DOI: https://doi.org/10.15407/pmach2024.04.022

UDC 621

FEATURES OF THE CALCULATED DETERMINATION OF THE THERMAL STATE OF THE TURBO GENERATOR BRUSH-CONTACT DEVICE

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The features of the calculation of the thermal state of the turbo generator brush-contact device are discussed in this paper. The author provides an algorithm for analytical calculation of the device, determines the expected temperatures of the elements provided that additional filters are installed in the ventilation duct. Using the finite element method, a three-dimensional calculation of the thermal state of the brush-contact device elements was performed. The obtained results confirm the possibility of improving the design of the brush-contact device by installing filtering elements in order to increase the reliability of the operation of this unit.

Keywords*: turbo generator, brush-contact device, three-dimensional thermal calculation.*

Introduction

A characteristic feature of synchronous electric machines, including turbo generators, is the need to power the excitation winding located on the rotor, which is necessary to create a magnetic field in the magnetic core of the electric machine.

One of the most common ways to power the rotor winding is to use a brush-contact device, which provides direct current power from the excitation system.

For turbo generators of large and medium power, the design of a brush-contact device is a rather complex task. To ensure the operability of all elements of the device, it is required for a design engineer to have a wide range of knowledge in various scientific fields, as the design includes both highly loaded contact electrical connections (slip rings in combination with the rotor current supply) on the rotor rotating at high speed, and structural elements of the brush holder device (brushes, brush holders, ventilation system), which must ensure uninterrupted operation, convenient and quick adjustment.

From the statistical data on the causes of typical emergency situations on electric generators of power plants, caused by failures of various types, it is clear that 14% of all failures are due to brush-contact devices. Such a fairly high percentage of failures indicates that increasing the reliability of this unit is a relevant task nowadays because the phenomena occurring in operating brush-contact devices are quite complex and require further study.

According to statistics, the main causes of failures of brush-contact devices are:

– all round fire;
– heating of slip rings above the maximum permissible value;
– uneven brush wear;
– local runout of slip rings;
– vibration and chipping of brushes;
– decrease in insulation resistance below the maximum permissible value.

An important feature of the design of the brush-contact device is that when performing the thermal calculation, it is necessary to solve the thermal problem with three types of heat generation: electrical losses in the classical formulation, losses on friction of brushes against the slip ring and additional losses caused by the action of parasitic currents. The main methods of calculation and design of brush-contact devices of electric machines of similar types are considered in the papers [1–2], but in general these papers do not allow to establish a real picture of the thermal state of the brush holder device in three-dimensional form. In this regard, to meet the requirements of reliability and operation, it is advisable to review existing methods in order to implement the solution in software complexes using CFD methods.

Design of the turbo generator brush holder device

The brush-contact device of a synchronous electric machine structurally consists of two main parts:

– slip rings (rotating part), which are usually part of the rotor of a synchronous machine;

– brush holder device (fixed part), which is attached mainly to the supporting units of the electric machine or directly to the base.

A typical design of the turbo generator brush holder device is shown in Fig. 1. The device is attached to the foundation plates provided for in the design on the turbo generator base and consists of the following main elements: welded frame (1), current collector device (2), insulated pins (3), output buses with terminal board (4), insulating sealing ring (5) and exhaust ventilation device. (6).

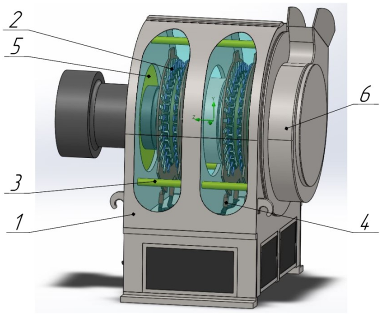

Fig. 1. Typical design of a brush-contact device

The welded frame consists of a base (bottom plate), vertical walls (end and side ones), a horizontal partition with windows for distributing cooling air between the slip rings, auxiliary elements for fastening other parts of the brush holder device. The welded frame has windows for cooling air inlet and easily removable inspection doors on each side of the device.

The current collector device includes four copper ring buses (two buses for each slip ring), on which the current collector elements themselves, namely special brackets and brush holders located in them, are fixed in circle.

