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Six-Phase Tooth-Coil Winding Starter-Generator Embedded in Aerospace Engine

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***Abstract*—**This paper is devoted to solve the problem of increasing the electrification of aircraft engines by installing a synchronous generator at high pressure shaft. Technical solution of this problem by various research centers is discussed. A design solution of the problem was proposed. To evaluate the effectiveness of the proposed cooling system, thermal analysis was carried out in ANSYS software.

***Keywords*—**Starter-generator, more electrical engine, aircraft engines, high pressure shaft. synchronous generator.

I. Introduction

A significant increase in the cost-effectiveness of civil aircraft and the profitability of air transportation is possible by increasing the environmental friendliness, controllability, and fuel efficiency of aircraft engines (AE). There are active works to increase the electrification of AE and for the creation of More Electrical Engine (MEE) to solve this problem by worldwide AE manufacturers such as Rolls-Royce, MTU Aero Engines, United Engine Corporation, and PW Canada [1], [2].

Refusal of transmission Auxiliary Gear-Box between the shaft of an AE and the electric machine (EM) is a major conceptual solution for the implementation of MEE. In the other words, the EM is mounted directly to the High Pressure Shaft (HPS) or Low Pressure Shaft (LPS) of AE. At the same time, environmental conditions for the installation of the EM to LPS did not create any difficulty, unlike HPS, where the ambient temperature is around 300-330 °C and 5 bars pressure. Therefore, this article examines the EM mounted on the shaft of the HPS.

HPS rotational speed is variable and changes depending on the performance aircraft flight mission mode (HPS AE speed ranges from 9 000 to 15 000 rpm). The frequency of the voltage generated by the synchronous generator (SG) will also change, so when integrating the SG on the HPS, a DC power system with voltage 270 V (according to the standard MIL-STD 704F), or AC voltage system with variable frequency 380-800 Hz is used. Both of these systems have certain advantages and disadvantages considered in [3]-[6]. In this case, the use of constant frequency 400 Hz will increase the weight and size of aircraft.

This paper examines SG, working with rectifier in 270 V aircraft DC power system. A frequency greater than 380 Hz can provide an EM with six poles or more at the minimum AE rotor speed 9000 rpm. 6-poles SG provides 750 Hz output voltage frequency at maximum rotor speed (15 000 rpm), but 8-poles SG will provide 1000 Hz output voltage frequency at maximum speed, that is not included within the specified frequency range (380-800 Hz). In the other words, for the 380-800 Hz power system, only 6-poles EM is suitable, which will provide a lower moment than 8 or 10-pole SG in starter mode. In addition, significant limitations on the SG output voltage quality (set in MIL-STD 704F standard) also place high demands on SG design features working directly on-board network, including requirements for the harmonic composition of the current and voltage, and so on.

The rectifier should be minimum 12-pulse [7]-[9] for compliance with the MIL-STD 704F standard in part of the higher harmonics attributable to the semiconductor converters. Therefore, in modern DC aircraft power systems between a three-phase EM and a six-phase rectifier is installed an interim inverter, that converts the three-phase voltage in the six-phase. This inverter has its weight, overall dimensions and cost, so also, the tendency of the aircraft power supply systems is the elimination of the intermediary, through the implementation of the SG with six or more phases. Also, multi-phase systems are used in integrated SG to improve reliability. In the case of one phase breakage, the other phase remains working, and this is very important for the SG mounted on HPS.

Besides the fact that the desired phases number is six, a SG mounted on HPS must be operated at an ambient temperature of 300-350 °C in the limited cooling conditions. Also, a problem is the high degree of SG integration into AE. When installing the SG on the HPS, the generator must be operated with whole AE as a single system, where the emergency situation in the SG causes emergency in AE. It is necessary that the SG had increased safety and reliability in order to avoid accidents in the AE. At the same time, the SG should have, like all aircraft systems, minimal weight and size to ensure the effectiveness of such integration and minimal losses in its active elements and the current density (increase in losses and the current density significantly complicate the SG operating temperature conditions). In the other words, the development of SG mounted on HPS is a highly complex, non-trivial task. Therefore, the new designs of EM enabling efficient implementation of MEE concept are developed by various universities and research centers.

