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Thermomechanical loads of powerful turbogenerator stator winding insulation in the presence of water cooling defects

Introduction. *An analysis of incidents linked to power units' emergency disconnecting from network as a result of turbogenerators' malfunction on the NPP of Ukraine is conducted. It is identified, that the reason of the majority of incidents is an insufficient reliability of the stator winding's direct cooling system.* ***Problem.*** *The most problematic point in winding for today is the frontal parts, where, while cooling is reduced, there are not only thermal, but also thermomechanical loadings on an insulation appearing. The level of these loading depends on structural design of frontal parts and a character of violation of coolant agent circulation in a bar. In some cases they can exceed limit values. The spread and the quality of research on this issue for today are insufficient.* ***Goal.*** *The aim of the completed research is to determine the thermomechanical loading of insulation of stator winding bar in a powerful turbogenerator with a direct liquid cooling under condition when coolant circulation is malfunctioned.* ***Methodology****. A complex mathematical model of thermomechanical processes in an insulation of stator winding bar of a powerful turbogenerator is developed. It takes into account the real geometry of the winding bar, variable thermal loading of core elements in radial and axial directions, as well as ways of fixation of slot and frontal winding parts. Studies of thermomechanical processes in an insulation of stator winding bar of turbogenerator are conducted.* ***Results****. Values of mechanical displacement and stress for the different modes of malfunction are obtained. Areas of bar, where mechanical loading may exceed the boundaries of mechanical durability of material of insulation of stator winding are identified. With decline of coolant liquid consumption the radial displacement and stress in the winding insulation bar in the area, where the bar exits from the slot are increasing along with that the values of radial stress of insulation of the winding bar in places of frontal parts' fixation exceed limit values.* ***Practical significance.*** *The offered mathematical models allow to realize calculation experiments and can be used in practice for development and validation of diagnostic systems, analysis, design and investigation of emergency situations during exploitation of turbogenerators on power stations of Ukraine.* References 20, table 1, figures 8.

Key words: **turbogenerator, stator winding, water cooling, violation of circulation, thermomechanical loading.**

Проведено аналіз інцидентів на АЕС України, пов'язаних із аварійним відключенням енергоблоків від мережі внаслідок відмов турбогенераторів. Встановлено, що причиною більшості із них є недостатня надійність системи безпосереднього охолодження обмотки статора. Найбільш проблемним вузлом обмотки на сьогодні є лобові частини, де при порушеннях охолодження окрім теплового виникають термомеханічні навантаження ізоляції. Рівень цих навантажень залежить від конструктивного виконання лобової частини і характеру порушення циркуляції холодоагенту в стержні. В деяких випадках вони можуть перевищувати граничні значення. Кількість і якість досліджень з цієї проблеми на сьогодні є недостатніми. Метою виконаного дослідження є визначення термомеханічних навантажень ізоляції стержня обмотки статора потужного турбогенератора з безпосереднім рідинним охолодженням при порушеннях циркуляції холодоагенту. Розроблена комплексна математична модель термомеханічних процесів в ізоляції стержнів обмотки статора потужного турбогенератора, що враховує реальну геометрію стержня обмотки, змінні теплові навантаження елементів осердя в радіальному та аксіальному напрямках, а також умови закріплення пазової та лобової частин обмотки. Проведені дослідження термомеханічних процесів в ізоляції стержня обмотки статора потужного турбогенератора. Отримані значення механічних переміщень і напружень для різних видів порушень. Встановлені ділянки стержня, на яких значення механічних навантажень при певних умовах можуть перевищувати межі механічної міцності матеріалу ізоляції обмотки статора. Зі зниженням витрати дистиляту збільшуються радіальні переміщення і напруження в ізоляції стержня обмотки в зоні виходу стержня із паза. При цьому значення радіальних напружень в ізоляції в місцях закріплення лобових частин перевищують припустимі значення. Запропоновані математичні моделі дозволяють реалізувати обчислювальні експерименти і можуть бути використані на практиці для створення та відпрацювання систем діагностики, аналізу, моделювання і розслідування аварійних ситуацій при експлуатації турбогенераторів на електростанціях України. Бібл. 20, табл. 1, рис. 8.

