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DEVISING A CALCULATION METHOD FOR MODERN STRUCTURES OF CURRENT-CONDUCTING ELEMENTS IN LARGE ELECTRIC MACHINES IN A THREE-DIMENSIONAL STATEMENT

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The jumpers of rotor pole-to-pole connections are highly stressed elements in a hydraulic generator structure. These assemblies often fail due to deformation that exceeds the size of an air gap. Existing methods do not take into account the thermal component and attempts to improve the design are not based on mathematical models that make it possible to perform calculations with an accuracy of more than 50 %. The method devised in this work makes it possible to obtain boundary conditions of the third kind on the basis of three-dimensional mathematical modeling of the ventilation system of the hydraulic unit without simplifications. The method accuracy is explained by taking into account the spatial thermal component. The heat transfer coefficient determined by this method in the pole-to-pole connections area was ~250 W/(m²·K). Using FEM, mathematical modeling of the thermal stress state of pole-to-pole connections was carried out, taking into account mechanical and thermal factors. This made it possible to design the improved connection structure with additional fastening elements, which make it possible to reduce the displacement to 0.03 mm, and the stress to 53 MPa at the rotor rotation frequency of 880 rpm. This design makes it possible to enable reliable operation of the hydraulic unit under the condition of increasing the rotor rotation frequency to overspeed with disconnected combinatorial dependence, provided that the actual stresses are 0.95 % of the material yield strength. The convergence of the values obtained by the proposed method and by the HSS method exceeded 99 %. The practical result is the proposals for the hydraulic generator design modernization

Keywords: hydraulic generator, rotor, pole-to-pole connection, pole-to-pole jumper, ventilation system of hydraulic generator, cooling conditions, stressed-strained state, three-dimensional calculation, strength of rotating parts

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1. Introduction

Current world trends in the study of electric machines are based on the use of three-dimensional approaches to the calculation of elements taking into account thermal boundary conditions and are aimed at obtaining effective solutions for improving structures, increasing their reliability, and reducing mass. The development and improvement of these approaches for the application of the study of the condition of electric machines, including hydraulic generators, is an extremely urgent issue.

A feature of hydraulic generator operation, which affects the design of all its elements, is the presence of a process that leads to exceeding the frequency of rotation of the rotor.

The reason for this is a structure solution in which the rotor is directly connected to the hydraulic turbine, the frequency of which can increase in the case of a sudden drop in the load on the hydraulic generator [1, 2].

Accordingly, all elements of the rotor in the hydraulic generator must be designed and calculated for a predefined excess of rotation frequency while the safety factor for average mechanical stresses must be at least 1.5 relative to the yield point of the material used [3, 4].

Given the above, it is a relevant task to carry out studies on the thermally exposed state of structural elements of hydraulic generators in order to increase reliability through a more accurate assessment of loads and temperature fields.

2. Literature review and problem statement

Works [5, 6] report general methods for calculating hydraulic generator ventilation systems based on the use of substitution schemes and finite volumes. The main drawback of the proposed methods in relation to the task of researching the thermal stress state of the current-conducting elements of the hydraulic generator is the impossibility of calculating the local heat transfer coefficients for parts about 30 m in size. The solution to the problems of determining the thermal state of individual components is presented in [7], in which the problem of cooling the support unit of the hydraulic generator is solved. In general, the development of the proposed algorithm could make it possible to make a preliminary assessment of the current-conducting elements located on the outer diametrical section of the rotor rim. The most difficult technological task of restoring a hydraulic generator is the task of restoring parts that have failed in the minimum amount of time. Work [8] reports the algorithm and principle of performing restoration technological operations. However, there is no specific mathematical apparatus that makes it possible to determine the performance of pole-to-pole jumpers. The task of cooling the pole-to-pole jumpers can be solved only in a three-dimensional setting since the deformation of the main objects will occur in three axes. Therefore, it is necessary to describe the boundary conditions and the turbulence model. The algorithm for selecting the parameters of the k-ε turbulence model for rotating parts is described in detail in [9]. However, it is not clear from the proposed analysis how this model would change for parts with a characteristic size of 5000 mm and 50 mm. Therefore, the ventilation task of finding boundary conditions should be considered separately. It is worth paying attention to work [10], in which a study of the ventilation system of the hydraulic generator was carried out. This solution can be applied subject to a more detailed analysis of the calculation grid parameters. The next important aspect of the problem of boundary conditions is the problem of heat release. Among the works worth noting are [11, 12], the results of which could allow us to set the necessary calculation parameters. Physical experiments are a necessary and sufficient parameter for determining the reliability of the obtained results. Studies [13, 14] present the concepts of conducting temperature studies of structures. The results obtained could make it possible to verify the data of the reported research. However, the lack of a gradient of temperature loads is an unsolved problem in these works. The main reasons for this were the difficulty of accurately calculating the turbulence parameters for the computing capabilities of the computer technology of that time.

For operating hydraulic units, there is a problem of frequent breakdowns of copper pole-to-pole connections [15]. At the same time, the existing solutions, typical of the design schools of countries such as the USA, Japan, Germany, Ukraine, etc., do not make it possible to fully solve this problem [16, 17]. Despite the insignificant geometric dimensions of these connections, their repair can last several weeks, and replacement requires further electrical tests of the rotor, which leads to the downtime of the hydraulic generator [18].