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II. Statement of Research Problems and the Type Selection of EM

Therefore, the concept of using six-phase, two-module EM as SG mounted on the HPS is proposed as shown in Fig. 1. In this case, the weight and overall dimensions of two-module SG should be no more than Thales SG or SG designed at University of Sheffield, at equivalent power and speed. In our solution, both rotors of each module are connected to the HPS rim of AE and established with a 60-degree offset relative to each other (to form a six-phase system), both modules of the stator winding output to a common 12-pulse rectifier with the possibility of disabling for each phase from the rectifier. Fireproof lining is set between the frontal parts of each module of the stator winding.

A stator is fixed inside AE so that, at the short circuit, a mechanical decoupling of the stator is ensured with a rigid mount accompanied by the fall of the stator in the radial direction to the mechanical coupling of the stator iron with rotor PM due to magnetic attraction forces (Fig. 2). Fig. 2 also shows the procedure action (a, b, c). This design will allow stopping the electromechanical conversion of energy due to the mechanical coupling of the stator and rotor at occurrence of interturn short circuit in one module. In this case, the power supply system of the aircraft continues to operate when disconnected from the rectifier module winding, as saved operability of the second module. It allows the normal functioning of the aircraft power supply system under emergency conditions in SG, without increasing of the SG weight and overall dimensions.

Both modules are three-phase EM with PM and external rotor, rotor back mounted on the rim made from Inconel 718 or titanium, which is part of the AE. The advantage of this design is that the external rotor is cooled by air, providing an acceptable operating temperature (330 ^{o}C) for PM (for example, magnets EEC 22-T450 [10], the maximum operating temperature which is not more than 450 ^{o}C), at the same time cooling system with an external blower of rotor does not complicate the SG design. Stator magnetic core and winding are cooled by air that passes through the holes and slots in the stator core. At the same time, heat shield is set in the air gap between the stator and the rotor, which prevents the PM from heat flows generated by stator windings and the heat shield is not electrically conductive.

Tooth-coil stator winding is used to minimize the active length of the SG. Tooth-coil stator winding has a minimum size of frontal parts, which makes this technology almost the key for various transport systems [11]. At the same time, it is necessary to consider the disadvantages of this tooth-coil winding: high losses in the PM and rotor back generated by eddy currents.

Studies of EM with tooth-coil windings are presented in numerous publications [12]-[17], but in this paper, we presented a design of SG with various unique technical solutions (mechanical decoupling of stator, modular six-phase structure), which is operated at high ambient temperatures (300-350 ^{o}C) and in terms of integration in AE. A study of EM with the requirement for overload and reliability is not represented in the literature, which proves the originality and relevance of research.