Ключові слова: **турбогенератор, обмотка статора, водяне охолодження, порушення циркуляції, термомеханічні навантаження.**

Introduction. The analysis of incidents related to unplanned emergency disconnections of power units of NPPs of Ukraine from the network and load reduction shows that a significant share of them (from 30 to 70 %) is the result of insufficient reliability of electrical equipment.

The largest share in underproduction of electricity due to failure of electrical equipment is accounted for by turbogenerators (TGs) (up to 70-80 %), relay protection and automation devices (up to 15 %), measuring transformers (up to 7.5 %), electric drive (5.8 %) and power transformers (up to 2.5 %) [1]. That is, TGs are currently the most problematic (unreliable) from the point of view of underproduction of electricity, since each TG damage leads to long and expensive repairs.

The creation of high-power TGs would be impossible without the use of modern cooling systems for the most electromagnetically loaded nodes. First of all, it concerns the stator winding. The introduction of direct liquid (water) cooling of the stator winding rods made it possible to increase the linear load up to 3000 A/cm and, as a result, to increase the unit power of power units, in particular nuclear power plants. Today, the unit power of most power units of nuclear power plants of 1000-1300 MW is a common phenomenon.

TGs with water-cooled windings have an increased risk of clogging the cooling channels (fouling process). Analysis of information on the occurrence and development of thermal defects of the TG stator windings shows that all of them are related to cooling disorders. The most dangerous violation is partial or complete blockage of the cooling channels. The main causes of this phenomenon are deposits in the water channels and the ingress of hydrogen into the distillate. When hollow conductors are blocked, their temperature can significantly exceed the permissible level [2].

A statistical analysis of data from the experience of operating powerful TGs with direct cooling of the stator winding shows that the share of failures associated with a violation of the circulation of the distillate in it is 10-20 % of the total number. And the idle time of the power unit for this reason takes about 12 % of the total [3]. In specific value, such failures are inferior only to failures caused by the loosening of the extreme packages of the stator core [4].

According to a large-scale study [5], more than half of all generator failures are related to insulation damage. The effect of high temperatures reduces the electrical and mechanical strength of the insulation due to accelerated thermal aging processes.

According to the results of inspections at power plants [6], 10 rods with reduced distillate consumption were found at 6 out of 15 TGs with direct cooling of the stator winding with power of 320 MW. That is, almost every third generator in operation has rods with clogged cooling channels and distillate consumption below technical standards. This is especially dangerous for TGs of maximum power (800 MW and above), since the current density in them is 2-2.5 times higher. In seven stator winding rods of the TVV-1000-4 type generator, a decrease in distillate consumption below the minimum permissible level was found. One rod of TVV-800-2 had a distillate flow significantly below the minimum acceptable level (about 72 % of the nominal), in two rods the reduction of the distillate flow reached 81 % and 51 % of the nominal.

There are known cases of TG damage caused, among other things, by a violation of the refrigerant circulation due to partial and complete blockage of empty conductors. A final event common to these cases, which requires significant financial and time costs for repair and elimination of the consequences, is a breakdown of the main insulation (in particular, the accident of the TVV-1000-4 type generator of power unit No. 1 of the Kalinin NPP, 1988; the breakdown of the insulation of the stator winding rod of the TVV-500-2U3 generator of the Chernobyl NPP, 1994; the accident of the generator type TVV-1000-2Y3 at Khmelnytska NPP, 1997; emergency disconnection from the network of unit No. 3 of the South Ukrainian NPP due to damage to the upper rod of the stator winding of the generator type TVV-1000-2Y3, 2003; emergency disconnection of the generator of power unit No. 1 of Khmelnytska NPP due to an unacceptable increase in the temperature of the stator winding rod during the execution of the program of start-up operations, 2019, etc.). Cases of clogging of the hollow conductors of the stator winding of four-pole generators of the NPP with power of 1000 MW were also recorded.

Problem definition. Since 2011, 10 out of 13 power units of the NPP of Ukraine have been inspected for the condition of the equipment and a set of works has been carried out to extend the terms of their operation. Among them, the mentioned measures also applied to electrotechnical equipment, including TGs and their support systems. The result of the performed works was the extension of the life of power units by another 20 years beyond the standard (30 years).

However, starting in 2016, the number of TG failures began to increase [1]. Moreover, this applies to machines with power of 1000 MW both in two-pole and four-pole versions. In particular, the damage rate of four-pole TGs with power of 1000 MW in the period 2015-2019 compared to 2006-2010 [7] increased threefold. The analysis of the available data allows us to conclude that the reliability indicators of three two-pole TGs out of five and three four-pole ones out of eight do not meet the requirements of GOST 533-2000.

