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THERMOMECHANICAL PARAMETERS OF STATOR WINDING INSULATION OF A TURBOGENERATOR WITH CONTROLLABLE COOLING

Abstract. A method of calculation the thermomechanical parameters of stator winding high-voltage insulation for the operating conditions of a powerful generator using the numerical finite element method is developed. This method allows timely to give a warning the thermomechanical stress inadmissible level for necessary decisions on the prevention of severe accidents. Implementation of a method requires the least costs and can be used for generators of any type. As an example, the distribution of thermomechanicals strain and stress in winding bar insulation of 800 MW turbogenerator with a load change and cooling control by a numerical method is calculated. The winding bar displacement relative to the stator core end packet are evaluated.

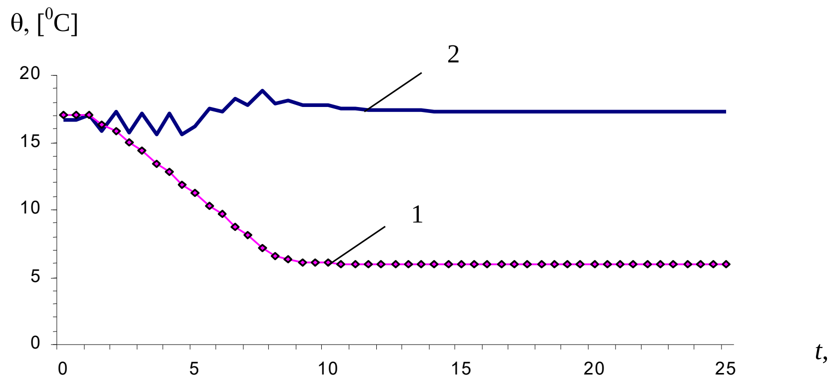
Keywords: powerful turbogenerator, end zone, stator core, stator winding frontal part, stator winding insulation, thermomechanical stress.

Improvement the reliability for main equipment of power plants is one of basic and urgent tasks of power engineering. The stator winding insulation and stator core end packets damages of a turbogenerators occupies an important place in accidents statistics. It is therefore necessary further study the conformity to natural laws of processes in these zones, as well as finding ways to reduce the negative impacts. In this paper the thermomechanicals strain and stress in stator winding bar insulation of a powerful turbogenerator with an electrical load change and cooling control is calculated.

The initial information of 800 MW full water cooled turbogenerator when calculation of heat process in winding are used [5]:

- the distillate rate in cooler: Q_{cool} = 91,7 m^3/hour;
- the technical water rate: Q_w = 300 m^3/hour;
- the distillate temperature at the outlet of winding: T_1 = 43 °C;
- the distillate temperature at the inlet to winding: T_2 = 23 °C;
- the technical water temperature at the inlet to cooler: T_{wcool} = 16 °C;
- the heat transfer coefficient from the distillate to the wall of cooler tube: h_d = 3500 W/m^2·K;
- the heat transfer coefficient from the wall of cooler tube to the technical water: h_w = 3160 W/m^2·K;
- the diameter of cooling tubes: d_{out} = 0,015 m, d_{in} = 0,013 m;
- the cooling surface: F = 129 m^2.

Heat calculation of winding with cooling control is carried out for a scheme provides the admission of hot distillate part past a cooler depending on the load [2]. The winding bar is considered as a single body with averaged parameters. The change of winding copper average temperature when a decrease of current load from the nominal value to 0,35I_{rat} with normal cooling (curve 1) and cooling control (curve 2) are shown in Fig. 1.



Thermo-stress condition the stator winding bar insulation of a turbogenerator according to results of heat calculation is determined. Taken the bar temperature is linearly distributed along the winding bar. The solving region is the most heated stator winding half-bar (slot and frontal parts) of a generator on the turbine side (Fig. 2).

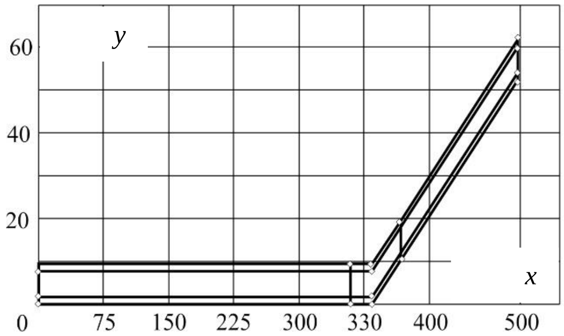


Fig. 2

The problem is solved on the basis of numerical mathematical simulation in a two-dimensional formulation by the finite element method [4].