The copper ring buses of the current collector device are attached to the welded frame using insulated pins and steel detachable holders.

The brackets consist of copper clamps, in rectangular sockets of which brass clips are fixed with bolts. The clamps are attached to copper ring buses with bolts through oval holes in the side shelves of the clamps, which allow adjusting their radial position relative to the slip rings. The brass clips fixed on the clamps have ventilation windows in each face to improve heat transfer from the brushes to the cooling air.

The clips are equipped with brush holders with electric brushes located in them. It is possible to use different types of brush holders and brushes. However, according to modern trends, the brush holders should be of quick-release type and equipped with springs with constant force for pressing the brushes.

A quick-release brush holder from one of the world's leading manufacturers of brush-contact equipment, Mersen (France), is shown in Fig. 2. The type of brush holder shown has an insulated handle, which allows the brush holder to be installed and removed even during generator operation, since safety for service personnel is ensured by the absence of human contact with the conductive parts of the traverse. The brush holder is removed by turning the handle. In addition, this type of brush holder has the following features:

– precise manufacturing of all components, which allows them to be used without prior adjustment or modification and without being tied to a specific location on the traverse;

– use of pressure mechanisms with constant pressure springs;

– the presence of a locking mechanism that prevents the electric brushes from falling out when installing and removing the brush holder;

Fig. 2. Quick-release brush holder

– possibility of using brushes with increased radial size, which provides a longer period between brush replacements.

The output insulated buses, consisting of flexible copper plates, depart from each pair of current collector rings and connect them to the terminal board of the device, designed for connecting external cables for supplying the excitation current to the rotor winding.

The detachable insulating ring is designed to close the space between the rotor shaft and the frame of the device on the generator side in order to ensure electrical safety for service personnel and organize a ventilation path for cooling the brush holder device.

The exhaust ventilation device includes a centrifugal fan installed near the rotor slip rings and a welded "spiral" in the form of an "Archimedean spiral" with a bellmouth for hot air outlet.

The current collector and the slip rings have an open cooling system with the intake of cooling air from the machine room and the discharge of hot air into the machine room or the foundation channel. The centrifugal fan wheel is mounted on the end of the rotor shaft. The cooling air enters through the ventilation holes in the lower cavity of the frame, and due to the ventilation windows in the horizontal partition, it is divided into three streams. The first stream enters the space between the vertical wall of the frame and the insulating partition located in front of the first annular copper bus, and then moves along the surface of the inner slip ring towards the "spiral" and cools the current collector bus with the elements located on it and the surface of the slip ring on its way. The second flow enters the space between the copper ring buses of the inner ring, where it cools the second current collector bus with the elements located on it and the rest of the inner slip ring, and then connects with the first flow. The third flow enters the space between the third bus and the middle vertical wall of the frame, where it cools the outer slip ring, the third and fourth current collector buses with the elements located on them, and then connects with the first and second flows before entering the "spiral".

Analytical calculation of the thermal state of a brush-contact device with installed filters

The current task when designing new equipment or reconstructing existing turbo generators is to ensure air filtration at the inlet to the brush holder device with maintenance of the pressure and air flow rate necessary for complete removal of heat losses. Installation of filters will increase the reliability of the brush contact device due to a significant reduction in the level of contamination of conductive and electrically insulating elements from impurities present in the air of the power plant engine room.

The case of installing filters on a brush-contact device designed for operation with the following parameters is considered:

– rated excitation current – 3130 A;
– rated excitation voltage – 453 V;
– rated speed – 3000 rpm;
– maximum cooling air temperature – 40 °C.

Installed panel-cell filters of the CFW30 type have the following parameters:

– filter material – polyester;
– frame material – metal;
– cleaning class according to EN 779 [3]: G3(EU3) – G4(EU4);
– cleaning efficiency – 89.8–90.8%;
– recommended air speed – 1.5 m/s;
– maximum operating temperature – 100 °C;
– maximum operating humidity – 100%;
– dimensions – 400×400×48 mm;
– filtration area – 0.27 m^2;
– estimated air flow rate – 1480 m^3/h;
– initial pressure drop – 64 Pa.