Today, one of the main problems identified during the operation and repair work of generators of the TVV-1000-4Y3 type is depressurization of the winding rods (zone I in Fig. 1). Most of the cases of depressurization of the winding are detected during the period of planned and preventive repairs, and only in six cases the loss of hermeticity of the winding led to emergency shutdowns of power units. The ingress of distillate into the body insulation during the flow of elementary conductors causes its gradual moistening and leads to its electrical breakdown. The rod fails. Whereupon – long-term repairs with significant economic costs. Table 1 shows the damage indicators of TGs type TVV-1000-4Y3 of power units of NPPs of Ukraine in 2015-2019. The specific damage rate of TGs in the four-pole design of type TVV-1000-4Y3 was 0.24 damages per generator year of operation [1].

Since TGs are one of the most responsible objects that ensure the functioning of the electric power system, the main efforts of specialists are directed to research of electromagnetic and thermal processes, force interactions, and the level of magnetic losses in the cores of stators of various designs [8-11]. However, the analysis of the thermomechanical loads of the stator winding elements under different operating conditions of the TG is also essential and important.

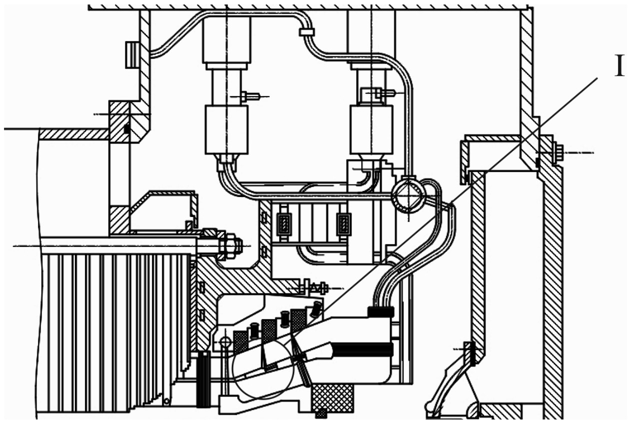

Fig. 1. The end zone of the TG stator of the TVV-1000-4Y3 type

Table 1
Indicators of damage of TGs type TVV-1000-4Y3

Number at the NPPs of Ukraine	8
Number of damage	6
Underproduction of electricity, million kW·h	2230

One of the nodes of the TG with increased damage is the end zone of the stator (Fig. 1), on the elements of which a complex of significant nonuniformly distributed electromagnetic, thermal and thermomechanical loads is concentrated. In connection with this, the actual task of the performed research is to determine the influence of these loads on the reliability of the elements of the end part of the stator winding at the exit from the core slot and in the area of its fastenings when the circulation of the refrigerant in the core is disturbed (zone I, Fig. 1).

The occurrence and development of most thermal defects of the stator winding are associated with cooling disorders. Here, overheating is dangerous not only due to an increase in the probability of a thermal breakdown of the body insulation, but also due to the thermomechanical effect on the elements of the conductors and insulation of the winding, due to the limitations of the thermal expansion of the rod [12].

Significant temperature gradients lead to the emergence of thermoelastic forces, and thermomechanical stresses may exceed the allowable rupture values for the corresponding structural materials. In a number of cases, a defect in the circulation of cooling water in the winding is detected when the process of intensive destruction of the body insulation is already taking place, which leads to its breakdown and a serious accident. Therefore, thermal and thermomechanical aspects of the survivability of high-power generators are among the most important issues subject to experimental research in the coming years [13].

In practice, thermomechanical processes in powerful TGs are modeled mainly by approximate analytical expressions or based on 1D rod calculation schemes.

In [14], the impact of the features of fixing the stator winding in the slot and frontal parts, the reduction of the level of frictional interaction between the winding and the teeth in the end zone at a certain length L_c on the nature of the core pressing pressure distribution was analyzed based on the results of calculations based on the eight-bar 1D model. The considered design with some equivalent thermal and mechanical parameters is considered symmetrical with respect to the middle of the stator. Here, it is assumed that all model's rods are heated uniformly along the length and bore of the stator; the body insulation and the electrically conductive part of the rod do not have mutual axial movements (displacements); the teeth and the back of the core are one whole. Thermomechanical processes are described by a system of 1D differential equations in the axial coordinate x. According to the results, it was concluded that the displacements of the stator winding in the slots lead to mechanical loading of the frontal parts and their fastening elements. These loads are all the greater, the higher the rigidity of the fastening of the frontal parts and the lower the density of fastening the rods in the slots.