According to the finite element method when minimizing of elastic body potential energy the fields of displacement vector nodal values are determined, then taking into account the corresponding initial and boundary conditions the strain and stress components in elements are calculated.

Following the minimizing process of elastic body potential energy is integrals enter into the equations for elements [4]:

$$[K] = \int_V [B]^T [D][B] dV, \quad (1)$$

$$\{f\} = -\int_V [N]^T \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} dV - \int_V [B]^T [D]\{\varepsilon_0\} dV - \int_S [N]^T \begin{Bmatrix} P_x \\ P_y \\ P_z \end{Bmatrix} dS - \{P\}, \quad (2)$$

where $[B]$ is the gradients matrix connecting the strain and displacement; $[D]$ is the matrix of elastic constants describing the mechanical properties; $\{\varepsilon_0\}$ is the initial deformation of element associated with the thermal expansion; $[N]$ is the matrix of form functions; X, Y, Z are the volume forces; P_x, P_y, P_z are the surface loads; $\{P\}$ is the column vector of nodal forces; S is the area of element; V is the volume of element.

Triangular simplex-element with six components of nodal displacements for solving the problem is used. The complete system of equations for an element will be:

$$[k] \cdot \begin{Bmatrix} U_{2i-1} \\ U_{2i} \\ U_{2j-1} \\ U_{2j} \\ U_{2m-1} \\ U_{2m} \end{Bmatrix} = \{f\}, \quad (3)$$

where i, j, m are the numbers of triangular simplex-element node.

The strain components in element after definition of displacement in nodes are determined as follows:

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{Bmatrix} = [B] \cdot \begin{Bmatrix} U_{2i-1} \\ U_{2i} \\ U_{2j-1} \\ U_{2j} \\ U_{2m-1} \\ U_{2m} \end{Bmatrix}. \quad (4)$$

The stress components $\{\sigma\}^T=[\sigma_x, \sigma_y, \tau_{xy}]$ are calculated according to Hooke law:

$$\{\sigma\} = [D] \cdot \{\varepsilon\} - [D] \cdot \{\varepsilon_0\} \quad (5)$$

or with help the nodal displacements:

$$\{\sigma\} = [D] \cdot [B] \cdot \{U\} - [D] \cdot \{\varepsilon_0\}. \quad (6)$$

On the first stage, a thermomechanical calculation of half the stator core in axial section (from the middle to the end zone on the turbine side) is carried out. The obtained values of stator nodes displacements component along the y-axis for each time moment is first kind boundary conditions for the nodes of bar model with the bandage fastening of frontal parts. Taking into account the recommendations [1] assumes along the x-axis the fastening does not prevent the frontal parts displacement in axial direction when thermal extension of stator winding rectilinear slot part.

The load stepped down process of a turbogenerator from the rated load condition to 0,35 rated capacity for 7 minutes with the subsequent generator cool off during the 25 minutes with and without temperature control of cool water is considered.

As is generally known [6], the temperature of hollow copper conductor's negligibility differs from the cool water temperature when direct forced liquid intensive cooling. At rated heat transfer the water temperature in winding is 20 °C [5]. Thus, in order to thermomechanical studies the copper temperature for the rated load condition was distributed in space on the half length of bar according to a linear law within from 33 °C (the middle of stator core) to 43 °C (the end zone of winding frontal parts). The temperature change along the half-bar when calculation the subsequent time points of stator cool off process after load down is taken in the appropriate proportion.

The change of core heat levels averaged on the volume caused mainly by steel losses slightly changing with load down and close in value to idling steel losses, is installed according to the research results [6]. In this case the stator core temperature is decreased on average from 63 °C to 57 °C.

The insulation temperature at any spatial point of bar slot part is taken as the average one between the winding and iron stator core and in the frontal part coincides with the copper temperature for each moment of time.

The indicated heat of stator constructive elements at time and space are the initial data for the subsequent calculation of nodes displacement in isolation (the right side of equations system (3)).

An approximate numerical solution by the finite element method of thermo-elasticity problem has the form of compact series the values of nodal displacements and stresses in elements.

Fig. 3 shows the stress components in insulation elements along the bar on the *x*- and *y*-axes under rated load of a generator (curve 1 – stress on the *x*-axis in bar slot zone for the point of outlet the winding from the slot («bend») and in the frontal part, curve 2 – on the *y*-axis, respectively). The obtained values of stress components on the *x*-axis are considerably less than the insulation breaking point (80 – 90 MPa), and on the *y*-axis are near to it for the point of fastening beginning the frontal part (so-called the «particular» point of a sharp change the boundary conditions and transition from the «free» state of bar to «fixed» one).