The air flow rate through the brush-contact device is determined based on calculations of the pressure characteristic of the fan and experimental data of the basic design of the brush-contact device.

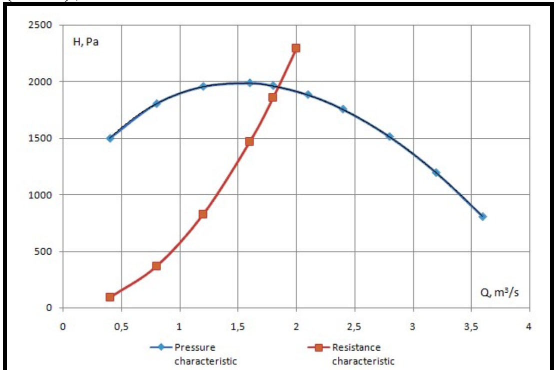

Fig. 3. Characteristics

According to the aerodynamic calculation performed according to the method [4], the centrifugal fan installed on the end of the shaft has the pressure characteristic given in Fig. 3 and Table 1.

Table 1. Pressure characteristic of the fan

Parameter	Value									
Air consumption, m^3/s	0.4	0.8	1.2	1.6	1.8	2.1	2.4	2.8	3.2	3.6
Fan pressure, Pa	1496.4	1802.8	1954.7	1985.4	1961.8	1882.7	1754.5	1512.4	1194.4	805.4

Based on the results of approximating the trend line of the graph of the fan pressure dependence on the air flow rate, the following polynomial approximation of this dependence can be obtained:

$$H(Q) = -0.537 \cdot Q^6 + 9.012 \cdot Q^5 - 64.132 \cdot Q^4 + 261.77 \cdot Q^3 - 902.42 \cdot Q^2 + 1610.5 \cdot Q + 981.4 ,$$

where H is the fan pressure, Pa; Q is the air flow through the fan, m^3/s.

For the basic design of the brush holder traverse, the air flow rate according to experimental data is Q_b=2.0 m^3/s.

The air pressure drop in the basic design, calculated using the above fan pressure characteristic, for the specified air flow rate is H_b=1914.8 Pa.

Thus, the hydraulic resistance of the basic structure to air flow is

$$R_b = \frac{H_b}{Q_b^2} = \frac{1914.8}{2.0^2} = 478.7 \text{ kg/m}^7.$$

The additional hydraulic resistance of filters is determined by their rated parameters

Q_f=1480 m^3/h=1480/3600=0.411 m^3/s;

P_f=64 Pa.

At the same time, four inlet windows with dimensions of about 400×200 mm can be placed in the welded frame of the brush holder device, which, in terms of the cross-sectional area of the window and its flow rate, is approximately equivalent to the parallel installation of two CFW30 type filters with dimensions of 400×400 mm. The hydraulic resistance of one such filter is

$$R_f = \frac{H_f}{Q_f^2} = \frac{64}{0.411^2} = 378.7 \text{ kg/m}^7.$$

When two filters are installed in parallel, their total hydraulic resistance is

$$R_{fp} = \frac{1}{\left(2 \cdot \frac{1}{\sqrt{R_f}}\right)^2} = \frac{R_f}{4} = 94.7 \text{ kg/m}^7.$$

The total hydraulic resistance of a new system with filters is determined as the sum of the resistances of the basic design of the brush holder device and the installed filters when they are connected in series

$$R_n = R_b + R_{fp} = 478.7 + 94.7 = 573.4 \text{ kg/m}^7.$$

From the obtained hydraulic resistance value for the new system, its resistance characteristic can be determined as

$$H(Q) = R_n \cdot Q^2 .$$

The indicated resistance characteristic of the new system and the pressure characteristic of the fan are shown in Fig. 3.

The intersection point of these two characteristics is the operating point of the new system. Thus, the graphically determined air flow rate for the brush holder device with installed filters is Q_n=1.846 m^3/s.

The temperature of the elements of the brush-contact device is determined by the heat losses that are released in them and by the cooling conditions.