The analysis of the results of thermomechanical studies in powerful TGs allows us to conclude that the choice of their parameters is crucial for the theoretical justification of 1D rod calculation schemes. A number of their combinations can usually be obtained only on the basis of the results of experimental studies, which, in turn, are extremely difficult to conduct on real objects in real operating conditions. A number of problems remain unsolved, associated with a relatively high deviation of the calculated results from the field test data, which may be unacceptable for assessing the mechanical condition of the responsible elements of the stator. Therefore, further improvement of approaches to modeling the strength characteristics of the latter is an urgent scientific and technical task.

Assessing the direct mechanical condition of the insulation system is difficult without building correct models of the connected elements of the stator, primarily the core and winding rods, which is due to the high level of model discretization.

In [15], using combined (numerical-analytical) thermomechanical models, mechanical stresses of thermal origin are investigated in a sectioned two-layer bulk winding made of 0.9 mm copper wire, impregnated with epoxy resin, on a segment of a 6-pole stator of a compact reactive machine. The dependencies of stress changes on the coefficient of linear temperature expansion and the coefficient of filling the slot with copper are given. It is noted that at high temperature of copper, stresses can significantly exceed the yield and strength limits of polymer coatings and lead to their destruction.

The paper [16] examines the process of pressing the coils of the stator winding of electric machines under high pressure in order to increase the filling factor of the slots and its effect on the insulation of the conductor of a thermoset polymer film with thickness of 0.05 to 0.1 mm (deformation and thermal conductivity). To predict the effective thermal conductivity of the windings, analytical and numerical (by the Finite Element Method) modeling of the thermal state in steady state and analysis of the mechanical stresses of the compressed electric coils were carried out.

In [17], it is noted that in the insulation of the stators of wind power plants during transient modes, increased levels of thermomechanical stresses occur. To determine their actual level, information on temperatures throughout the year was collected, and their distribution was analyzed using statistical methods.

In [18], a finite element model of the vibration characteristics of the end zone of the TG stator with power of 600 MW is described. The main physical and mechanical properties of the stator elements used in the model are determined by the results of field experiments. Windings cores with direct water cooling, taking into account the complexity of the internal structure, are modeled with a homogeneous isotropic material with properties determined by bending tests.

Approximate methods of solving problems of thermoelasticity are based on the generalized principle of minimum potential energy of deformation together with expressions approximating possible stresses [3]. Here, it is assumed that the body is under the action of surface and volume forces with a known distribution of the temperature field.

Obtaining the most complete results for the values of displacements, deformations and stresses when the temperature changes in the generator elements can be achieved by mathematical modeling of thermomechanical processes in the rods using the Finite Element Method (FEM) in both stationary and transient modes of operation.

The goal of the paper is to develop a mathematical model and analyze thermomechanical processes in the stator elements of the turbogenerator, taking into account the presence of thermal defects and determining the areas of the rod where the thermomechanical stresses are the greatest.

The paper presents the results of theoretical studies of the thermomechanical load parameters of the elements of the stator winding of the generator (rod insulation) in different temperature modes of its operation, in particular, at different distillate consumption (thermal defects of cooling).

Modeling of thermomechanical processes in the insulation of the rods of the stator winding of a water-cooled turbogenerator. Solution of the formulated problem is carried out by using FEM.

The input parameters for studying the thermomechanical displacements and stresses of the nodes of the finite element model under different cooling conditions of the stator winding rod are the temperature distributions of the main nodes of the stator core in a 2D formulation from the central section of the machine to the end zones on the turbine side, as well as the thermomechanical properties of the construction materials (steel, copper, insulation) – their modulus of elasticity *E*, coefficient of thermal expansion *α* and Poisson coefficient *μ* [3].

To solve the problem of thermoelasticity, we use a triangular finite element according to six components of nodal displacements. The coordinates of vertices (nodes) *i*, *j*, *m* in the Cartesian coordinate system can be chosen arbitrarily, which is a significant advantage of FEM. Each element is also characterized by the thickness *t* and the deviation of its temperature from some equilibrium value *ΔT*.