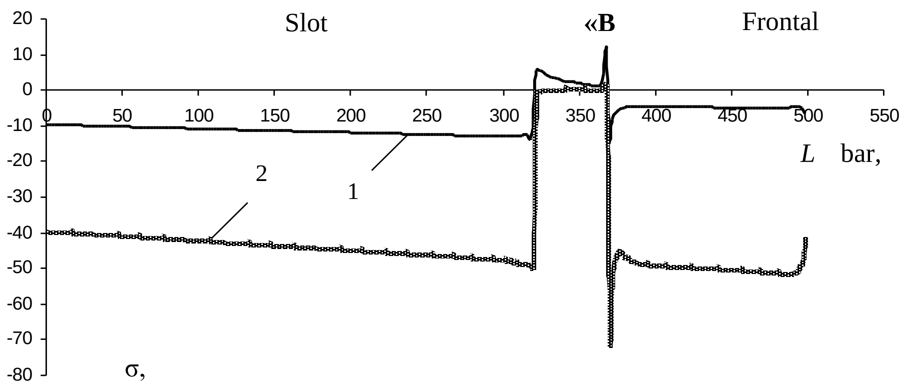


Fig. 3

Fig. 4 shows the graphs of stress components variation in insulation element at time near outlet the winding from the slot on the *x*- and *y*-axes without and with temperature control of cool water (curves 1, 2 and 3, 4, respectively). As shown in Fig. 4, the thermomechanical stress in insulation with water temperature control and load down process is nearly invariable because the maintenance of water temperature in winding at the rated condition level.

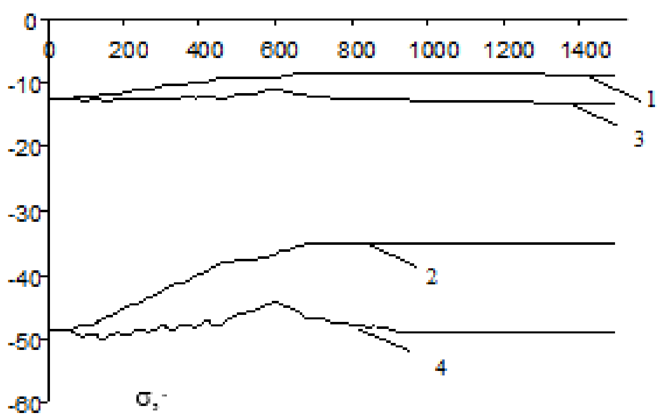


Fig. 4

Another important negative factor contributing to the exfoliation of stator core end packet is the mechanical interaction between one and winding bar at the outlet from the slot with a load change [7]. In [3] shown the presence of cyclical displacement of winding copper relative to the end packet is the reason for initial exfoliation, insulation deterioration and destruction.

The displacement of winding bar section at the outlet from the slot relative to the stator core end with an electrical load change from P_{rat} to $0,35P_{rat}$ is shown in Fig. 5. Curve 1 corresponds to normal cooling, curve 2 – controllable cooling. It can be seen from Fig. 5, that the variation diapason of winding bar displacement relative to the core end packet decreases from 0,6 mm with normal cooling to 0,2 mm with controllable cooling, i.e. almost three times.

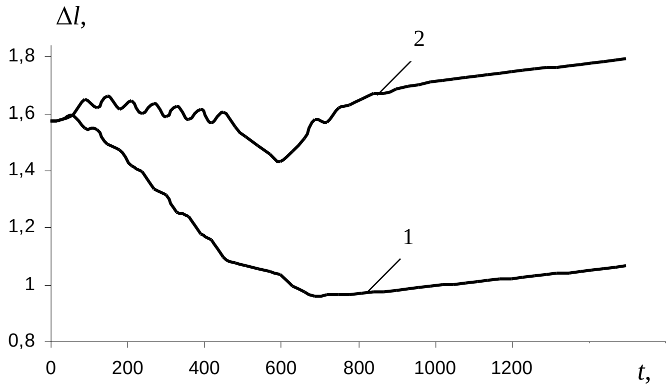


Fig. 5

On the basis of foregoing the following conclusion could be obtained:

Taking into account the fact that in a turbogenerator with the stator core gas cooling the heat level of core and winding is much higher and, accordingly, the variation diapason of winding bar displacement relative to the core end zone is wider, then the winding cooling control is more expedient.

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