Thermal losses consist of losses in the transition contacts and ohmic losses in the conductive parts. Losses in the transition contacts are established based on the requirements of the DSTU IEC 60034-2-1:2019 standard [5], according to which they are defined as the product of the current and the voltage drop in the transition contact ΔU=1 V. Based on experimental data, it can be stated that during the generators operation these losses can increase due to contamination and disturbances in the device settings, therefore, for the calculation they are taken with a margin of 50%. Thus, for two slip rings, the losses in the transition contacts are

$$P_r = 1.5 \cdot 2 \cdot I \cdot \Delta U = 1.5 \cdot 2 \cdot 3130 \cdot 1 = 9390 \text{ W},$$

where I=3130 A is the rated excitation cur.

The resulting losses are conventionally divided into two equal parts, one of which is allocated in the slip rings, and the other one – in the brushes on the current collector rings of the brush holder device.

The calculated ohmic losses occurring in the current collector buses are P_s=105 W at a bus temperature of 95 °C, which is adopted in accordance with the recommendations of DSTU IEC 60034-1 [6] for temperature exceedances according to insulation heat resistance class B.

The air flow rate for current collector buses is determined based on the geometric data of the brush-contact device

$$V_1 = \frac{Q_n}{F} = \frac{1.846}{0.7321} = 2.52 \text{ m/s},$$

where F=0.7321 m^2 is the cross-sectional area of one of the current collector buses.

The determination of the heat transfer coefficient from the surface of the current collector buses is performed on the basis of known criterion equations

$$\mathrm{Re}_1 = \frac{V_1 \cdot l_1}{\nu} = \frac{2.52 \cdot 0.01}{15.06 \cdot 10^{-6}} = 1.67 \cdot 10^3;$$

$$\mathrm{Nu}_1 = 0.46 \cdot \mathrm{Re}_1^{0.5} = 0.46 \cdot (1.67 \cdot 10^3)^{0.5} = 18.82,$$

where Re is the Reynolds number; l_1=0.01 m is the characteristic size (thickness) of the bus; ν=15.06·10^{-6} m^2/s is the kinematic coefficient of air viscosity; Nu is the Nusselt number.

The heat transfer coefficient from the surface of the current collector buses is

$$\alpha_1 = \mathrm{Nu}_1 \cdot \frac{\lambda}{l_1} = 18.82 \cdot \frac{0.0276}{0.01} = 51.95 \text{ W/(m}^2\text{·K)},$$

where λ=0.0276 W/(m·K) is the coefficient of thermal conductivity of air.

The heat flux density for the surface of all four current collector buses is

$$q_1 = \frac{\frac{P_r}{2} + P_s}{4 \cdot F_1} = \frac{\frac{9320}{2} + 105}{4 \cdot 0.467} = 2567 \text{ W/m}^2,$$

де F_1=0.467 m^2 is the surface area of one bus.

Thus, the temperature of the outer surface of the buses is

$$T_1 = T_0 + \frac{q_1}{\alpha_1} = 40 + \frac{2567}{51.95} = 89.4 \text{ °C},$$

where T_0=40 °C is the cooling air temperature.

The temperature of the outer surface of the slip rings is calculated using a similar principle.

The speed on the working surface of the slip rings is

$$V_2 = \frac{\pi \cdot d_r \cdot n}{60} = \frac{\pi \cdot 0.45 \cdot 3000}{60} = 70.69 \text{ m/s},$$

where d_r=0.45 m is the slip ring diameter; n=3000 rpm is the rated speed of the turbo generator.

The criterion equations for slip rings are as follows:

$$\mathrm{Re}_2 = \frac{V_2 \cdot l_2}{\nu} = \frac{70.69 \cdot 0.13}{15.06 \cdot 10^{-6}} = 6.1 \cdot 10^5;$$

$$\mathrm{Nu}_2 = 0.46 \cdot \mathrm{Re}_2^{0.5} = 0.46 \cdot (6.1 \cdot 10^5)^{0.5} = 359.3,$$

where l_2=0.13 m is the characteristic size (axial width) of the ring.