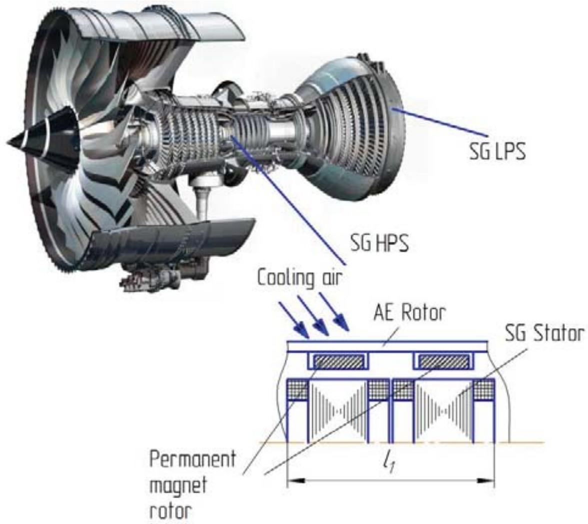


Fig. 1 SG mounted on HPS

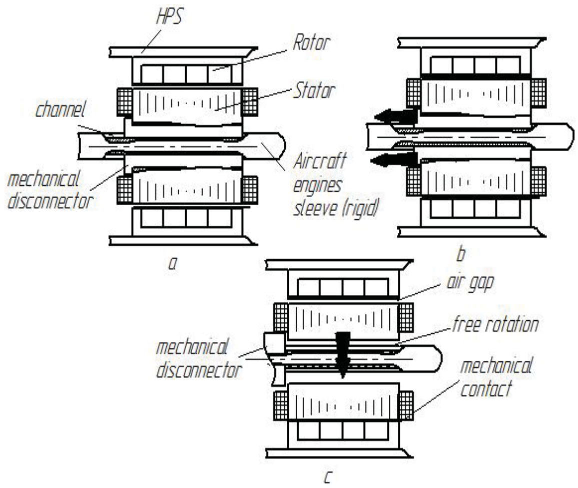


Fig. 2 Stator mechanical disconnector when interturn short circuit

III. Machine

High-temperature six-phase SG with the possibility of integration on the HPS of AE is the subject of research work. SG has facing design with tooth-coil windings and two magnetic cores, each magnetic core has 12 teeth, and rotor has 10 poles. This teeth and pole ratio is selected in view of its effectiveness [12] (Figs. 3 and 4).

Particular attention at SG mounted on HPS designing should be given to the stator winding. Currently, industry produces several types of high-temperature wire: high-temperature wire in which electric conductor is made from chrome bronze BrHNB (Cr-0.3, Nb-0.1, Cu-0.4, 0.2 impurities, e.g. PRP 400, PRP 450 wire designed for electrical equipment of nuclear power stations). Maximum operating temperature of wire does not exceed 450 ^{o}C, and the thermal conductivity is 380 W/m*K. Thus, the resistivity of the wire is 0.0185 Ohm/m at 20 ºC and 0.0517 Ohm/m at 400 ºC. Another type is a wire of nickel-plated copper, which has a working temperature up to 600 ºC (HELUTHERM 600). Wire sectional area is 1 mm^2, and active resistance is 0.088 Ohm/m at 20 ºC. Active resistance of the wire is five times greater than the resistance of copper, which of course will result to increased Ohmic losses in the high-temperature SG. Therefore, it is necessary to use 450 POT wire in the module SG mounted on HPS, but the winding and the cooling system should be designed so that the wires maximum temperature do not exceed 420-430 ºC at ambient temperature 300-350 ºC. Hydrocarbon nanotubes may be a competitor for nickel and bronze high temperature wires in the future [18].