It is assumed that the temperature along the length of the rod varies according to a linear law, while the maximum temperature value is reached at the exit of the winding on the side of the turbine, where the heating of the cooling water in the hollow conductors of the rods is the greatest.

The complete system of equations of the element for the calculation of unknown displacements *U* in nodes [19] is written as

$$[k]\begin{Bmatrix} U_{2i-1} \\ U_{2i} \\ U_{2j-1} \\ U_{2j} \\ U_{2m-1} \\ U_{2m} \end{Bmatrix} = \{f\}, \qquad (1)$$

where [*k*] is the stiffness matrix of the element; variables *U* with indices «2» (i.e., in the 2D formulation of the problem) correspond to the values of displacement along the *y* axis, and with indices «2-1» – along the *x* axis; {*f*} is the load vector of the element due to thermal effects.

The solution for displacement fields using FEM is carried out by minimizing the potential energy of an elastic body [3]. The left-hand side of the system of equations for the elements of the area:

$$[K] = \int_V [B]^T [D][B] dV , \qquad (2)$$

where [*B*] is the matrix of gradients connecting deformations and displacements; $[[B]^T$ is the transposed matrix; [*D*] is the matrix of elastic constants describing the mechanical properties of connected elements; *V* is the volume of the finite element.

The right-hand side of the system of equations:

$$\{f\} = -\int_V [N]^T \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} dV - \int_V [B]^T [D]\{\varepsilon_0\} dV - -\int_S [N]^T \begin{Bmatrix} P_x \\ P_y \\ P_z \end{Bmatrix} dS - \{P\}, \qquad (3)$$

where $[N]^T$ is the transposed matrix of shape functions; *X*, *Y*, *Z* are the volumetric forces; $\{\varepsilon_0\}$ is the initial deformation of the element due to thermal expansion; *S* is the area of the finite element; P_x, P_y, P_z are the surface loads; {*P*} is the column vector of nodal forces.

Matrix of gradients:

$$[B] = \frac{1}{2S}\begin{bmatrix} b_i & 0 & b_j & 0 & b_m & 0 \\ 0 & c_i & 0 & c_j & 0 & c_m \\ c_i & b_i & c_j & b_j & c_m & b_m \end{bmatrix}, \qquad (4)$$

where the coefficients are related to the coordinates of the vertices of the element:

$$\begin{aligned} b_i &= y_j - y_m, & c_i &= x_m - x_j, \\ b_j &= y_m - y_i, & c_j &= x_i - x_m, \\ b_m &= y_i - y_j, & c_m &= x_j - x_i, \end{aligned} \qquad (5)$$

matrix of elastic constants:

$$[D] = \frac{E}{1-\mu^2}\begin{bmatrix} 1 & \mu & 0 \\ \mu & 1 & 0 \\ 0 & 0 & \frac{1-\mu}{2} \end{bmatrix}. \qquad (6)$$

Then

$$[k] = [B]^T [D][B] tS , \qquad (7)$$

$$\{\varepsilon_0\} = \alpha \Delta T \begin{Bmatrix} 1 \\ 1 \\ 0 \end{Bmatrix}, \quad (8)$$

$$\{f\} = [B]^T [D] \{\varepsilon_0\} tS = \frac{\alpha E t \Delta T}{2(1-\mu)} \begin{Bmatrix} b_i \\ c_i \\ b_j \\ c_j \\ b_m \\ c_m \end{Bmatrix}. \quad (9)$$

The resulting system of algebraic equations of high order (equal to twice the number of nodes) is solved by the Gaussian elimination method.

After determining the nodal values of the displacement vector based on the heating data of each element and the thermomechanical coefficients of its material, the components of the deformations in the elements are calculated taking into account the corresponding initial and boundary conditions using the solution of the system:

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{Bmatrix} = [B] \cdot \begin{Bmatrix} U_{2i-1} \\ U_{2i} \\ U_{2j-1} \\ U_{2j} \\ U_{2m-1} \\ U_{2m} \end{Bmatrix}. \quad (10)$$

Stress components in the material inside the finite element are determined by the difference between the existing and initial deformations of the body due to temperature effects. Thus, the non-zero stress components $\{\sigma\}^T = [\sigma_x, \sigma_y, \tau_{xy}]$ in the elements are calculated according to Hooke law

$$\{\sigma\} = [D]\{\varepsilon\} - [D]\{\varepsilon_0\}. \quad (11)$$

Analysis of the results of numerical investigations. The study was carried out for a four-pole generator type TVV-1000-4Y3 with power of 1000 MW.