The heat transfer coefficient from the surface of the slip rings is

$$\alpha_2 = \mathrm{Nu}_2 \cdot \frac{\lambda}{l_2} = 359.3 \cdot \frac{0.0276}{0.13} = 76.29 \text{ W/(m}^2\text{·K)}.$$

The heat flux density for the surface of the two slip rings is

$$q_2 = \frac{P_r/2}{2 \cdot F_2} = \frac{9390/2}{2 \cdot 0.504} = 4657 \text{ W/m}^2,$$

where F_2=0.504 m^2 is the surface area of one slip ring, taking into account the helical grooves and end surfaces.

The temperature of the outer surface of the slip rings is

$$T_2 = T_0 + \frac{q_2}{\alpha_2} = 40 + \frac{4657}{76.29} = 101.0 \text{ °C}.$$

The air temperature at the outlet of the brush-contact device is determined by the formula

$$T_3 = T_0 + \frac{P_r + P_s}{C_p \cdot \rho \cdot Q_n} = T_0 + \frac{9390 + 105}{1006 \cdot 1.128 \cdot 1.846} = 44.5\ °\text{C},$$

where C_p=1006 J/(kg·K) is the specific volumetric heat capacity of air; ρ=1.128 kg/m^3 is the air density.

According to the results of analytical calculation, the obtained temperatures of the brush-contact device elements do not exceed the permissible temperature accepted at the level of insulation heat resistance class B (120 °C) according to DSTU IEC 60034-1 [6] to increase reliability and extend the service life of the turbo generator, despite the use of insulation materials of heat resistance class F (155 °C) in the design.

Three-dimensional calculation of the thermal state of a brush-contact device

The parameters of the cooling air of the brush holder device in a three-dimensional setting are determined using the SolidWorks Flow Simulation computational package [7]. For this purpose, a three-dimensional model of the brush-contact device was built, the design was considered as a whole.

The heat transfer coefficients are set automatically using the simulation of the cooling air flow. The following parameters are set as initial data:

– three-dimensional geometry of the computational domain (Fig. 4);
– pressure characteristic of a centrifugal fan, calculated in an analytical calculation;
– characteristic of the hydraulic resistance of filters, calculated in the analytical calculation;
– air parameters under normal conditions (Fig. 5);
– heat dissipation capacity separately for each element based on analytically calculated heat losses.

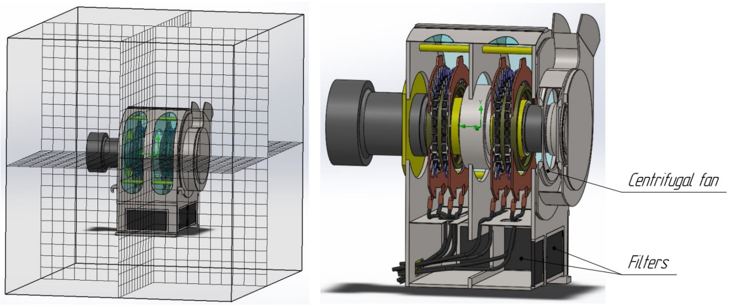

Fig. 4. Three-dimensional model of the computational domain

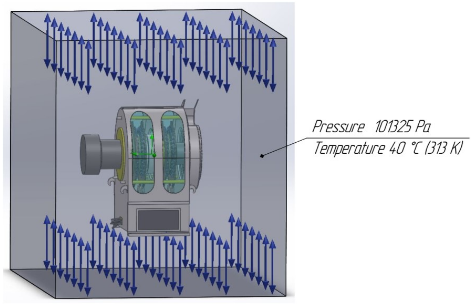

Fig. 5. Initial calculation conditions

The air flow simulation through the brush contact device was performed with the standard settings of the calculation grid detail.

The following values by volume were specified as the convergence criteria for the solution: minimum, average and maximum static pressure in the studied area; average mass flow rate; average heat flux on the specified surfaces; temperature distribution of air and structural elements of the brush-contact device.

The calculation was performed under the conditions of achieving the convergence criteria based on the results of at least three calculations of the studied area.

Based on the specified initial conditions, the cooling air flow simulation was carried out in the brush-contact device with installed filters.

The obtained trajectories and calculated air flow velocities are shown in Fig. 6, the flow velocities in the cross section are shown in Fig. 7.

The distribution of air temperatures in different parts of its trajectory within the calculation area is shown in Fig. 8.