It is worth noting that in the classic mechanical calculation of the connection, which was carried out in accordance with the recommendations for the structure of hydraulic generators, there are a number of significant shortcomings. The main one is that the strength calculation is carried out in a one-dimensional statement and thermal factors are not taken into account, and the pole-to-pole jumper is calculated as a rigidly fixed beam. At the same time, the geometric characteristics are given by the concentration coefficients in an averaged form. These features of the calculation do not make it possible to take into account compensatory radii and deformations caused by thermal expansion [19]. In addition, no matter what type of fastening is chosen (soldering, bolted connection, fit with tension), previous technological stresses are not taken into account.

Existing algorithms do not provide reasonable accuracy, which in practice is expressed in the deformation of objects. At the same time, although the calculated values of the mechanical stresses do not exceed the permissible ones, the structure is actually destroyed. Therefore, it is advisable to devise a method that would enable an accurate calculation of the design of pole-to-pole connections. This method must provide justification for the ability of these connections to work at actual stresses of no more than 0.95 % of the material's yield strength.

3. The aim and objectives of the study

The purpose of our study is to devise a method for calculating the structures of current-conducting elements of large electric machines, which will take into account the geometry of the structure, the features of fastening components and mechanical loads (caused by centrifugal force), and thermal boundary conditions in a three-dimensional setting. This will make it possible to design a new structure of the inter-polar connection and to prepare proposals for modernizing the structure of current-conducting elements in high-power electric machines.

To achieve the goal, the following tasks were set:

– calculation of thermal boundary conditions for the coupled strength problem;

– research and design of an improved structure of the pole-to-pole connection, determination of parameters for strength calculation;

– determination of stresses and movements of the improved pole-to-pole connection under normal operating conditions due to the action of centrifugal force at rotation and heating;

– determination of stresses and displacements of the calculated plate of the improved pole-to-pole connection at the acceleration frequency of rotation due to the action of centrifugal force at rotation and heating;

– assessment of the reliability of the results obtained by the HSS (Hot Spot Stress) method.

4. The study materials and methods

The object of research is the structure of pole-to-pole connections.

The main scientific hypothesis of the study assumed the joint action of spatial electromagnetic, thermal, and mechanical forces. At the same time, it is necessary to take into account that for normal modes, the heat release is calculated for the main power of the unit. In turn, for critical modes, the base temperature is the maximum (as for the stationary mode), and there is no heat generation (protective automated systems instantly disconnect the excitation current).

Typical for the pole-to-pole connections of the hydraulic generator rotor is a design in which the rigid copper taps of the pole coils are connected by means of a flexible jumper in the form of a stack of thin-sheet copper plates (Fig. 1). These plates are fastened together by soldering in the middle part of the jumper. The jumper is usually attached to the coil taps with a solderless bolted connection to facilitate maintenance of the hydraulic generator rotor.

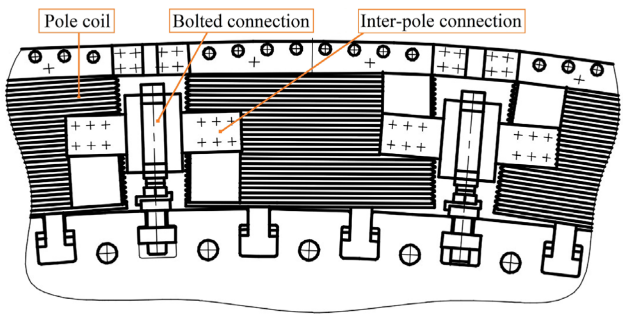

Fig. 1. Typical structure of a pole-to-pole connection

This jumper design allows for easy adjustment of its position during installation or repair in accordance with the actual position of the coil leads but has limitations in terms of mechanical strength. Therefore, in some cases, pole-to-pole jumpers require additional fastening to the rotor rim. The need for such fastening is determined on the basis of a preliminary mechanical calculation with determination of mechanical stresses and deformations of structural elements.

In another possible design, the pole taps are made flexible and are connected directly to each other. In such a case, due to the lack of rigid elements, the presence of fastening to the rotor rim becomes practically mandatory. Two types of pole-to-pole connections using cantilever and bolted connections are shown in Fig. 2, 3, respectively.

It should also be taken into account that for any design of additional fastening, the pole-to-pole connection itself must be electrically isolated relative to the rim [20].

Factors affecting the stressed-strained state of the pole-to-pole connection elements during operation are the following:

– normal mechanical loads caused by radial centrifugal forces;

– tangential mechanical loads caused by the presence of a tangential component of radial centrifugal forces due to the different angular position of the elements of the pole-to-pole connection on the rotor;

– thermal deformations caused by ohmic losses from the excitation current flowing in the jumper.

As a simplification, the study adopted the use of normal orthogonal forces without taking into account minor design features of the eccentricity position of the element distribution. In fact, it can be at the level of 0.5 angular degrees.

All the above loads are schematically shown in Fig. 4.

