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High-Performance Generator for a New Generation of Aircrafts

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ABSTRACT

The article describes multidisciplinary design process of high-performance electric generator for advanced aircrafts by analytical methods and computer modeling techniques (electromagnetic, thermal and mechanical calculations). New technical solutions used in its development are described. The main ideas are revealed of the method of EG voltage stabilization we used. To improve the heat dissipation efficiency, we have developed a new cooling system, and provide its study and description in this paper. The advantages of this cooling system include the fact that EG is made with dry, uncooled rotor. This allowed eliminating additional pumps, and significantly reducing the size of CSD. According to the results of our study, we created an experimental full capacity layout, and its studies are also provided in this paper.

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1. INTRODUCTION

Electric generators (EG) for advanced power supply systems of autonomous objects play a very important role in today's aerospace industry. Power, reliability and EG weight and size characteristics largely determine functionality, performance and fuel efficiency of civil and military aircrafts (A/C) [1]. Electrical machines, which eliminate pneumatic or hydraulic constant speed drive are promising to improve A/C efficiency (electric machines made to a variable speed, similar to Boeing 787 starter-generators) or electrical machines, integrated in the aircraft engine or auxiliary power plant without gear [2-5]. [2] provide multi-criteria selection of the type of a high-speed electrical machines for the aerospace industry. This analysis shows that the use of electrical machines with permanent magnets (PM) is the most effective. The similar conclusion was obtained in [3] – [9]. [10] also describes a high speed EG for commercial A/C. there are almost no papers devoted to the design and development of EG with PM in A/C systems with constant rotor speed of not more than 24,000 rpm and an output voltage of 400 Hz, except publications [11], [12] which does not describe the process of designing and creating such EG, and describe methods of protection of EG with PM from short circuit.

Output voltage with a frequency of 400 Hz is provided by EG, which are integrated into a constant speed drive (CSD) with a rotor speed of not more than 24,000 rpm. Although, as was shown above, the prospect is to get rid of CSD, the use of CSD for some aircrafts (military and transport aviation) is a technical solution that provides the required reliability of A/C, and eliminating this unit is economically and technically inexpedient at this stage. Therefore, in addition to the development of promising directions for creating integrated electric machines for aircrafts, it is also very important to improve power characteristics of EG integrated in CSD of A/C, while minimizing their weight and size, and this task is not fully disclosed in the publications.

To solve this problem, our research team in the interests of our industrial partner, has designed a high-performance EG with permanent magnets (PM), a power of 100 kW, with a weight of 22 kg. Together with this EG, we developed a voltage stabilization system weighing 10 kg. EG is configured to 24,000 rpm, with an output frequency of 400 Hz (two-pole rotor) and designed to be integrated in the fixed speed hydraulic actuator of A/C. This paper describes multidisciplinary design process (electromagnetic, thermal and mechanical calculations) of the developed EG, as well as new technical solutions used in its creation, including the main ideas of EG voltage stabilization method that we used. To improve heat dissipation efficiency, we have developed a new cooling system also described in this paper. The advantages of this cooling system include the fact that EG is made with a dry, uncooled rotor. This eliminated additional pumps and significantly reduced CSD size. According to the results of our study, we made a full capacity experimental layout also described in this paper.

2. REQUIREMENTS FOR EG AND EG TOPOLOGY SELECTION

Specifications of the developed EG for advanced A/C with CSD, were given by our industrial partner. The main ones are:

1. Rated power of EG – 100 kVA;
2. Rated voltage – 115/200 V;
3. The number of phases – 3;
4. Nominal frequency of the alternating current – 400 Hz at a nominal EG shaft rotational frequency of 24,000 rpm;
5. EG operational load: 100 kVA.
6. EG overloads:
7. Long-term operating power of 150 kVA for not more than 5 minutes;
8. Overload capacity of 200% of the generator rated power of 200 kVA for 5 seconds.

The industrial partner has also established very strict limits on the length: the total length of EG (taking into account frontal parts) was not to be greater than 145 mm, weight and overall dimensions of EG together with the control system – not more than 35 kg. With all of this, EG and its control system were to ensure quality of the output power within MIL STD 704IE.

