculations the high-temperature SG prototype for aerospace applications was created. The main feature of the prototype is that it is capable of operating at temperatures of more than 300 °C with air cooling and thus providing integration into the shafts of the AE. These results are up-to-date and extremely promising for the aerospace industry.

The designed prototype was subjected to a full test cycle at the experimental stand at a temperature of 217 °C, that is, it was tested under real operating conditions. As a result of these tests, full efficiency of the proposed concepts and the chosen research direction was proved.

Also from the experimental studies it was found that when the prototype is in the oven for 5 minutes at ambient temperature of 217 °C a power and energy characteristics of SG are almost unchanged. This is due to the fact that for a given period of time the prototype does not have time to heat up because of the high thermal time constant.

When the prototype was in an oven at an ambient temperature of 217 °C for 1 hour its power decreased by 15-17%. The magnets temperature was 113 °C and the winding temperature was 130 °C. When the prototype was tested under load, the cooling was not provided. It is important to note that with increasing load the VI-characteristics of the prototype has become less rigid compared to the tests at 25 °C. When the SG load changes from idling to 1.5 times the nominal current overload the VI-characteristic decreases by 15 %. When the SG load changes from 1.5 times to 3 times the nominal current overload the VI-characteristic decreases from 50% (overcurrent was 2.2 In) to 90% (overcurrent was 3 In).

The obtained data also show the fact that the SG power and torque will be 20-25% higher in starter mode than in generator mode. This is due to the fact that the HPS temperature is less than 50 °C when AE starts and SG does not have time to warm up (start time is 60 sec.).

Moreover, as a result of the studies it was shown that the value of the short-circuit current largely depends on the SG temperature (with a 5 times increase in the temperature of the SG active elements the short-circuit current for a three-phase sudden short circuit decreases by 25%). Also, general theoretical remarks were made on the calculation and determination of short-circuit currents for high-temperature SG integrated in AE.

It should be noted that the experimental results carried out on the scalable model are quite accurately consistent with the computer models developed by the authors earlier. The obtained empirical results of the joint research of electromagnetic and thermal processes can be used by various researchers to create promising high-temperature electromechanical energy converters for the aerospace industry.

Based on the conducted research the authors proposed a new architecture of the aircraft power supply system. Its effectiveness was also evaluated in this paper.

Acknowledgment

The work was supported by grant No. 8–1277–2017/PP.

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