HEAT EXCHANGE MODELS IN AVIATION STARTER-GENERATOR WITH COMBINED EXCITATION

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ABSTRACT

The paper dwells upon the creation of an aviation starter-generator with combined excitation for development of aircraft power supply systems in order to provide conceptual, technical, and experimental design of high-speed synchronous generators with electromagnetic excitation in aviation.

Key words: electric starter-generator with combined excitation, magnetoelectric starter-generator, electric generator cooling, cooling system modeling.
1. INTRODUCTION

Increase in electric power of aircraft is of immediate interest in designing, retrofitting and maintenance of aircraft [1, 2]. Therefore, the requirements to aircraft power supply systems [3-6] constantly become more stringent. Current requirements can be met by a system built on the basis of a contactless generator created according to the scheme of two electric machines – a magnetoelectric generator (MEG) and an inductor generator (IG) [7, 9].

The system of development of electric power generators for aircraft power supply systems, which supports the processes of conceptual, technical, and experimental design and aircraft high-speed synchronous generators and starter-generators with electromagnetic excitation, includes the methodology of modeling, calculation, verification of calculations, analysis and synthesis for cooling systems, technical maintenance of electromechanical converters in operation, databases and knowledge bases in the form of algorithms and programs, hardware for information storage and processing, a set of modified production hierarchical rules and recommendations on decision-making.

The power generating system for average-sized multipurpose helicopters has a DC power rating of 9 ... 12 kW per channel with the electric power quality according to GOST R 54073-2010 [8]. It is easy enough to use a system of direct current of such power in the helicopter’s propulsion engine electric startup system.

The contactless electric machine of combined excitation with the functions of a starter-generator has high specific energy characteristics, low mass and dimensions, and low maintenance burden. The structural feature of an electric machine with combined excitation is its cooling system.

2. OBJECTIVE, TASKS

The objective of the study is the methodology of designing cooling systems for starter-generators of an average-sized multipurpose helicopter and their operational properties.

Proceeding from the stated objective, the following interrelated scientific tasks were solved: gas-dynamic and thermal calculations of the starter generator were performed to check the compliance with the requirements to the allowable temperature of separate elements; a rational method for intensifying the heat exchange of the starter generator in operation was determined; the content of the operational documentation was evaluated against the adequacy of information for its maintenance.

The considered starter-generator of an average-sized multipurpose helicopter is a six-phase inductor machine of combined excitation. The starter-generator is cooled by the fan located on the electric machine rotor, through blowing the intake air through the structure.

The design methods are borrowed from the Simulink and Matlab methodologies, the Software Maintenance Service support, and the Team centre package of scalable software for supporting the product life cycle.
The design process begins with the establishment of the functionality of the starter-generator of the aircraft power supply system (PSS). The essence of the item’s purpose is determined by the purpose of the aircraft as a complex object, which is expressed by a tuple:

$$Q_{PSS} = \sum \{ r^+, r, x, M, N, P, V \} y,$$

where \( r^+ \in R^+ \) and \( r \in R \) are, respectively, sets and permissible clusters of used and created properties of the object; \( x \in X \) are state parameters from a permissible cluster of properties; \( M \) is a selection of constant parameters of the object; \( N \) is a rule (operator), by which the variable characteristics of the object are determined; \( P \) is a physical parameter of the process; \( P=(t, s) \) is time and spatial characteristics of localization, coordinates and their permissible cluster; \( Y=(r, M, t, X) \) is a rule for determining the projected property of the object’s functionality.

The properties of the designed object of the power supply system and its states are established through the development of logical and transformational rules:

$$O : \{ PSS \} P_i \Rightarrow P_j,$$

where \( P_i \) is a description of the required state of the system; \( i \) is the distinguishing feature (number) of the system; \( P_j \) is a description of the current state of the system; \( j \) is a distinguishing feature (number) of the current state of the system; \( k \) is the distinguishing feature (number) of the component object of the system; \( l \) is the distinguishing feature (number) of the property of the component object of the system; \( n \) is the number of different features of the object; \( U_{ki} \) is the method (metrics) of monitoring (check calculation) of the system object.