From the analysis of publications, as well as from practical experience of EG designing, we have found that the only EG type able to provide these characteristics is EG with permanent magnets (PM). At the same time to reduce the overall dimensions of EG with PM, it is appropriate to use the tooth winding [13-15]. At the same time the use of tooth winding results in significant harmonic distortion of the output voltage of EG due to spatial harmonics of MMF. To reduce these distortions and EG output power compliance with the requirements of MIL STD 704IE, a frequency converter at full power equal to EG power is used together with EG with tooth winding. But even the use of the most advanced element base does not allow to create a rectifier or frequency converter with a power of 100 kW and a weight of less than 22-25 kg [16]. Given that our industrial partner has established the requirements to EG weight with the control system was not more than 35 kg, and EG rotor speed – not more than 24,000 rpm, it is evident that the use of frequency converter and EG with tooth winding in this case is not possible. At a weight of frequency inverter of 25 kg, EG had to weigh not more than 10 kg and provide power of 100 kW at a speed of 24,000 rpm, and overload capacity of 150 kW also at 24,000 rpm. At this stage of development, practical implementation of these parameters is not possible.

Therefore, we have chosen topology of EG with PM with distributed winding and two-pole magnetic system, Figure 1, which made it possible to improve the output voltage quality. In order to stabilize EG output voltage, we used not a serial frequency converter at full power, but parallel one at power of not more than 40% of the rated power, Figure 2. This converter (digital module (DM)) is designed to stabilize voltage with the change in the load to EG at a constant rotor speed. Permanent frequency is provided by CSD. The essence of the control method used and EG output voltage stabilization is in fact that voltage is controlled by the magnetic field of EG response anchors by inductive or capacitive current generated by DM. DM is connected parallel to the load upstream EG feeder and consumes current shifted relative to voltage EG strictly to ±90°. Thus DM intensifies the magnetic field of EG response anchors and reduces its voltage (inductive current), or lowers the magnetic field of armature reaction and increases EG voltage (capacitive current). In this case, DM current is reactive for EG and does not generate additional heat losses in EG winding and mechanical load on the shaft.

To protect against short circuits, EG phases are connected to star configuration through bi-directional semiconductor switches that open in short-circuit (SC), thereby isolating the point of short circuit. The solution used is similar to the solution proposed by Honeywell International [17], but our solution uses new algorithms to improve performance of the whole protection system. It would be more efficient to use a highly inductive EG (High-reactance permanent magnet machine), but since short-circuit current is not much higher than the rated current in this type of electric machines, we would not be able to fulfill the requirements for overload, established by our industrial partner. Therefore, we rejected this solution at the stage of topology selection.

To maximize heat dissipation, we used our developed and patented EG cooling system [18]. The uniqueness of this cooling system is that it uses two counter flows of cooled liquid, Figure 3, while providing uniform and effective heat dissipation.

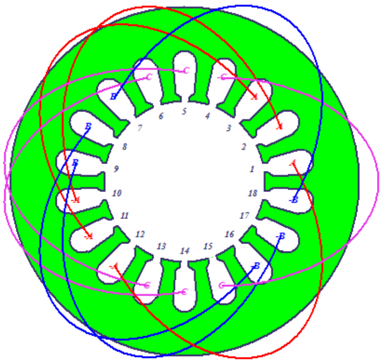

Figure 1. EG winding connection scheme

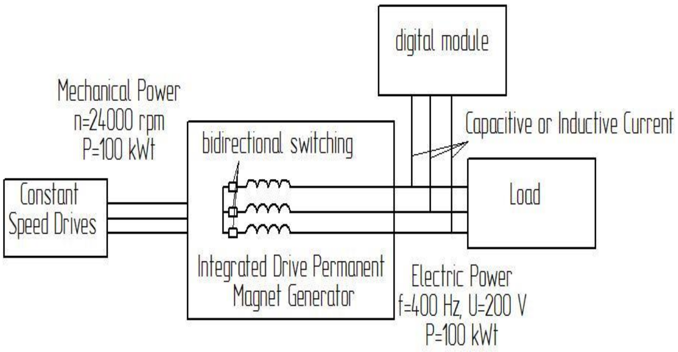

Figure 2. Schematic diagram of EG with DM

This EG liquid-cooling system operates as follows: the pump is pumping the coolant through the inlet fittings, which is simultaneously supplied to the first manifold and the second manifold where the front parts are installed. By washing the front parts, the coolant from the first and the second manifolds enters the coolers, made in the form of a cylinder with helical channels, and the coolant flows from the first and the second manifolds oppositely and then flows out through the outlet fitting. To prove effectiveness of all of the technical solutions, it is necessary to make multidisciplinary EG calculations. The algorithm proposed in [19, 20] was adopted as a basis in multidisciplinary calculations.