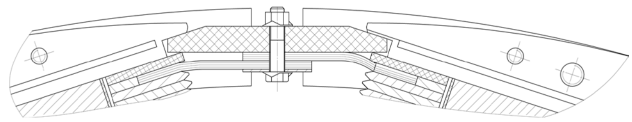

Fig. 2. Pole-to-pole connection using a cantilever mount

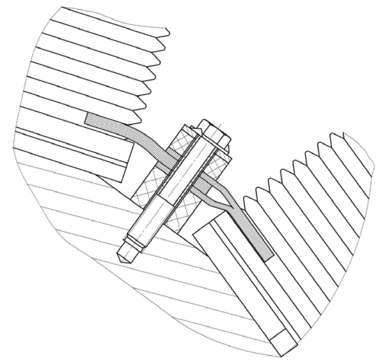

Fig. 3. Pole-to-pole connection using bolted connections

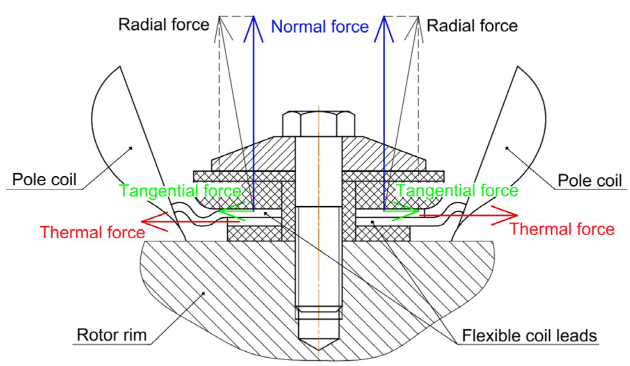

Fig. 4. Loads affecting the stressed-strained state of the pole-to-pole connection

The problem of analyzing the stressed-strained state of the pole-to-pole connection is solved in a three-dimensional statement [21]. At the same time, it is assumed that the problem of thermoelasticity is unrelated, which is explained by the relatively small heating of the generator design elements.

For the general case, three main problems are solved within the framework of three-dimensional modeling [22–24]:

– determination of heat exchange parameters of generator units by solving the three-dimensional problem of generator ventilation as a whole;

– determination of temperature fields in generator nodes;

– determination of the stressed-strained state of generator nodes under known force and temperature loads.

Fig. 5 shows a block diagram of the analysis of the stressed-strained state of the generator design elements based on three-dimensional modeling.

The three-dimensional problem of ventilation is considered taking into account the turbulence of the flow. This makes it possible to obtain refined local, rather than averaged, characteristics of heat exchange on characteristic surfaces. The problems of thermal conductivity and thermoelasticity are also solved in three-dimensional statements, which makes it possible to take into account the spatial nature of the distribution of stresses and deformations in the structure and more accurately determine the strength of the structural elements [25].

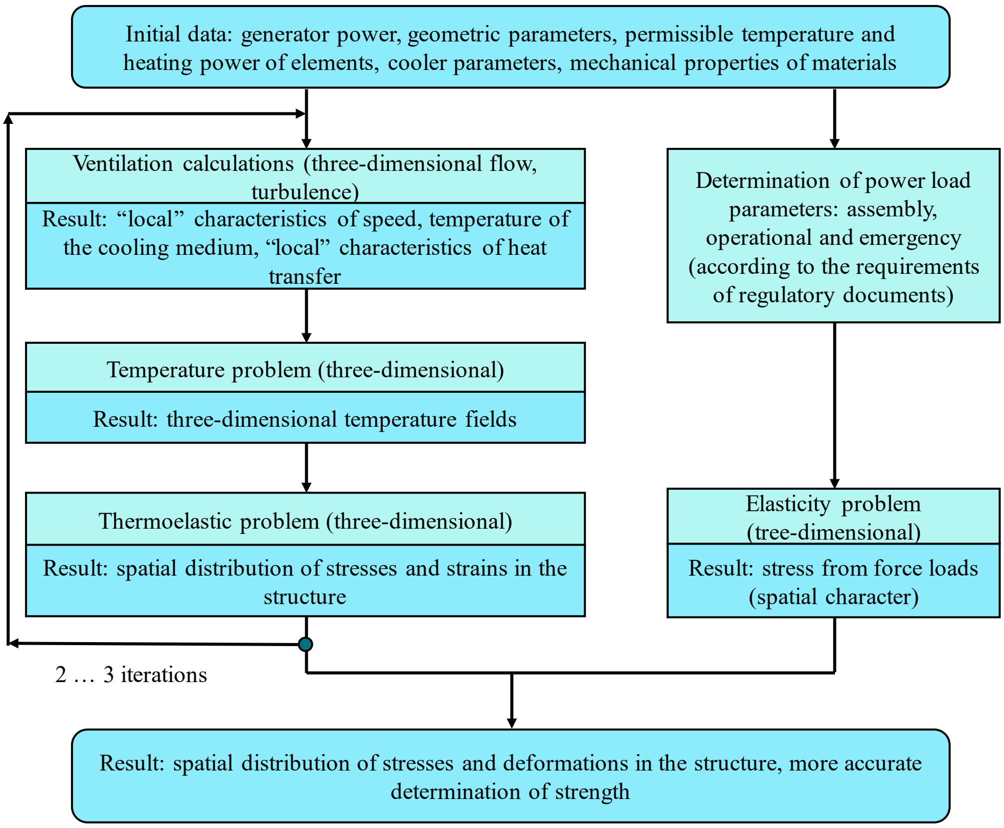

Fig. 5. Block diagram for analyzing the stressed-strained state of the generator design elements

At the first stage of solving the problem, the operation of the entire generator ventilation system is calculated, taking into account its real geometry and according to the specified, based on regulatory documents, temperatures of the generator nodes [26]. The speeds of their flow around the cooler are determined and the heat exchange coefficients are set based on analytical dependences. At the next stage, the thermal problem is solved and the real temperatures on the surfaces of the nodes are specified. A new calculation of the ventilation system is carried out taking into account the given temperature values, after which the thermal problem is solved again. This calculation is repeated until the solutions on two adjacent iterations do not differ by more than 5 %.