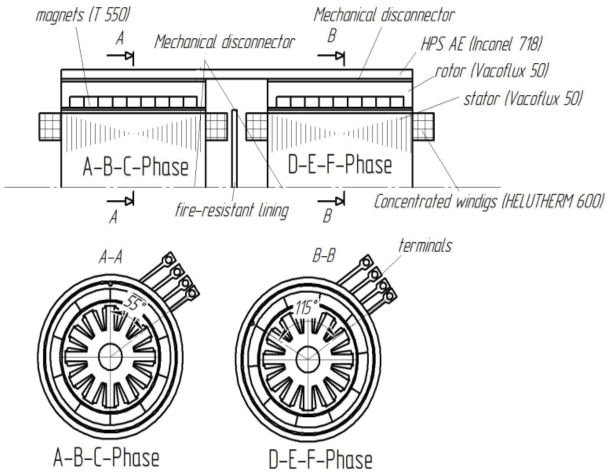


Fig. 3 Six-Phase high-temperature SG HPS

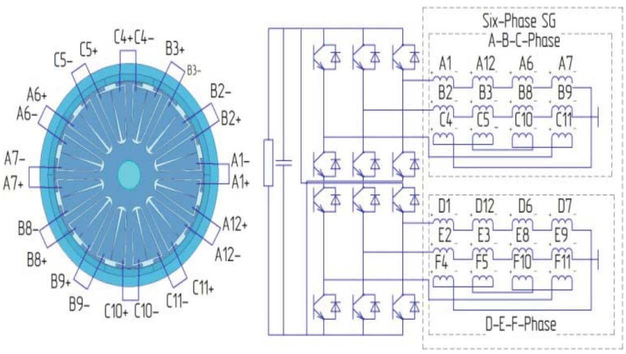


Fig. 4 Six-Phase SG winding connection circuit

22 EEC-T450 is used as the PM magnets (PM is based on the alloy Sm_2Co_{17} with working temperature up to 450 ºC) [10]. Stator material is Vacoflux 50 (cobalt alloy) with 0.1 mm sheet thickness [19]. Preliminary geometrical dimensions, power, rotor speed, and the voltage are shown in Table I and selected on the basis of [1], [20], [21]. Controlled rectifier is made on power upto 110 kW, so it could work with the overload in the event of one SG failure (Fig. 4).

TABLE I
PRELIMINARY PARAMETERS OF THE RESEARCHED SG MOUNTED ON HPS

	SG with external rotor
Power in the generator mode, kW	150
Rotor speed, rpm	13 500 (9 000–15 000)
Number of poles	10
Number of phases	6
Number of teeth	2x12
Rated voltage, V	200
Rotor outer diameter, mm	300–315
Active length, mm	120–150
PM thickness, mm	8–12
Stator outer diameter, mm	260–264

A. Mechanical Design

The location of the PM rotor on nonmagnetic rim is the main requirement for the SG rotor magnetic system integrated into AE. Furthermore, this magnetic system should provide maximum flux density in the magnetic air gap and the mechanical strength of the rotor AD. A nonmagnetic rim is made from heat-resistant titanium alloy or from Inconel 718, depending on the AE design.

Halbach magnetic arrays are typically applied when using a non-magnetic rotor back [22], therefore initially it was assumed to use Halbach array in the considered SG design.

Computer modeling of the two magnetic systems for evaluating the effectiveness of this technical solution was carried out in the software package Ansoft Maxwell: a magnetic Halbach assembly on nonmagnetic rim and a magnetic system with radial PM on the rim made from Vacoflux 50.

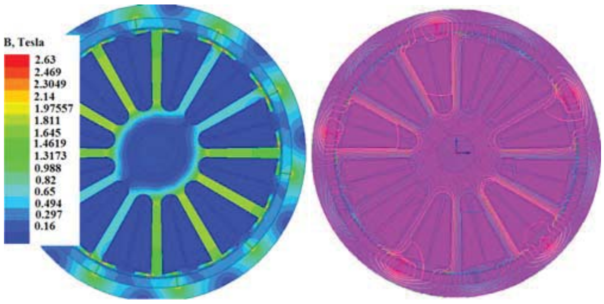
The simulation results show that the flux density in the magnetic air gap is 0.59 T by using the Halbach magnetic array and 0.5 T using a magnetic system with radial PM. But in this case, the flux density of SG pole decreases due to the pole area reduction in the Halbach magnetic array (1/2 pole arc does not create radial component of the magnetic field and are used for passage of flux density in a tangential direction). At 2 and 4-pole magnetic systems are advantageous to use Halbach arrays, while at 10-pole system efficiency is lower in comparison with the magnetic system with radial PM. But, the use of a magnetic system with radial PM at the non-magnetic rotor back is not effective. Therefore, the following embodiment of a high-temperature SG rotor magnetic system has been considered: PM with radial magnetization from the EEC 22-T450 is located at the 10 mm thick hub from Vacoflux 50, which is later pressed into the 5-7 mm thick rim from Inconel 718 or titanium alloy. Cooling ducts are configured similar to the rim ducts formed on the AE blades. This allows providing PM cooling, while maintaining the necessary electromagnetic load.

B. Electromagnetic Design

The electromagnetic design of the machine is carried out with the finite element software Ansoft Maxwell. Preliminary geometrical dimensions of SG mounted on HPS module were calculated by using analytical methods. Computer modeling was carried out in the generate mode at the speed of 13 500 rpm.