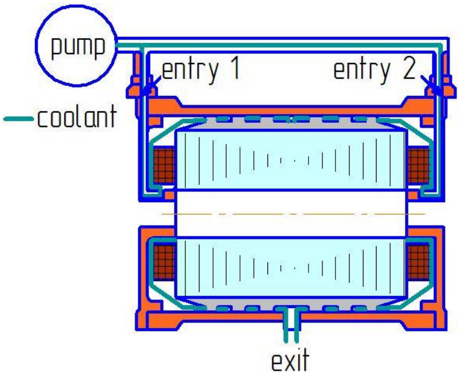

Figure 3. Structural diagram of EG cooling system

3. ELECTROMAGNETIC CALCULATIONS OF EG

In electromagnetic calculations, we have initially used the analytical expressions to calculate the preliminary geometrical dimensions of EG. After that, based on these geometric dimensions, a finite element model was developed. Sm2Co17 with residual induction B_r not less than 1.1 T and permanent magnet coercive force in terms of magnetization of $H_c = 812$ kA/m are used as a material of permanent magnets. The maximum preliminary temperature of PM ($\Theta_{pm} = 175\,^{\circ}\mathrm{C}$) is defined on the basis of empirical data.

Based on this, characteristics of a permanent magnet are determined at the maximum operating temperature:

$$B_r(\Theta) = B_r\left(1 - \frac{k_{Br}(\Theta_{pm} - 23)}{100}\right) = 1{,}05\ T \tag{1}$$

$$H_b(\Theta) = H_b\left(1 - \frac{k_{Hc}(\Theta_{pm} - 23)}{100}\right) = 600\ \text{kA/m} \tag{2}$$

Based on empirical data, preliminary rotor diameter and PM thickness is given: $D_p = 100\ \text{mm},\ h_m = 11\ \text{mm}.$

Based on the thickness of permanent magnets, rotor bandage sheath is determined according to [20]. The total thickness of bandage sheath was 2.2 mm made of carbon fiber, while the relative air gap of the generator is equal to:

$$\delta^* = \frac{2\,\delta}{D_p} = \frac{2*0.003}{0.1} = 0{,}06\ \text{mm} \tag{3}$$

The coefficients taking into account the change in the magnetic induction vector along the air gap length are determined:

$$k_z = \frac{1}{p\,\delta^*}\,\frac{\left(1+\delta^*\right)^{2p} - 1}{\left(1+\delta^*\right)^{2p} + 1} = 0{,}97 \tag{4}$$

A coefficient taking into account the fall in MMF in steel sections

$$k_F = 1{,}15 \tag{5}$$

Dissipation coefficient:

$$k_p = 1{,}15 \tag{6}$$

Induction in the air gap at idle can be determined by expression [21]:

$$B_{\delta 0} = \frac{1}{1 + \left(\frac{2\,\delta}{2h_m}\right) k_z \left(\frac{1}{\mu_0}\right)\left(\frac{B_r}{k_p H_c}\right)}\,\frac{B_r}{k_p} = 0.694\ \text{T} \tag{7}$$

Further, according to Arnold equation, a linear current generator load is determined:

$$A = \frac{6{,}03P}{D_p^2 l\,\alpha k_f k_w k_z B_\delta n} = \frac{6{,}03*100000}{(0{,}1)^2 0{,}115*0{,}85*0{,}92*1{,}27*24000*0{,}66*0{,}97} \approx 33100\frac{\text{A}}{\text{m}} \tag{8}$$