The calculation area is the most heated half of the rod (slot and frontal parts) of the stator winding on the turbine side (Fig. 2).

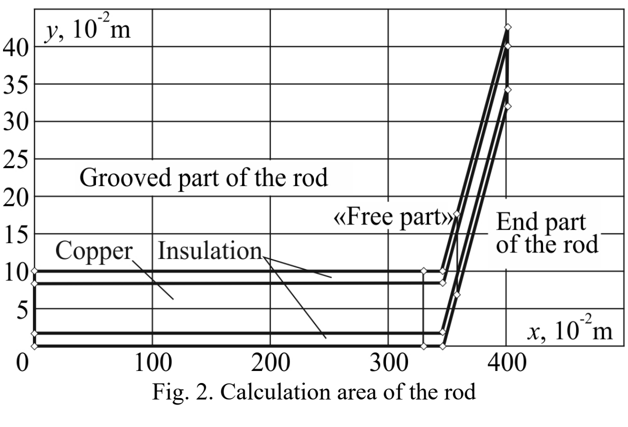

Fig. 2. Calculation area of the rod

For clarity, the upper and lower layers of the model, corresponding to the insulation, are highlighted with a violation of scale. The «free» (from fasteners) zone of the rod is highlighted by vertical lines at the point where the winding exits the slot. Here, it was assumed that the displacements along the x axis in the middle of the rod in the active zone of the stator (in the central cross-section of the machine) are equal to zero. The displacements of all nodes of the model along the y axis at the bottom of the slot and at the border of the upper and lower rods of the stator winding (slot part of the winding) are also absent. In this area under research, the components free to move – only along the x axis.

Thermomechanical characteristics (displacements and stresses in the insulation of the stator winding rod of the generator) were analyzed in nominal load modes under normal conditions of its cooling, as well as in the presence of thermal defects – at 1/2 and 1/3 distillate consumption through the rod.

The fastening should not prevent the displacements of the frontal parts in the axial direction (along the x axis) during thermal elongation of the rectilinear slot part of the stator winding. Here, according to the results of the thermomechanical calculation of the half of the stator (from the middle to the end zone on the side of the turbine), the obtained values of the displacements components of the core nodes in the axial section were the boundary conditions of the first kind for the nodes of the rod model, in which the fastening of the frontal parts was «carried out».

Insulation temperatures in the element of each cross-section in the slot part were calculated as the arithmetic mean between the values in the copper of the winding and the iron of the stator of the core model. The change in the temperature of the rod nodes during the transition from element to element along the length of the model was set according to a linear law. As a result, we get rows of values of nodal displacements and stresses in finite elements.

Figures 3, 4 show graphs of changes in thermomechanical displacements and stresses along the insulation layer along the x and y coordinates (hereinafter curves 1 and 2) in the slot and frontal parts of the winding under the nominal cooling conditions of the stator winding rods.