The importance of the general formulation and solution of the problem stated in this paper consists in an end-to-end interconnected cycle of processes and procedures for design and maintenance, in contrast to numerous analogues of system designing, where these procedures are distributed among the objects of the system.

For measured objects, metric, physical, quantitative, unconditioned, and mathematical values are applied. Estimated objects are expressed through means of natural language and non-metric, qualitative, and conditional values. A formal description for calculating the properties of the designed object of the power supply system has the following expression:

$$O_i = \{ (a_i, A_i) | j \in N_n \}, (b_j, B_j) | j \in N_m \},$$

where \( N_n \) of \((1, 2, 3, \ldots, n)\) and \( N_m \) of \((1, 2, 3, \ldots, m)\) is a set of values of natural numbers; \( a_i, A_i \) is a property of the designed object and its many manifestations; \( b_j, B_j \) is a basis and its many elements.

The content of the task is structured as follows: a) establishment of a set and composition of concepts, terms of measurement and evaluation; b) establishment of the necessary composition of numeric and non-numerical ranges of definitions; c) solution of the problem of matching the left and right boundaries of the ranges of definitions; d) rationale for choosing the main range of definitions, which is the main basis for observing the properties of objects; e) compilation of a metric space diagram and its formal description; e) development of a methodology for calculating the values of the selected domain.

The calculation procedure includes the following actions.
At the first stage, a geometric model is prepared. Then, based on this geometric model, a grid model is constructed that has the necessary quality and “thickening” of the grid elements in the appropriate places.

At the second stage, preprocessing is performed; that is, choosing the appropriate physical model of calculation, setting the conditions of single-valuedness, boundary and initial conditions.

At the third stage, the calculation itself is performed in the methodological environment.

At the fourth stage, post-processing takes place; that is, viewing and analysis of the calculation results.

At the final stage, the results are evaluated; and this evaluation either satisfies (and then we proceed to the designing process), or the calculation model can be adjusted based on the results of the analysis of the results. After the adjustment, the iterative process of calculation is repeated from the stage where the correction was made.

3. METHODS AND MATERIALS

The methodology for optimal designing of a starter-generator with electromagnetic excitation is based on four principles:

- The complete design of the electrical machine is created at the stage of technical designing. This principle provides two ways of manufacturing a product in any project – either by traditional technology through the release of working design documentation, or by electronic technology.

- Optimal designing of the product, based on the previously described properties of aircraft electrical machines. This principle is implemented through searching for the best local optimality criterion by achieving local optima at each of the product design stages.

- Unity of the constituent parts. In this case, at all design stages included in a single algorithm, the principle is observed that states: the properties of the component parts of the object obtained at earlier stages of development are inherited.

- Construction, maintenance, presentation and registration of operational documentation for after-sales support of operation and repair are implemented in a single design, test and production algorithm.

The geometric model is a computational domain, which includes the elements of the starter-generator and the volume modeling the environment – the area of the cooling air flow. The computational domain is axisymmetric; it is divided into sectors to use in a detailed grid model.

The total number of grid model elements for the construction of a starter-generator weighing 15.8 kg, the overall dimensions of which represent a cylinder with a diameter of 160 mm along the flange and a height of 220 mm, is 16 million. To resolve the boundary layer along the surfaces of solid bodies, prismatic layers were constructed.

As single-valuedness conditions at the cooling air input and output, boundary conditions of the “free-exit” type are given, with the following parameters: pressure $P=1$ atmosphere, ambient temperature $T_f=+60^\circ C$, the working medium is air.

The values of the rotor speed were from 6500 ... 13000 rpm in accordance with the operating modes.
The model for the production of solid bodies included steel, aluminum and titanium alloys, taking into account their thermal conductivity.

The thermal conductivity of the stacks from the rotor steel sheets and the IG stator in the axial direction is given by the equivalent thermal conductivity coefficient determined by the formula for a multilayer wall [10]:

$$\lambda_{tt,eq} = \frac{\delta_{tt} + \delta_{ad}}{\lambda_{tt} + \delta_{ad}}$$  \hspace{1cm} (4)

where $\delta_{tt}$ is the total thickness of the steel sheets in the stack; $\delta_{ad}$ is the total thickness of adhesive in the stack; $\lambda_{tt}$, $\lambda_{ad}$ are thermal conductivity coefficients of the corresponding layers.