The number of slots per pole and phase

$$q = 3 \tag{9}$$

The number of teeth

$$z = 2\cdot m\cdot p\cdot q = 2\cdot 3\cdot 1\cdot 3 = 18 \tag{10}$$

Then, the number of effective conductors in the slot:

$$N=\frac{\pi aD_S A}{Z_1 I_n}=\frac{3{,}14*1*0{,}106*33100}{18*306{,}22}=1{,}99 \qquad (11)$$

$$N=2 \qquad (12)$$

Adjusted value of the linear current load:

$$A=\frac{Z_1 I_n N}{\pi aD_S}=\frac{18*306{,}22*2}{3{,}14*1*0{,}106}\approx 33120\frac{\text{A}}{\text{m}} \qquad (13)$$

Then the effective windings in the stator winding phase:

$$w=2pq\frac{N}{2}\frac{1}{a}=6 \qquad (14)$$

Idling EMF [24, 25]:

$$E=\frac{4k_w k_f\, fB_{\delta 0} D_p l w_f\, \pi}{p}= \\ =4*0.92*1.11*400*0.694*0.1*0.115*6=122{,}83\ \text{V} \qquad (15)$$

According to the obtained geometric dimensions, a computer model was developed in Ansoft Maxwell software package. The simulation results are given in Figure 4. Upon the results of computer simulation (Figure 4), the results of preliminary settlement calculations were confirmed, and certain basic parameters of EG were determined, Table 1. EG calculations were performed under load and overload. Furthermore, the results of computer simulation show that the maximum induction in the stator yoke is not more than 2 T, which is permissible for CoFe alloy. In building the external characteristics of EG, we used the known technique to describe the external characteristics with the ellipse equation.

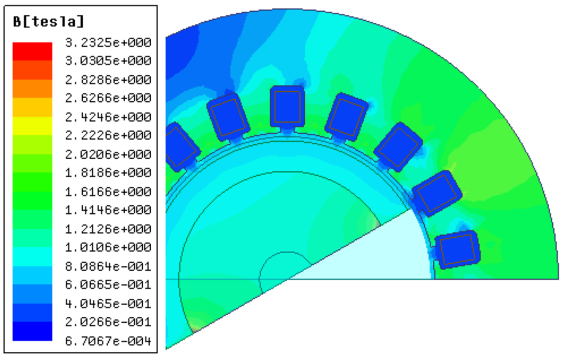

Figure 4. The results of EG computer simulation

In this case, inter alia, in building the external characteristic, we took into account the change in PM characteristics due to temperature.

$$\left(\frac{U}{E_0}\right)^2+\left(\frac{I}{I_k}\right)^2+2\left(\frac{U}{E_0}\frac{I}{I_k}\right)\cos\left(\phi-\text{arctg}\frac{x_d}{r_a}\right)=1 \qquad (16)$$

PM flowchart was built to determine current Ik, and it was found from it that Ik for the operating temperature of 175°C is 14173 kA. Given these values, and also based on calculations in Table 1, we have built the external EG characteristic, Figure 5.

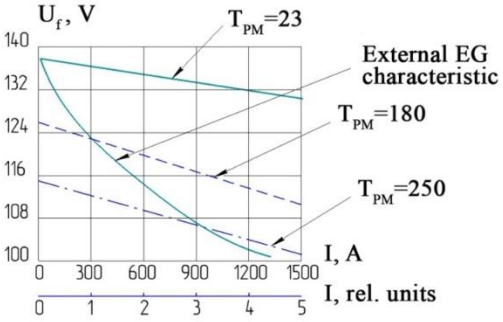

Figure 5. The external EG characteristic

Table 1 shows that the developed generator has a current density in the winding of 12 A/mm^2, which corresponds to the selected cooling system. At the same time, it is able to withstand three times multiplicity of demagnetization current, which also corresponds to the requirements for aircraft generators of this type. Specific electric loading of the designed generator also does not exceed the limits for the selected cooling system. Therefore, it can be concluded that the calculated data obtained in Table 1 fully satisfy the task.

As a result of electromagnetic calculations, a certain main structural diagram of EG and its parameters were determined, which fully meet the conditions set by our industrial partners.

Figure 5 shows that the external characteristic of the generator being developed is affected both by electric parameters, and also to a great extent by thermal processes. The external characteristic becomes nonlinear when they are taken into account.