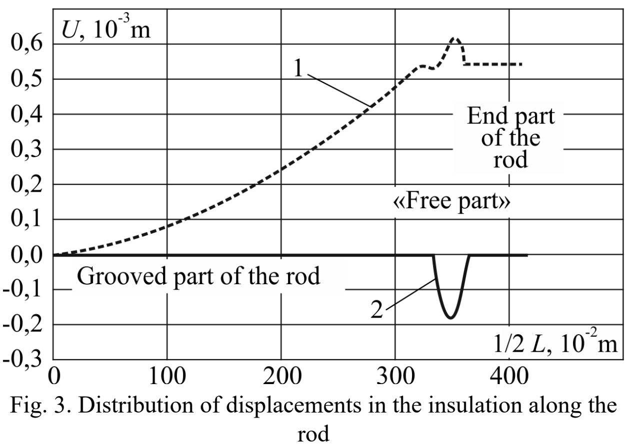

Fig. 3. Distribution of displacements in the insulation along the rod

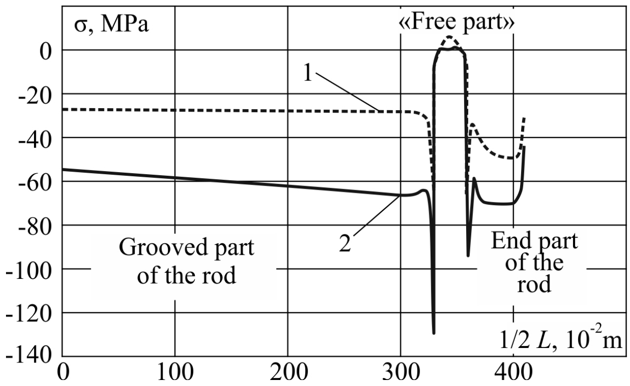

Fig. 4. Distribution of stresses in the insulation along the rod

As can be seen, when the winding is heated, there is an axial displacement of the rods relative to the stator core (Fig. 3, curve 1), which corresponds to the condition of structurally ensuring the freedom of movement of the rod along the *x* axis.

In the area where the winding exits the slot, radial «deformation» of the rod occurs in the area «free» from fasteners (Fig. 3, curve 2). Here, fixing the winding in the frontal zone prevents «unlimited free» displacement, as a result of which compressive forces arise in the rods and in the details of the frontal parts fastening (Fig. 4, curves 1, 2).

In the slot part, the compressive stresses are explained by the boundary conditions in the middle of the model and the impossibility of radial displacements of the rod nodes. There are practically no stresses in the «free» zone of the rod (on its «knee»). «Peaks» at the exit from the slot and at the place of the beginning of fasteners in the frontal part are caused by a sharp change in the boundary conditions at these so-called «special points» and methodical properties of the approximate finite element approach (by the degree of discretization of the computational domain) to solving the problem.

Thus, at the nominal temperature of the winding and its cooling conditions, the values of radial and axial stresses in the insulation along the length of the rod generally do not exceed the permissible values (80-90 MPa).

Figures 5, 6 reflect, respectively, the value and nature of changes in thermomechanical displacements and stresses in the insulation at 1/2 of the flow rate of the coolant through the rod. The flow reduction was assumed to be uniform across all cooling channels.

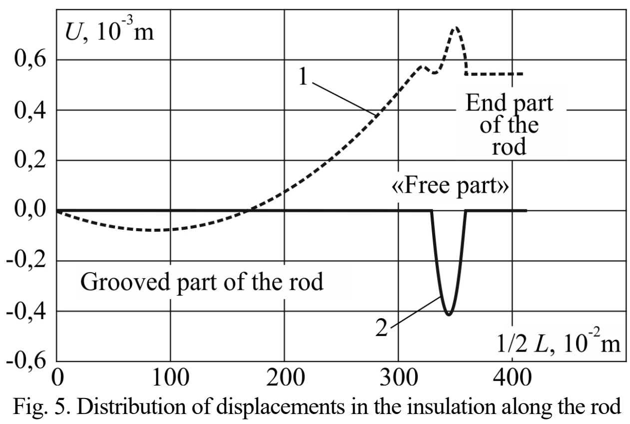

Fig. 5. Distribution of displacements in the insulation along the rod

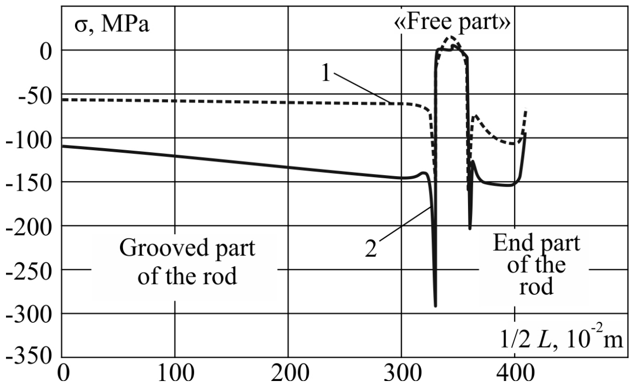

Fig. 6. Distribution of stresses in the insulation along the rod

With a decrease in water flow by 50 %, the axial displacements increase slightly and radial displacements increase significantly (more than two times) at the point where the rod exits the slot. Here, the values of the radial stresses in the insulation elements of the slot zone and in the places where the frontal parts are fastened exceed the permissible values. In the latter, the same applies to axial stresses, too.