The adhesive thickness in the rotor stack $\delta_{ad}$ is determined by the steel filling factor, which for the rotor when using adhesive and sheets with a thickness of 1 mm is 0.95 [10], and for the stator when using adhesive and sheets with a thickness of 0.5 mm is 0.93 [10]. It was found that the equivalent thermal conductivity of the rotor sheet stack (the stack thermal conductivity in the axial direction) is $\lambda_{tt,eq} = 5 \text{ W/(m-K)}$ and the equivalent thermal conductivity of the stator sheet stack is $\lambda_{tt,eq} = 4 \text{ W/(m-K)}$.

The excitation winding and its insulation are characterized by an equivalent coefficient of thermal conductivity in the axial and radial directions. The value of the equivalent coefficient of thermal conductivity is determined by the type of winding laying, impregnation quality, thermal conductivity of wire insulation and impregnating composition, wire diameter.

The laying type affects the filling factor [10, 11], which is the ratio of the cross-sectional area of all insulated wires to the sectional area of the coil or slot, minus the main or slot insulation $F_0$:

$$k_f = n_{cond} \cdot \frac{d_i^2}{F_0} \text{,}$$  \hspace{1cm} (5)

where $k_f$ is the filling factor; $n_{cond}$ is number of conductors in the winding; $d_i$ is the wire diameter; $F_0$ is the filling factor.

The impregnation quality is characterized by coefficient $k_{imp}$.

$$k_{imp} = k_0 \cdot k_{sol} \text{,}$$  \hspace{1cm} (6)

where $k_0$ is the ratio of the volume of liquid varnish penetrating into the winding to the volume of air between the wires prior impregnation; it depends on the impregnation technology, can be 0.24 after short dipping, 0.76 after multiple dipping, and 0.98 after vacuum impregnation [9]; $k_m$ is the content of solid particles of the varnish base (in varnishes with solvents $k_m = 0.4 ... 0.6$).

The equivalent coefficient of thermal conductivity for round wires with layer laying [4] is determined by the formula:
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\[
\lambda_{eq} = \lambda_{eq}' \cdot \left[ \frac{\arcsin\left(\frac{d}{d_i}\right) \cdot \sqrt{k_i + 1.57}}{\sqrt{1 - \left(\frac{d}{d_i}\right)^2} \cdot k_i} - 1.57 \right],
\]  

(7)

where \( d \) is the diameter of a bare wire; \( \lambda_{eq}' \) is the equivalent coefficient of thermal conductivity of the gaps between the wires, determined by the formula:

\[
\lambda_{eq}' = \frac{\delta_i + \delta_{air} + \delta_{lin}}{\lambda_i + \lambda_{air,eq} + \lambda_{lin}},
\]  

(8)

where \( \delta_i \) is the bilateral thickness of the wire insulation; \( \delta_{lin} \) is the thickness of the insulating liner between the winding rows; \( \delta_{air} \) is the thickness of air gaps between wires calculated by the formula:

\[
\delta_{air} = 0.5 \cdot d_i \cdot \left[ 1 - \sqrt{1 - \left(\frac{d}{d_i}\right)^2} \right],
\]  

(9)

where \( \lambda_i, \lambda_{air,eq}, \lambda_{lin} \) are coefficients of thermal conductivity of the corresponding layers, and

\[
\lambda_{air,eq} = \frac{2 \cdot \lambda_{air} \cdot \lambda_{imp} \cdot \left[ \lambda_{imp} \cdot k_{imp} + \lambda_{air} \cdot (1 - k_{imp}) \right]}{\lambda_{air} \cdot \lambda_{imp} + \left[ \lambda_{imp} \cdot k_{imp} + \lambda_{air} \cdot (1 - k_{imp}) \right] \cdot \left[ \lambda_{air} \cdot k_{imp} + \lambda_{imp} \cdot (1 - k_{imp}) \right]},
\]  

(10)

where \( \lambda_{air} \) is the coefficient of thermal conductivity of the air; \( \lambda_{imp} \) is the coefficient of thermal conductivity of the impregnating composition.