At the final stage, based on the already known temperature field and power load, the thermal strength of the generator nodes is calculated.

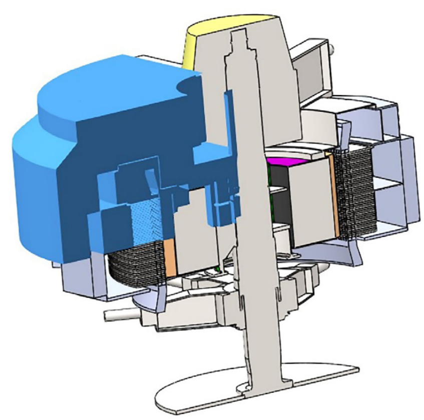

Fig. 6. Three-dimensional calculation model of the hydraulic generator ventilation system

5. Results of investigating the strength of the pole-to-pole connection

5. 1. Calculation of thermal boundary conditions for the bound strength problem

The three-dimensional calculation model of the hydraulic generator ventilation system, which was used to calculate the thermal limit conditions, is shown in Fig. 6. The calculation area is marked in blue.

Fig. 7 shows the calculated fan; the air flow at the fan inlet is indicated by a blue arrow, the air flow at the fan outlet is indicated by a red arrow. The calculated parameters of the fan are as follows:

– volumetric air consumption – 40 m^3/s;

– pressure drop – 1500 Pa.

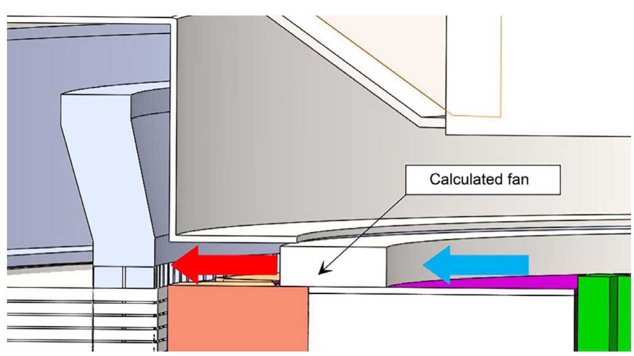

Fig. 7. Fan

Fig. 8 shows the air cooler; the red arrow indicates the incoming flow of heated air; the blue arrow indicates the cooled air at the outlet of the air cooler. The estimated pressure drop in the air cooler is 250 Pa.

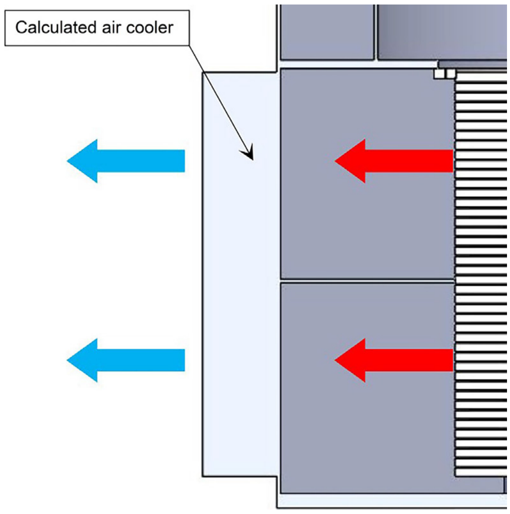

Fig. 8. Estimated air cooler

To obtain detailed calculation data, a study of the entire hydraulic generator was conducted [27]. Fig. 9 shows the calculation model of the hydraulic generator and grid parameters. In the calculation, optimization of narrow channels with improvement of the resolution of the calculation grid was performed. Symmetry conditions are set on the boundaries of the calculation grid.

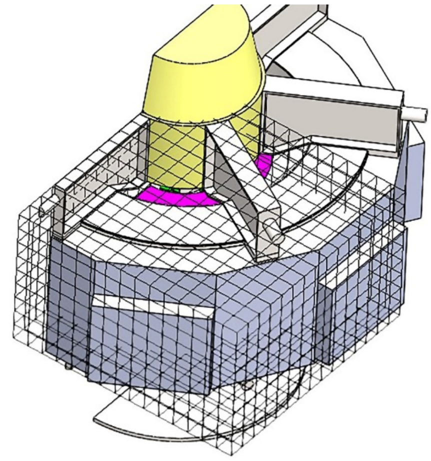

Fig. 9. Calculation model of the hydraulic generator and grid parameters

Fig. 10, 11 show selected calculation results in the cross-section of the structure in the area where the pole-to-pole connections are located.