Since both modules (EM) included in the SG are the same then the calculations considered only one module included in SG. Preliminary module power was 75 kW. Computer modeling was carried out taking into account the SG load and overload as well as the demagnetization action of armature reaction. The calculations take into account reduction of the energy characteristics of the PM rotor under the influence of temperature (magnet temperature was assumed to be 330 °C, and the residual flux density EEC 22-T450 was 0.83 T, and the coercive force was 400 kA/m). Two modes of SG operation modes are considered in the electromagnetic calculations: the nominal and overloading.

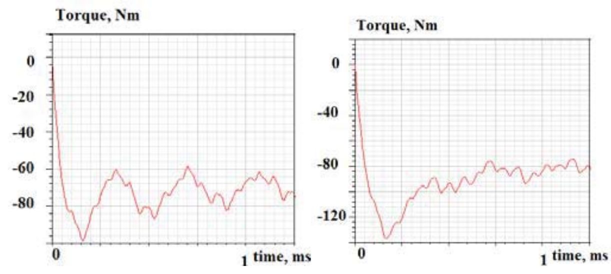
The magnetic flux density in the SG active elements and the distribution of the magnetic flux lines in the SG at rated load are shown in Fig. 5. The electromagnetic torque and phase flux linkage at rated load and overload are shown in Figs. 6 and 7, respectively.



(a) (b)

Fig. 5 The magnetic flux density (a) and distribution of the magnetic flux lines (b) in SG module mounted on HPS

Fig. 5 shows that the maximum flux density in the teeth reaches 1.81-1.9 T, 0.65 T in the stator back, 0.48-0.5 T in the magnetic air gap. The obtained values of flux density in active elements of the SG used in further calculations. Analysis of the magnetic field distribution also shows that 30% of the stator back area of the magnetic field is very low. This allows performing magnetic annular cooling ducts at these parts without reducing the SG electromagnetic characteristics. From these electromagnetic torque curves can be seen that there are electromagnetic torque pulsations which are characteristic of EM with tooth-coil winding [13]. The amplitude of the ripple is 20 Nm. It is also found that the SG module at rated load and at specified geometric dimensions provides power of $P = \frac{M \cdot n}{9550} = \frac{60 \cdot 13500}{9550} = 84$ kW. The SG module power will be 94 kW at maximum speed (15 000 rpm), and 54 kW at a minimum speed of HPS (9 000 rpm). That is, the total power of SG in the nominal mode is from 108 to 188 kW. SG module power is 113 kW at 13 500 rpm in the overloading mode, and the SG power is 226 kW, i.e. the SG available overload is 130% with two working modules in continuous operation.



(a) (b)

Fig. 6 SG electromagnetic torque in generator mode at rated load (a) and overload (b)

If the aircraft (power consumption 334 kW) has two AE with two-module six-phase SG (4 modules on the aircraft, two modules at AE) and in case of the modules (84 kW) fails, its power is evenly (33%) divided into three operating modules. Then, the power of each module at a 9 000 rpm speed is 111.5 kW, and these values correspond to long-term SG overloading operation mode. In this case, the aircraft power system operates without disconnecting power consumers and all over power system is still work at 334 kW power, which of course increases the reliability of the aircraft power supply system.

If two modules fail, then the system power is 230 kW taking into account the possibility of module overloading. This requires reducing the load power on 104 kW, and a similar situation would occur with a traditional design with two three-phase SG or SG with duplicated winding.

Fig. 7 shows the flux of the windings at rated speed and overload and voltage harmonic composition and flux at rated load. From Fig. 7, it is seen that flux linkage and hence the SG voltage decreases at 15-18% due to the magnetic field of the armature reaction during overload. This makes the task of increasing the SG voltage mandatory.