Table 1. Results of EG parameters calculations determined as a result of computer simulation

Active area steel grade	-	CoFe
Thickness of sheets	mm	0.07
Phase current frequency	Hz	400
Phase voltage	V	124
Phase current (rms)	A	306,22
Current density in the winding	A/mm^2	12,2
Specific Electric Loading	A/m	33104
Heat factor	A/mm^2* *A/sm	3972
Generator power	kVA	108
Shortening coefficient	-	0,965
Distribution coefficient	-	0,957
Active resistance and dissipation resistance	Ohm	0,00268/0,0255
Multiplicity of demagnetization current	-	3,3
Inductive phase resistance along axes d-q	Ohm	0,099/0,099

3.1. Calculations of EG rotor mechanical strength

The developed EG has a sufficiently larger rotor diameter at relatively high speed, so it is necessary to make more accurate calculations of mechanical strength of rotor bandage sheath.

At a thickness of the sheath of 2.2 mm, and taking into account the mass of magnets (2.6 kg), centrifugal forces were calculated acting on the rotor bandage taking into account increased speed (28,800 rpm):

$$F = \omega^2 R m_{\text{mag}} = 3015^2 \cdot 0.05 \cdot 2{,}6 \approx 1181729H \tag{17}$$

where ω is the rotor speed (24,000 rpm or 2,514 rad/sec), R is the rotor radius (determined from electromagnetic calculations and is 50 mm), m_{mag} is the mass of the magnets is 2.6 kg.

Taking into account the geometric parameters and the resulting magnitude of centrifugal forces, a finite element model was developed in Solid Works software package, and stress in the rotor sheath was calculated as, Figure 6. Figure 6 shows that the stresses in the rotor sheath do not exceed 609 MPa, and this provides a safety factor for the projected generator of 1.76. The above calculations confirm performance of the proposed design.

4. EG ROTOR DYNAMICS ANALYSIS

A rotor developed at the stage of electromagnetic calculation is considered when calculating the critical rotor speed. The problem of dynamics analysis was solved using Ansys software package, Figure 7.

As a result of the calculation (Figure 7), it was found that the maximum lateral force acting on the rotor is 2,652 N, the first critical speed is at 98,000 rpm, i.e. is much higher than the rated speed. This proves performance of the selected constructive scheme of the rotor.

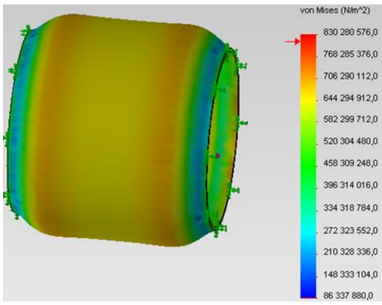

Figure 6. Calculations made in Solid Works software package

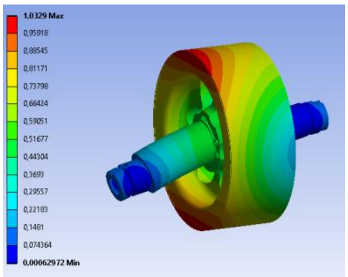

Figure 7. Deflection of the magnetoelectric generator rotor at the first critical rotation speed

5. CALCULATION OF LOSSES AND EVALUATION OF EG EFFICIENCY, AND COOLING SYSTEM CALCULATION

EG loss calculation is an important step in the design. Due to the limited EG volume, total losses in the active elements should be calculated as accurately as possible, to ensure maximum heat dissipation and reliability of EG. Mechanical losses in EG can be determined according to the procedure given in [22]. Losses in Co-Fe alloys for 400 Hz are usually specified by the manufacturer [23], and can be estimated based on the weight of the magnetic circuit and the magnetic flux density values obtained in electromagnetic calculations, Figure 5. Particular attention should be paid to losses for eddy current in permanent magnets, since the rotor in the developed EG is not cooled, and there will be virtually no heat dissipation from PM. Losses in PM were calculated by finite element method, Figure 8.

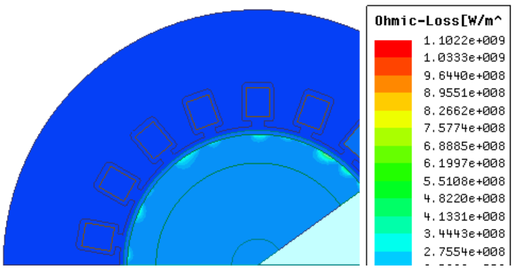

Figure 8. Distribution of losses for eddy currents in PM

Results EG loss calculations are shown in Table 2. Based on this calculation, the cooling system was designed described above. The estimate of temperatures by finite element method showed that the maximum PM temperature is not more than 180 °C, and winding temperature is not more than 205 °C, which fully provides EG performance.