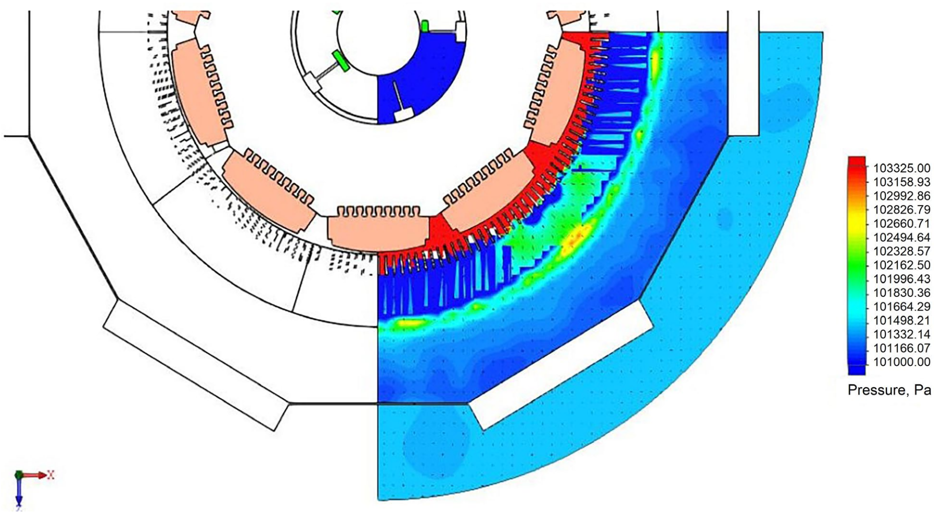

Fig. 10. Cooling air pressure parameters

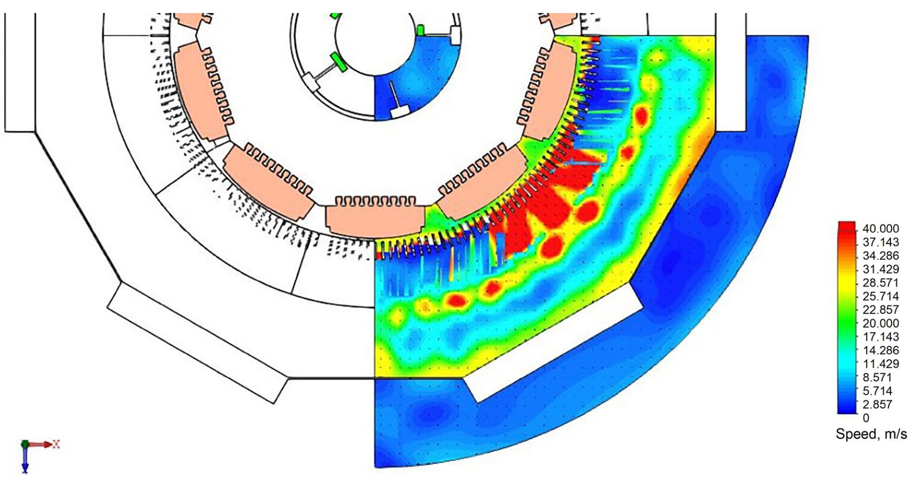

Fig. 11. Cooling air velocity parameters

The heat transfer coefficients are determined based on the obtained air velocities in the area of the pole-to-pole connections according to the known solution obtained for the plate.

The heat transfer coefficient is determined from the ratio:

$$\alpha = \frac{Nu \cdot \lambda}{\nu}, \quad (1)$$

where Nu is the Nusselt number; λ – specific thermal conductivity of air; ν is the kinematic air viscosity coefficient.

The Nusselt number is related to the Reynolds number by the formula:

$$Nu = 0.032 \cdot Re^{0.8}. \quad (2)$$

Reynolds number:

$$Re = \frac{W \cdot l}{\nu}, \quad (3)$$

where W is the cooling air movement speed, m/s, determined by the results of the ventilation calculation; l is the determining dimension, m (the length of the pole-to-pole connection).

The physical parameters of air at P=101325 Pa and T=40 °C are:

– specific thermal conductivity λ=0.0276 J/(kg·K);

– kinematic coefficient of viscosity ν=0.00001696 m^2/s.

According to our calculation, the heat transfer coefficient a was ~250 W/(m^2·K).

In this part of the study, the boundary conditions of the mixed type and the parameters of the cooling air were calculated, and the initial data were selected to determine characteristics for the main materials of the pole-to-pole connection.

5. 2. Research and construction of an improved design of the pole-to-pole connection, determination of parameters for strength calculation

Fig. 12 shows the basic structure of the pole-to-pole connection. It should be noted that the existing loosening of the copper plates is caused by an incorrect assessment of the stressed-strained state of the basic structure. One of the significant disadvantages of the basic design selection is the lack of calculation of deformations.

Fig. 12. Basic design of the pole-to-pole connection

Taking into account the shortcomings found during hydraulic generator operation, it is proposed to revise the design in such a way as to increase the bending radii of the jumpers, reduce the height of the indentation (to reduce the centrifugal force), and also reduce the mass of the metal part of the fastener. The adjusted structure of the pole-to-pole connection under investigation is shown in Fig. 13.