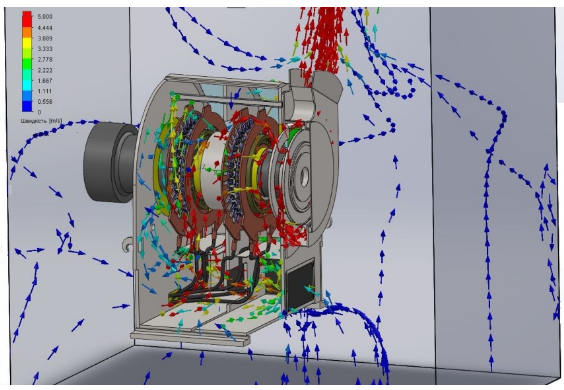

Fig. 6. Flow trajectories and velocities

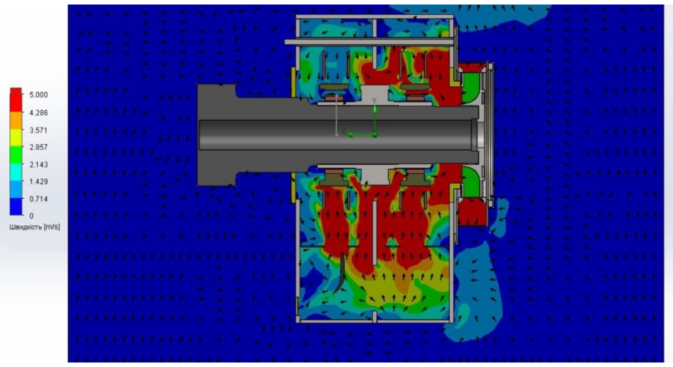

Fig. 7. Cross section and flow velocity

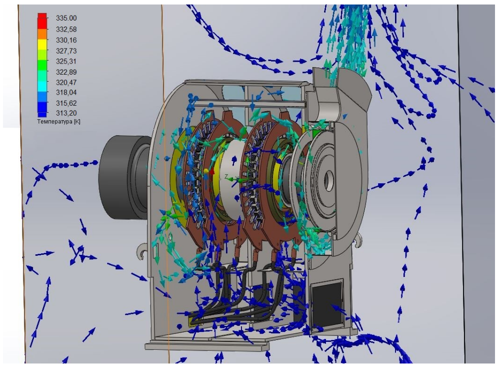

Fig. 8. Flow trajectories and temperatures

Below are the distributions of solid body heating temperatures for different current collector buses, with the numbering of buses taken in the direction towards the fan, i.e. bus No. 1 is the furthest, and bus No. 4 is the closest to it.

The heating temperature distribution of current collector bus No. 1 is shown in Fig. 9, the temperature distribution graph along the circumference of this bus is shown in Fig. 10.

The heating temperature distribution of current collector bus No. 4 is shown in Fig. 11, the temperature distribution graph along the circumference of this bus is shown in Fig. 12.

The temperature distribution on the surface of the slip ring is shown in Fig. 13.

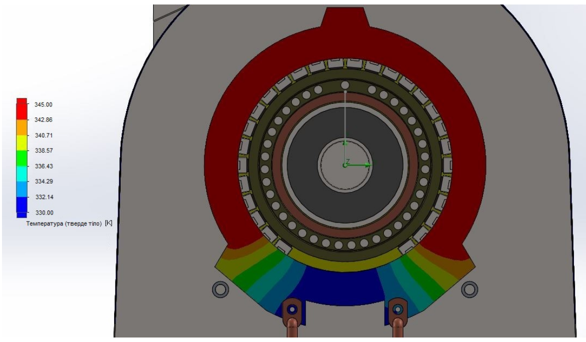

Fig. 9. Bus No. 1 temperature

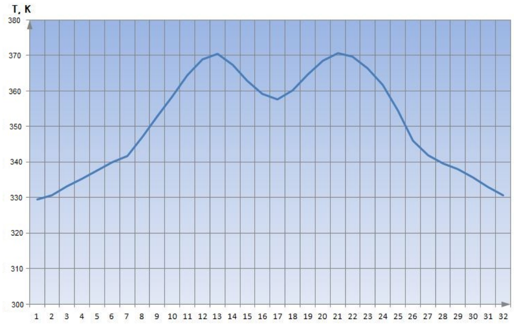

Fig. 10. Temperature distribution graph (bus No. 1)