The effect of the equivalent coefficient of thermal conductivity of the winding on the thermal state was estimated for \( \lambda_{eq} = 0.922 \text{ W/(m·K)} \), which corresponds to vacuum impregnation, for \( \lambda_{eq} = 0.795 \text{ W/(m·K)} \), which corresponds to impregnation with multiple dipping, and for \( \lambda_{eq} = 0.360 \text{ W/(m·K)} \), which corresponds to impregnation with short-term dipping.

The values of heat release in the stator elements [7, 9, 10] of the generator in various modes are shown in Table.

<table>
<thead>
<tr>
<th>Table 1 Heat release in the stator elements in various modes</th>
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<td>Rotor speed, rpm</td>
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<td>Rated active power, W</td>
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<td>Mode duration, s</td>
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<td>Losses in IG stator steel, W</td>
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<td>Losses in MEG stator steel, W</td>
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<td>Losses of the stator winding, W</td>
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<td>Losses of the excitation winding, W</td>
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Heat release in the rotor elements of the generator at a speed of 6500 rpm was 210 W. The eddy current losses in the rotor were evaluated along the upper boundary. Heat release was applied in the upper layer (1 mm thick) of crosses and a stack of steel sheets of the magnetoelectric part of the rotor.

Heat transfer in the gap between the stator and the rotor occurs in the field of centrifugal forces and is accompanied by axial and secondary currents. The geometric model included the gap between the stator and the rotor of an electric machine of 0.5 mm thick and was a sector of a rotating cylinder with an angle of 7.5 degrees, which corresponds to one slot.

The internal volume of the starter-generator, which represents the ventilation path, has axial channels for air flow passage through the rotor elements; there are no channels in the stator provided. In addition, air can pass through the unclosed part of the stator winding slot and through the gap between the stator and the rotor, causing additional pressure losses along the path.

The joint operation of the fan and the path, and the gap between the stator and the rotor is characterized by an air flow of 39.5 kg/h at an operating pressure of 820 Pa and a rotation speed of 6500 rpm and, respectively, 80.6 kg/h, 3450 Pa and 13000 rpm.

Based on the calculation results in the starter mode, the maximum winding temperature increases from +112°C to +230°C in 300 seconds, which exceeds the permissible temperature of the wire for long-term operation. Assuming that the starter-generator operates in this mode for a limited time, we have a margin for the wire winding resource.

A contactless electric machine of combined excitation with the functions of a starter-generator in a multipurpose average-sized helicopter is cooled by intake air with an axial eleven blade fan mounted on the rotor shaft.

Heat transfer occurs in the field of centrifugal forces and is accompanied by axial and secondary currents. The process model in the gap between the stator and the rotor of the electric machine was a sector of a rotating rotor cylinder and a stator sector equal to one slot.

Without axial motion of the flow, flow instability arises when the inner cylinder rotates in the annular gap after reaching the critical value of the Taylor number. The flow mode changes, toroidal Taylor vortices are formed in the gap, which affect the heat transfer. The Taylor number $\text{Ta}$ is determined by the formula [10]:

$$\text{Ta} = \frac{r_m^{0.5} \cdot \delta^{1.5} \cdot \omega \cdot \rho}{\mu},$$

where $r_m$ is the mean radius between the radii of the rotor and the stator, m; $\delta$ is the thickness of the gap between the rotor and the stator, m; $\rho$ is the density of the medium, kg/m$^3$; $\mu$ is the dynamic viscosity of the medium, Pa·s; $\omega$ is the angular velocity of the rotor, rad/s.

The Taylor vortices form a periodic structure with pairwise rotation in different directions. In the presence of axial motion of gas in the gap, the vortices have a less pronounced structure, up to their complete absence (Fig. 1).
Under these conditions, the effective velocity in the gap increases, and the average value of the heat transfer coefficient over the surface of the rotor reaches 88.2 W/(m²·K), with a nominal value of 75.5 W/(m²·K), which allowed the rotor model inside of the generator body to take into account both cylindrical surfaces and crosses, which increase aerodynamic losses at high rotational speeds, due to the friction of the surfaces on the air [10, 12, 13, 16].