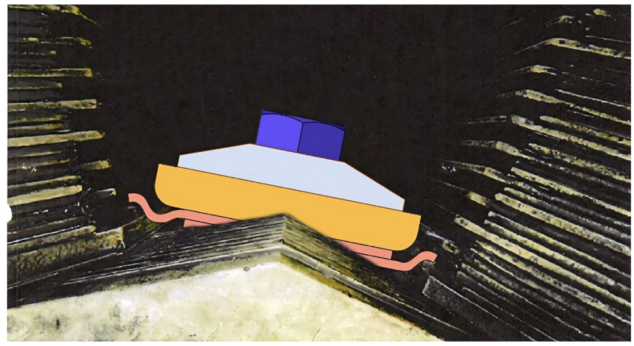

Fig. 13. Structure of the advanced pole interconnection under investigation

For the calculation, the heating parameters of the node due to the passage of current are set. Based on the known frequency of rotation of the rotor, heat transfer coefficients are determined and the temperature distribution on the surface of the body is specified. The speed of the cooling air when working under critical modes can vary and is determined from the following formula:

$$\upsilon_{surface} = \varphi(t). \quad (4)$$

The calculation is carried out using the constructed three-dimensional model of the pole-to-pole jumper. Grid parameters and boundary conditions for static analysis are shown in Fig. 14 (the fixing of taps to the coils and the fixing of part of the rotor rim is marked in green).

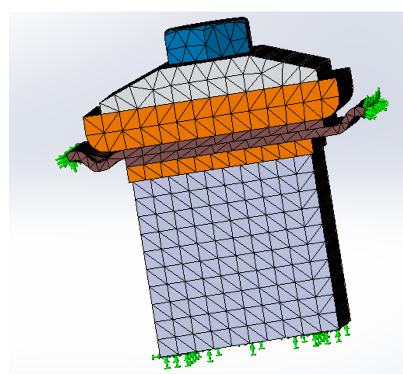

Fig. 14. Finite element grid

The raw data used in the calculation are given below.

Frequency characteristics:

– rated rotation frequency n=600 rpm;

– acceleration frequency n_p=880 rpm.

Calculation parameters:

– calculated ohmic losses in the pole-to-pole connection from the excitation current P=16.2 W;

– the temperature of the cooling medium T=40 °C.

Mechanical properties:

– jumper material – DPRNM sheet 3.0 M1 DSTU GOST 1173:2007 with yield strength σ_{02}=70 MPa;

– the material of the pad is glass textolite STEF-I with yield strength σ_{02}=100 MPa;

– the moment of tightening the bolt connection corresponds to a stress of 100 MPa.

Mathematical modeling was carried out for a rated rotation frequency of 600 rpm and for mechanical load of 880 rpm. The problem was solved in a static statement. Ventilation calculations are not carried out for acceleration speed since the operation of the hydraulic unit under this mode is limited by the time (up to one minute), during which the automatic protection systems of the hydraulic generator turn off the current loads. Despite the short time of operation in this mode, the technical requirements of the manufacturing plant require confirmation of the possibility of operation of the hydraulic unit under a steady mode in order to exclude fatigue destruction of the structure.

The determined parameters will be used to calculate the structure shown in Fig. 13. These calculations will make it possible to theoretically substantiate the capability of the improved design to enable normal operation of the connection at the rated and acceleration frequency of rotor rotation in the hydraulic generator.

5. 3. Determining the stresses and displacements of the improved pole-to-pole connection under normal operating conditions

The finite element method, implemented in the SolidWorks Simulation software package, was used to analyze the strength of the node under all modes of its operation, taking into account the thermal state.

The most critical elements for this design are the flexible pole-to-pole connections themselves. The result of the three-dimensional calculation of the connection at the rated frequency of rotation of the rotor is the determined stresses and displacements in them. Stress diagram in the pole-to-pole connection at a rotation frequency of 600 rpm is shown in Fig. 15.

Fig. 16 shows the displacement field in the pole-to-pole connection at a rotation frequency of 600 rpm.

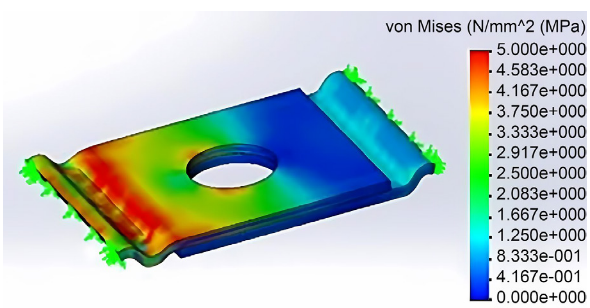

Fig. 15. Diagram of stresses in a pole-to-pole connection

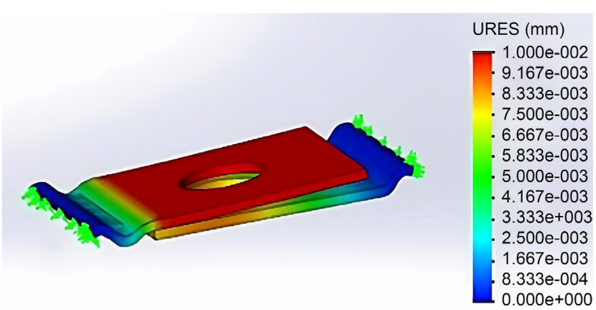

Fig. 16. Diagram of displacements in an pole-to-pole connection

Thus, our calculation of the thermally stressed state of the pole-to-pole connection for the considered mode of generator operation showed that the average stresses in the jumpers do not exceed 50 MPa, the maximum displacements in the structure do not exceed 0.01 mm.

5. 4. Determining the stresses and displacements of the calculated plate in the improved pole-to-pole connection at the acceleration frequency of rotation

The design of the elements of the rotor group must withstand an accelerating rotation frequency of 880 rpm, and a design feature of the taps of the coils of the rotor poles is their assembly from a group of plates with a thickness of 0.5 mm. In this regard, it is necessary to consider the stressed-deformed state of one plate, located between the fixings of the coil lead (Fig. 17).