All EMs with tooth-coil winding have a voltage and flux linkage with significant third harmonic (12-14% of the basic harmonic for the voltage) and also fifth harmonic (8-10% of the basic harmonic for the voltage). For the flux linkage, fifth harmonic is more than third. The emergences of the third and fifth harmonics are caused by eddy current losses in the rotor sleeve and PM. Standard methods, such as PM skewing or use of dummy slots may be used to reduce the voltage and flux linkage harmonic order [22]. FEMM analysis have also been made to evaluate the effectiveness. As a result of this analysis, it was found that these methods allow reducing the amplitude of third harmonic of the voltage almost at 30-35%.

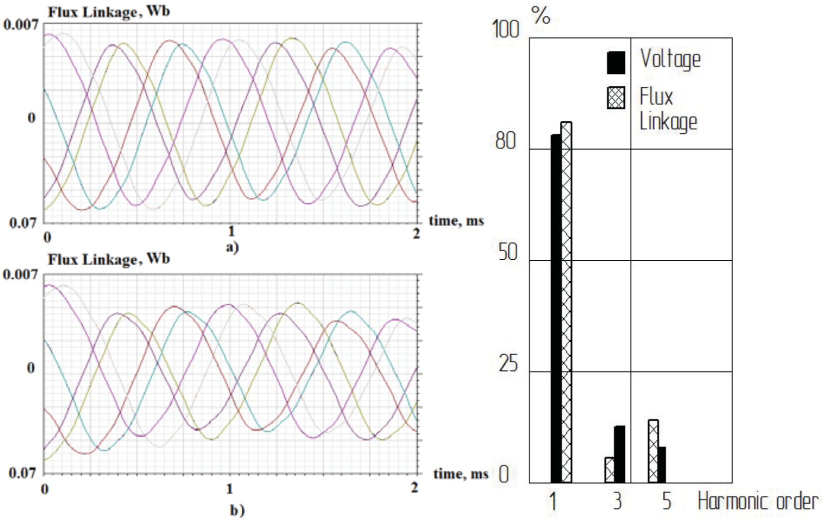


Fig. 7 Flux linkage at rated load (a), during overload (b) and voltage harmonic order (c)

TABLE II
RESULTS OF SG MOUNTED ON HPS CALCULATION

	A	B	C
Maximum power in generator mode, kW	188	150	150
Rotor speed, rpm	9000-15000	9000-15000	9000-15000
Number of poles	10	8	8
Number of phases	6	3x2	3x2
Number of teeth	2x12	48	48
Rated current, A	2x257 (514)	440	476
Rated voltage,V	200	200	200
Current density, A/mm^2	2.8-2.9	2.3	3.74
Moment of rotor inertia, kg*m^2	0.84	0.84	0.137
Mechanical time constant, sec	2.84	2.84	0.42
Inductive resistance along the d/q axes, Ohm	0.17/0.17	0.09/0.09	0.16/0.16
Flux density in the magnetic air gap, T	0.5	0.54	0.3
Flux density in the stator teeth, T	1.81	1.7	1.44
Flux density in the stator back, T	0.65	0.45	1.45
The rotor outer diameter, mm	300	300	186
The stator outer diameter, mm	262	261.5	300
Non-magnetic gap size, mm	2	2.25	6
The SG mass of active elements, kg	58.896	75.34	82
Magnets weight, kg	8.34	8.34	-
Magnetic core weight, kg	11.7x2 (23.4)	30	-
Winding weight, kg	9.078x2 (18.156)	28	-
Rotor back weight, kg	9	9	-
Active length, mm	2x70 (140)	122	150
Full-length, mm	210	246	250-270
The length of the frontal parts, mm	15	62	40-60
Stator teeth weight, kg	2x4.83 (9.66)	14	-
Stator back weight, kg	2x6.87 (13.74)	16	-

Table II shows the parameters and dimensions of the developed SG mounted on HPS by FEMM and analytical methods. Comparisons of developed construction (A) with SG with duplicated three-phase windings (B) and SG construction by Thales (C) are shown for clarity [20]. As can be seen from Table II, the presented SG design has a minimum weight and overall dimensions in comparison with analogues at maximum power. Designed and studied SG at 188 kW power weighs 59 kg, when the analogs weight is 75 and 82 kg at a 150 kW power, respectively, and the weight and reliability of aircraft systems is the priority criteria. The current density of the designed SG is 20% more than current density of SG with distributed, replicated three-phase winding, due to the higher power of developed SG. These results confirm the prospects of the proposed design, as it has a minimal weight and overall dimensions, high reliability and maximum power. In addition, the proposed construction is cooled by an external blowing that greatly simplifies the task of integrating it into AE.