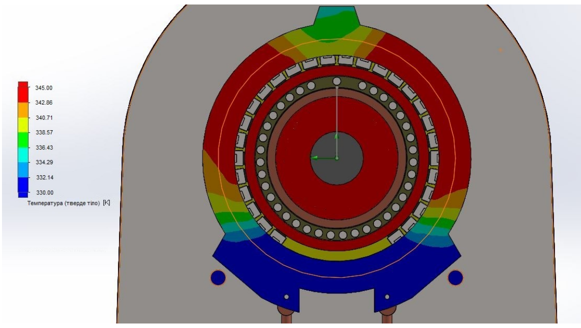

Fig. 11. Bus No. 4 temperature

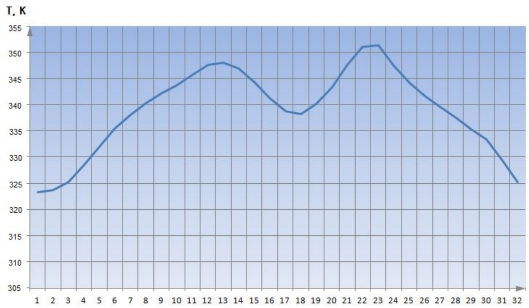

Fig. 12. Temperature distribution graph (bus No. 4)

Conclusions

Comparison of the results of the analytical calculation with the results of the analysis in three-dimensional formulation using the SolidWorks Flow Simulation software package indicates that the analytical calculation allows to obtain the correct averaged value of the temperature of individual elements, but does not give a complete picture of the temperature distribution between individual similar elements. The performed calculation in three-dimensional formulation allows to determine the temperature distribution of the elements of the brush-contact device, as well as the fact that it is associated with the peculiarities of the flow of cooling air in different parts of the ventilation duct and, accordingly, different cooling conditions for each individual section of the conductive parts.

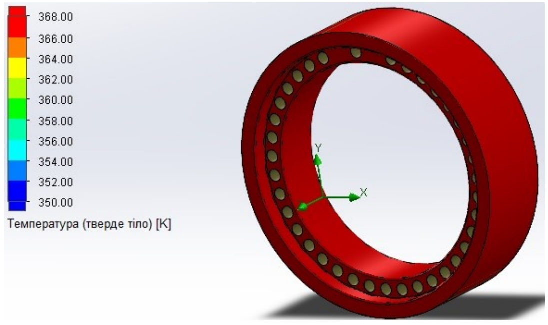

Fig. 13. Slip ring temperature

The maximum temperature of the conductive buses according to the analytical calculation is 89.4 °C, and according to the results of the three-dimensional calculation -97 °C (370 K). The maximum temperature of the slip rings according to the analytical calculation is 101.0 °C, and according to the results of the three-dimensional calculation -95 °C (368 K).

Thus, the temperatures of the conductive parts of the brush-contact device obtained in the calculation showed that when changing the design of the cooling system (installation of filters according to Fig. 4), the distribution of cooling air flows, air pressure in the system, thermal state of air and conductive parts will ensure the possibility of safe operation of the device in all permitted operating modes of the turbo generator in compliance with the conditions and at permissible temperatures at the level of insulation heat resistance class B (120 °C).

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Received 07 December 2024

Особливості розрахункового визначення теплового стану щітково-контактного апарату турбогенератора

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У даній статті розглянуті питання особливостей розрахункового визначення теплового стану щітково-контактного апарату турбогенератора. Автором наведений алгоритм аналітичного розрахунку апарату, визначені очікувані температури елементів за умови встановлення додаткових фільтрів у вентиляційному тракті. За допомогою методу скінченних елементів був виконаний тривимірний розрахунок теплового стану елементів щітково-контактного апарату. Отримані результати підтверджують можливість удосконалення конструкції щітково-контактного апарату за рахунок встановлення фільтруючих елементів з метою підвищення надійності роботи даного вузла.

***Ключові слова**: турбогенератор, щітково-контактний апарат, тривимірний тепловий розрахунок.*

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