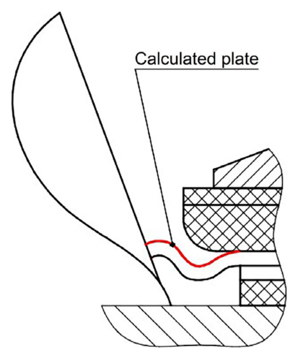

Fig. 17. Estimated plate

The results of calculating the stresses in the estimated plate at the acceleration speed are shown in Fig. 18.

The diagram of movements for the estimated plate at n_p=880 rpm is shown in Fig. 19 (initial state of the plate is marked in gray, scale factor 350).

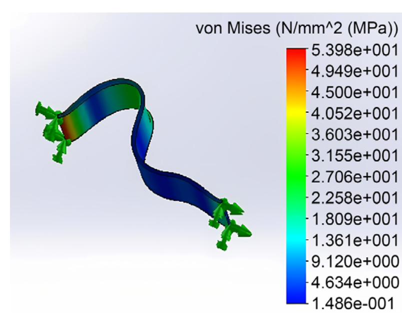

Fig. 18. Stress diagram in the estimated plate at n_p=880 rpm

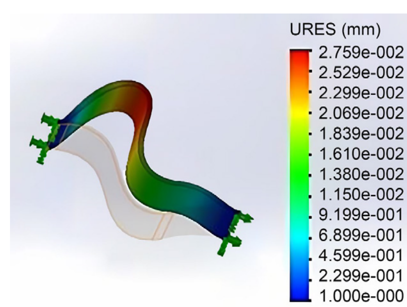

Fig. 19. Diagram of movements for the estimated plate at n=880 rpm

Thus, our calculation of the pole-to-pole connection at the acceleration speed showed that the average stress in the jumpers does not exceed 53 MPa, and the maximum displacements in the structure do not exceed 0.03 mm.

It should be noted that the obtained maximum stresses and displacements occurring in the structural elements of the pole-to-pole connections under all calculated modes of operation are permissible under the conditions of mechanical strength.

5. 5. Verifying the reliability of results obtained by the HSS method

To eliminate the singularity when determining the concentrator stresses using the HSS method [28], a grid is used with the dimensions of the elements near the place of attachment of the coil lead (stress concentrator) not exceeding half the thickness of the lead *t*. The stress is determined at a distance of 0.5*t* and 1.5*t* from the place of attachment (Fig. 20).

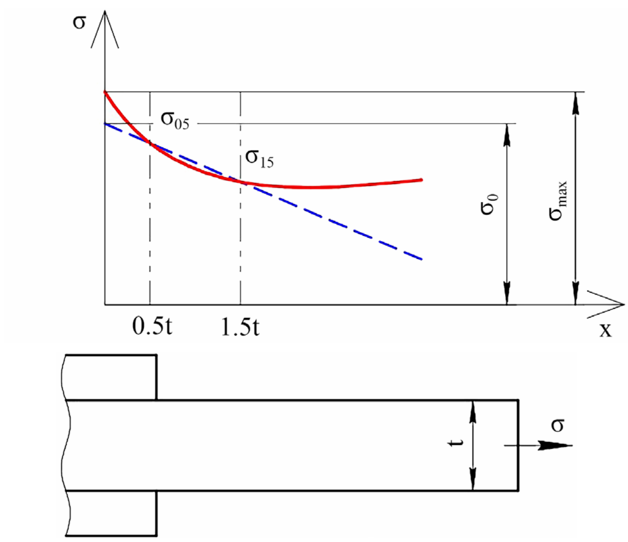

Fig. 20. Applying the HSS method for determining geometric stresses

The interpolation line (AB) is located perpendicular to the direction of the end part of the fastener. The grid step is chosen so that the test values of stresses σ_0 and σ_{15} are calculated in different elements. Rated (geometric) stresses σ_0 in the concentrator are determined by linear interpolation according to the formula:

$$\sigma_0 = 1.5\sigma_{05} - 0.5\sigma_{15}. \quad (5)$$

The results of the HSS analysis for the pole-to-pole jumper are shown in Fig. 21.

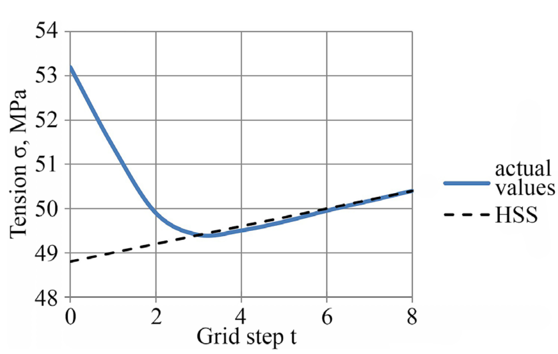

Fig. 21. Results of using the HSS method to determine geometric stresses

Our calculation results demonstrate that in pole-to-pole connections calculated by the HSS method, the rated (geometric) stresses in all elements do not exceed 53.2 MPa for copper parts.