The aerodynamic losses for the cylinder are calculated by the formula:

$$P_{fr} = c_f \cdot \pi \cdot \rho \cdot \omega^3 \cdot R^4 \cdot L,$$

(12)

where $c_f$ is the coefficient of friction between the rotor and the medium; $R$ is the rotor radius, m; $L$ is the length of the section for which losses are determined, m.

The value of the friction coefficient depends on the type and structure of the flow. At a rotor speed of 650 rpm, the aerodynamic losses are 7.8 W, which is quite small with overall losses.

For modes with a nominal active power of 9000 W and 13500 W (starter mode of not more than 300 s) and rotor speeds of 6500 rpm, a series of calculations were made with various values of the equivalent thermal conductivity coefficient of the excitation winding in order to evaluate the influence of the impregnation quality of this winding on its thermal state.
Based on the results of the calculation, changes of the maximum temperature of the excitation winding are plotted as a function of time, as shown in Fig. 2. The maximum winding temperature exceeds the permissible temperature of the wire for long-term operation in 300 s, but due to short-term operation in the starter mode, the necessary margin for the winding wire resource is provided.

The maximum temperature occurs in the central loops of the excitation winding, because of the thermal resistance of the winding on the path of the heat flow between the turns (Fig. 3), and the temperature drop over the excitation winding exceeds 100°C.

![Figure 3](image)

**Figure 3** Changes of generator elements temperature along the radius, 300 s mode

The maximum temperature is on the surface layer of the MEG steel sheet stack, where heat is released; the magnets also have temperatures close to the maximum ones, since they are in its proximity.

According to [13], the maximum operating temperature of the material is 139.85°C, while the volumetric average temperature of the magnets, as calculated, is 148.8°C, which is higher than the maximum operating temperature.

The temperatures of the fan impeller are minimal due to high values of heat losses and intake of air of a temperature of +60 °C.

The general view of the designed starter-generator is shown in Fig. 4.

![Figure 4](image)

**Figure 4** 9 kW starter-generator
As an object of maintenance, the starter generator is characterized by its durability, adaptability to maintenance and restorability – that is, durability and repairability.

The content of the operational documentation is formed on the basis of the requirements of the aviation manual AM 1.1-S1000DR-2007 [15] and estimates $K_1$ that reflects the general reliability index of the structure determined by reliability and maintainability, and $K_2$ that reflects the general index of reliability and operational maintainability.

$$K_1 = \frac{T_{\text{Mean}}}{T_{\text{Mean}} + t_{\text{rec}}}, \quad K_2 = \frac{T_{\text{Mean}}}{T_{\text{Mean}} + t_{\text{rec}} + t_{\text{sch}}}$$  \hspace{1cm} (13)

where $T_{\text{Mean}}$ is the mean time between failures and damages; $t_{\text{rest}}$ is the mean time to recovery; $t_{\text{sch}}$ is the average duration of scheduled maintenance.

The quality of the operational documentation is sufficient if the values of the coefficients $K_1$ and $K_2$ exceed the normative values of 0.67 and 0.25, respectively. The developed operational documentation has the values $K_1 = 0.79$ and $K_2 = 0.26$, which corresponds to the necessary requirements.

4. RESULTS AND DISCUSSIONS

In the construction of the starter-generator, the most thermally-loaded elements of the rotor are a stack of steel sheets and magnets; amongst the stator elements it is an excitation winding. The thermal state of the winding depends on the quality of its impregnation. There is an uneven distribution of temperature along the length of the starter-generator in general and over the volume of the magnet.

Intensification of the excitation winding cooling can be ensured by increasing its equivalent coefficient of thermal conductivity in the axial and radial directions.

5. CONCLUSIONS

The starter-generator of the multipurpose average-sized helicopter has the most thermally-loaded elements such as a stack of steel sheets and rotor magnets.

In order to improve the thermal conductivity of the excitation winding, it is recommended to use the vacuum impregnation technology, non-shrinking winding fillers, modification of impregnating silicone insulating varnishes with aluminum nitride [14], optimization of the fan casing design, the impeller design and fins of the outer surface of the casing.

The quality of the starter-generator operational documentation created on the basis of the aviation manual AM 1.1-S1000DR-2007, is considered sufficient for the operator.

REFERENCES