Table 2. Losses in active EG elements

Ohmic losses in the stator copper	W	1,154
Losses in steel	W	693
Surface losses in the rotor due to tooth harmonics of the stator	W	193
Losses in the winding due to proximity effect and eddy currents	W	528

Analysis of Table 2 shows that the developed aircraft electric generator has a sufficiently high efficiency. Total losses in the designed structure do not exceed 2.6 kW, which at an electric power of 100 kW provides efficiency of 97%. Maximum losses take place in the stator winding, while losses are not significant in the stator iron. Minimum losses in the stator iron were achieved due to the use of the siliceous electrical steel with a sheet thickness of 0.18 mm. In general, as shown by thermal analysis, all these losses are diverted by the selected cooling system, which confirms workability of the developed electric generator in terms of thermal loads.

6. EG VOLTAGE CONTROL AND STABILIZATION SYSTEM

An important task in creating EG is the design of its control system, implementing the method described above. A block diagram of the control method and voltage stabilization implemented by DM, is shown in Figure 9.

To confirm efficiency of the proposed control and stabilization method for the output voltage of A/C EG and prove its practical implementation, the authors have developed a simulation model of generation channel in Matlab software package, which allows evaluating efficiency of the proposed control and stabilization method for EG output voltage, as well as duration of transients, voltage stabilization accuracy and to obtain DM adjustment characteristics.

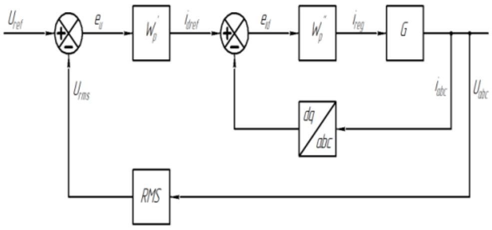

Figure 9. Block diagram of EG control method

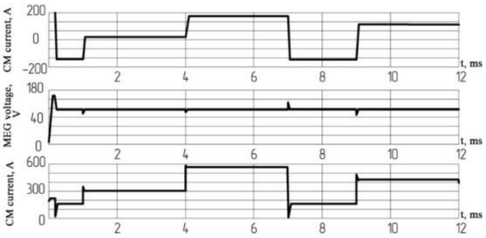

Figure 10. Simulation results of EG control processes (CM current, A VS t, ms; MEG voltage, A VS t, ms; CM current, A VS t, ms)

The developed simulation model consists of several units: a load unit (Load), DM unit including Current Regulator and Solver, as well as drive-generator unit (Generator). EG model is implemented in dq coordinates, and allows simulating operation of EG in generator mode as part of a constant speed drive in the range of loads from idling to three-fold overload. The simulation takes into account EG with the following numerical parameters: speed – 24,000 rpm, rated power – 100 kVA, frequency of the generated voltage – 400 Hz, magnetic induction in the air gap – 0.66 T. As a result of the simulation, Figure 10, DM current values were obtained, as well as voltage and current of the generator at a sharp change of the load and adjustment characteristic of DM, Figure 11. The analysis of simulation results Figure 10 shows that the proposed EG voltage control and stabilization method is efficient and allows controlling EG voltage over a wide range of load changes. Also the simulation results show that the maximum duration of the transient process is observed when the load changes from two-fold overload up to idling and is 70 ms. In this case the generator voltage reaches 140 V, that is, increased by 21.7%, and then restored to the nominal value.