C. Thermal Analysis

Variant with external and internal blowing has been selected when creating a cooling system. The internal air flows through ducts in the stator slot, and the outer air blows HPS rim for cooling the PM. The proposed cooling system is shown in Fig. 8.

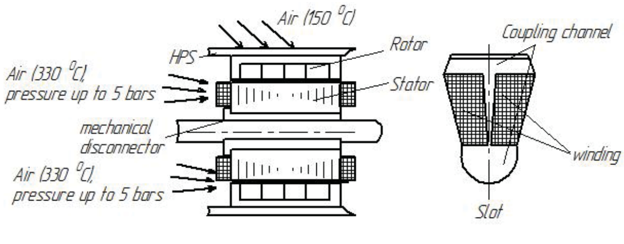


Fig. 8 Cooling system of SG mounted on HPS

The computer simulation was carried out in ANSYS software complex to evaluate the effectiveness of the proposed cooling system. The results are shown in Fig. 9.

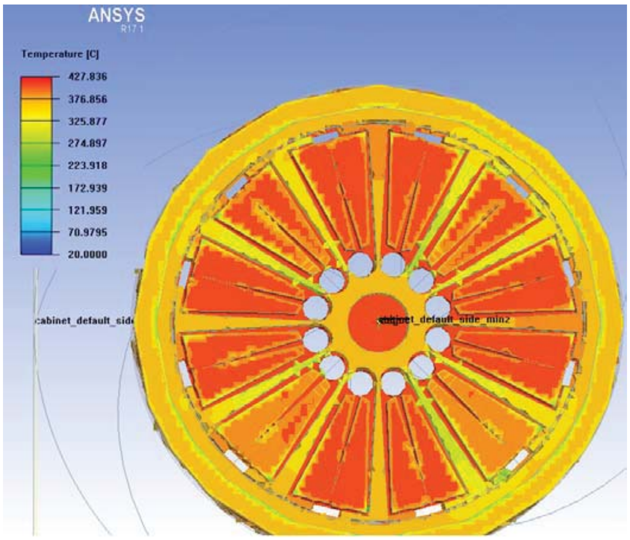


Fig. 9 The results of thermal calculation

The results of thermal calculation show that the winding temperature does not exceed 400-427 ºC, and the temperature of the PM is 320-350 ºC, which corresponds to the accepted calculated data and operating conditions, and consequently proves efficiency of the proposed SG design and its cooling system.

IV. Results and Conclusions

The publications analysis is devoted to the creation of the high temperature SG for MEE concept implementation, determining their weaknesses, and general trends were made. As a result of analytical studies, a new design of the SG mounted on HPS is developed with minimal weight and overall dimensions and improved reliability compared to the known analogues. The materials used in this design are also justified in the present paper. Electromagnetic and thermal calculations by FEMM are made. High temperature SG cooling system has been designed, and system of mechanical decoupling of the stator at short circuits is presented. All this has allowed developing a SG project, which weighs 59 kg at 188 kW power when analogues weigh 75 and 82 kg, with a 150 kW power, respectively, and the weight and reliability of aircraft systems is a priority criterion. This project is now transferred to our industrial partner for the manufacture of an experimental layout. These results confirm the promising proposals design, as it has a minimal weight and overall dimensions, high reliability, and maximum power. In addition, the proposed design is cooled by blowing air, which greatly simplifies the task of integrating it into AE.

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