6. Discussion of results related to investigating the strength of the pole-to-pole connection

The current research has made it possible to obtain external boundary conditions based on criterion equations for calculating the thermal stress state of pole-to-pole connections. This made it possible to model actual thermal deformations and thermal stresses of the structure and to take into account their effect in pole-to-pole connections. The proposed method could be used to calculate the connected problem of the design elements of the rotor group of large electric machines. In turn, the algorithm described in works [5, 6] makes it possible to calculate only averaged thermal parameters.

Existing designs of pole-to-pole connections were considered, and it was established that the existing structure of pole-to-pole jumpers cannot withstand the forces caused by the centrifugal force that occurs when the rotor rotates. It was found that a new form of structure with heat compensators is needed. But the reliability of such a structure needs to be substantiated by three-dimensional methods of mathematical modeling, which will take into account the spatial distribution of forces. Taking into account the results reported in [11, 12], it was possible to find a way to design an optimal structure and improve methods of thermal stress calculation. A proposal for the modernization of the design of current-conducting elements of high-power electric machines is the use of the developed (Fig. 13) modified structure of the pole-to-pole connection. This structure includes additional fasteners that reduce displacement to 0.03 mm and stress to 53 MPa. This makes it possible to enable reliable operation of the hydraulic generator under the condition of increasing the rotor rotation frequency to acceleration with a disconnected combinatorial dependence, provided that the actual stresses are 0.95 % of the yield strength of the material (copper).

According to the technical requirements for the design and operation of hydraulic units, the parameters for calculating the strength of the pole-to-pole connection have been determined. The parameters were determined for normal operating conditions and for an emergency mode with disconnected combinatorial dependence of the turbine and the hydraulic generator.

A method of calculating modern structures of current-conducting elements of large electric machines has been devised, which takes into account the geometry of the structure, the features of fastening components and mechanical loads, and thermal boundary conditions in a three-dimensional statement. This made it possible to calculate the actual stresses and displacements in the pole-to-pole jumpers (Fig. 15, 16, 18, 19) and to theoretically substantiate the performance of the designed improved structure of pole-to-pole connections.

Comparison of the results of three-dimensional calculations in pole-to-pole connections with the results calculated by the HSS method showed a high convergence. The rated (geometric) stresses obtained by the HSS method in all elements of the pole-to-pole connection do not exceed 53.2 MPa for copper parts, that is, they are permissible. The diagram in Fig. 21 shows that the actual results of our research coincide with the trend line obtained by the HSS method. Based on this, it can be concluded that the results are reliable.

The availability of modern computer equipment with high computing power (multi-core processors, cluster systems) made it possible to solve three-dimensional problems without introducing additional symmetry conditions in acceptable time intervals. This makes it possible to take into account the imbalance in the design of components of electric machines, caused by the presence of elements of additional fasteners. Previously, these elements were introduced as additional masses or were not taken into account at all.

The use of an improved structure of the pole-to-pole connection with thermal compensators and more rigid fasteners can be implemented at the hydroelectric units by PRAT «UKRHIDROENERGO». Replacement of existing connections with improved ones can be carried out during full or partial replacement of current-conducting components during planned and preliminary repairs without long-term decommissioning of the hydraulic unit. The practical value of the work is in improving reliability and increasing the period of operation between planned repairs of the hydraulic generator due to the use of a new connection design. As a result, it will reduce the economic costs caused by the removal of hydraulic units from operation with their subsequent repair and testing.

The pole-to-pole connection structure designed according to the devised method of three-dimensional modeling meets the requirements of EN IEC 60034-33:2022 [20] for thermal and mechanical standards.

The disadvantage of this work is that only a static problem was solved. Inertial force and shock loads on the short-circuit connection were not taken into account.

A further development of this research may be the introduction of trend lines obtained during full-scale tests of hydraulic generators at power plants.

7. Conclusions

1. In the course of the study, thermal boundary conditions were calculated in a three-dimensional statement. Three-dimensional values of heat transfer coefficients in characteristic sections were calculated using classical criterion equations. Based on the obtained air velocities in the area of the location of the pole-to-pole connections according to the known solution obtained for the plate, the heat transfer coefficient a was ~250 W/(m^2·K).

2. Based on the basic design of the pole-to-pole jumper, a structure with thermal compensators and more rigid fasteners was developed. The mechanical characteristics of the main materials of the pole-to-pole connection were also determined: the jumper material is a copper sheet with a yield strength of σ_{02}=70 MPa; the pad material is fiberglass with a yield strength of σ_{02}=100 MPa. The tightening torque of the bolted connection corresponds to a stress of 100 MPa.

3. We have obtained displacements up to 0.01 mm and mechanical stresses up to 50 MPa in the pole-to-pole connection under normal operating conditions. The maximum stresses and displacements are permissible under the conditions of mechanical strength.

4. Displacements of up to 0.03 mm and mechanical stresses of up to 53 MPa in the pole-to-pole connection at the acceleration speed of the rotor were obtained. The maximum stresses and displacements are admissible under the conditions of mechanical strength and provide a theoretical basis for the operation of the improved structure. This makes it possible to provide reliable operation of the hydraulic unit under the condition of increasing the rotor rotation frequency to acceleration with a disconnected combinatorial dependence, provided that the actual stresses are 0.95 % of the yield strength of the material.

5. The reliability of the results of our calculation of the strength of pole-to-pole connections has been estimated by the HSS method. The calculations showed that the convergence of the obtained values is at the level exceeding 99 %, which indicates the high quality of our research results.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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