As the cooling conditions worsen (when there is only 1/3 of the distillate flow through the winding – Fig. 7, 8), the thermomechanical characteristics of the insulation deteriorate significantly along the entire length of the rod, the stress values exceed the permissible values beyond the mechanical tensile strength of the material, which is unacceptable.

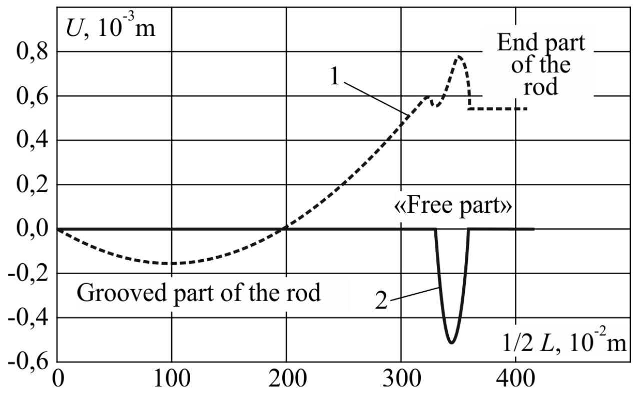

Fig. 7. Distribution of displacements in the insulation along the rod

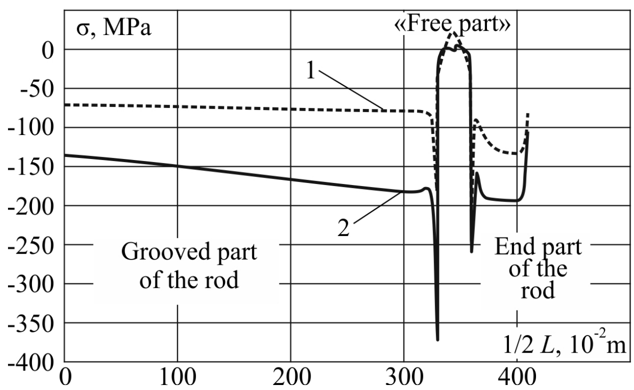

Fig. 8. Distribution of stresses in the insulation along the rod

Thus, in order to avoid emergency situations, it is necessary to constantly monitor the temperature of the stator winding rods. The work [20] emphasizes the importance of thorough regular leak testing of water-cooled rods, contains information on the causes and development of water leaks, describes recommended methods of inspection, pressure drop testing, maintenance, and also offers possible options for timely repair.

Conclusions.

1. A mathematical model and technique of numerical calculation of thermomechanical characteristics in the rod elements of the stator winding of a powerful turbogenerator in the presence of cooling defects have been developed. The technique is based on the Finite Element Method implemented as a package of applied software for a personal computer.

2. The paper presents the results of numerical calculations of the thermomechanical stresses of the elements of the stator winding (rod insulation) of a four-pole generator of the TVV-1000-4Y3 type with power of 1000 MW, depending on the temperature mode, taking into account the change in the distillate flow rate. It is shown that under the nominal cooling conditions of the stator winding rods, displacements reach 600 μm (axial) and 200 μm (radial), thermomechanical stresses are on average 60 MPa and 70 MPa at temperatures of 69.8 °C and 85.3 °C in the slot and front parts of the winding in accordance. In case of violations: 705 μm and 401 μm; stresses – 125 MPa and 150 MPa at temperatures of 100.8 °C and 147.3 °C (1/2 of distillate consumption); 790 μm and 500 μm, 160 MPa and 190 MPa at temperatures of 116.3 °C and 178.3 °C (1/3 of distillate consumption).

3. A comparative analysis of thermomechanical stresses in the insulation of the rod in case of violations of the circulation of the distillate in the stator winding showed that their greatest values are observed near the exit of the rod from the slot and the places where the frontal parts are attached. As the cooling conditions deteriorate, even in the nominal load mode, their values in individual insulation nodes exceed the limit of the material's mechanical tensile strength. At lower than nominal water consumption, the thermal and thermomechanical characteristics of the elements of the winding rod are significantly enhanced in terms of the violation of the physical properties of the insulation material and the reliability of the machine as a whole.

4. The developed models and techniques can be used for the study of thermal and thermomechanical processes, taking into account cooling defects different from those considered in the paper, as well as the presence of external mechanical influences, in maneuvering modes of starting and resetting the electrical load of the TG, for studying the effectiveness of various methods of cooling regulation, etc.

Conflict of interest. The authors of the article declare that there is no conflict of interest.

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