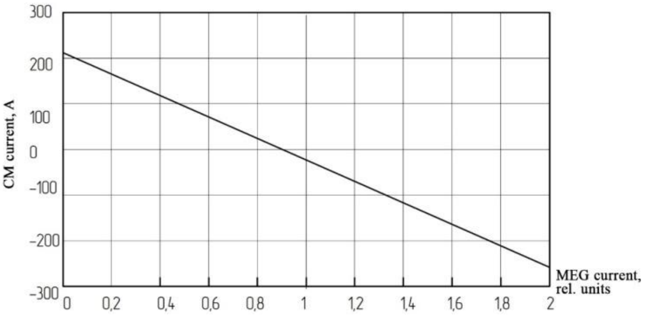

Figure 11. EG adjustment characteristics (CM current, A VS MEG current, rel. units)

As seen in Figure 11, DM current varies in the range of 0 A at 80% load to 200 A at idling or 160% load. In this case, in generator idling mode, DM current is behind voltage, and in overload mode – it is ahead by 90°, which also confirms validity of the proposed voltage control method.

7. EXPERIMENTAL EG LAYOUT

Based on the results, by the geometric dimensions, Table 1, full power EG demonstration layout was developed, as well as the layout of its control system was designed, Figure 12, 13.

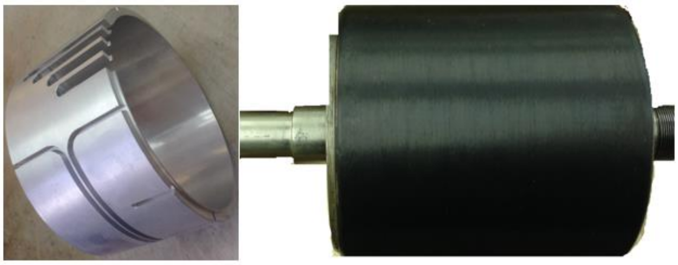

Figure 12. EG cooling jacket (left) and EG rotor (right)

Figure 13. Full-size EG layout (left)

As a result of research, the effectiveness of our solution has been fully proved, and all technical requirements specified by our industrial partner were complied with. A further step in our research was stand tests simulating A/C systems.

8. RESULTS AND CONCLUSIONS

Thus, the paper describes a process of multidisciplinary design of a high-performance EG with permanent magnets (PM), power of 100 kW, weight of 22 kg. Together with this EG, we have developed a system of voltage stabilization weighing 10–12 kg. EG is configured to 24,000 rpm, with an output frequency of 400 Hz (two-pole rotor) and is designed for integration into CSD of A/C.

Comparing our results with works of other authors, we can conclude that the new aircraft generator that we have created has minimized mass parameters at sufficiently high energy values. The control system proposed by us is of particular value in this case, which also outperforms analogs in terms of mass parameters. At the same time, the mass in aerospace industry is the main criterion for making decisions, since it allows to significantly minimize the economic costs associated with the fuel efficiency of the aircraft. Table 3 provides comparisons of our generator and known aircraft electric generators described in [1] – [18].

Table 3. Comparison of the developed generator and other types of generators with permanent magnets, used on various aircrafts

	Developed power generator	Electric generator with permanent magnets and bias windings	Electric generator with permanent magnets and full power inverter	Combined excitation generator
Rated/overload power, kW	100 / 150	100 / 150	100/150	100 / 150
Generator weight, kg	24,2	27,2	20,2	34
Control system weight, kg	12	11	25	5
Total system weight, kg	36,2	38,2	45,2	39
Losses in the stator magnetic circuit, W	693	693	700	1050
Losses in rotor, W	193	210	300–350	700
Aerodynamic losses, W	26	26	26	120
Ohmic losses in the	1154	1154	1200	1154

main winding, W				
Additional losses, W	528	528	550	700
Total losses, W	2594	2611	2826	3724

The analysis of Table 3 shows that since the rectifier and the full power inverter are not used together with our generator, the eddy current losses in it created in permanent magnets are lower than in other options. This is due to the fact that in our generator the eddy current losses are induced only because of the spatial harmonics of MMF, the time harmonics in our generator are not significant. In other competing options, losses in permanent magnets are greater, since the time harmonics are significant in them. The combined excitation generator is also inferior to our solution both in terms of efficiency and mass of the system.

Table 3 shows that our system has minimal mass-dimension parameters and minimal energy losses. And this, in the aggregate, shows the high efficiency of the solution developed. All this is achieved due to the optimal electric generator design. The basis of this method was set forth by us in [24], and also thanks to the use of a new method of stabilizing the generator voltage. Our conclusions are confirmed by the results of experimental studies of the full-size model.

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