Calculation of final heating temperature of turbogenerator stator winding for control over development of winding thermal damage

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Keywords:

Turbogenerator
Cooling
Stator
Winding
Forecasting

Article history:

Received 22.05.2014
Received in revised form 23.06.2014
Accepted 30.06.2014

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Abstract

Introduction. It is important for control of turbogenerator to accurately predict the final temperature of the thermal process, which increase in the event of defects in the mashine. Methods of technical diagnostics for manage the development of the defect is necessary.

Materials and methods. Based on the analysis of classical and graphical methods for calculating the final temperature of the stator windings have developed a new method for calculating the steady-state temperature electrical insulation of the stator winding.

Results and discussion. Classical method can be used at a constant value of heat transfer coefficient. That is, when the cooling system is in mode stator and stator temperature rise caused by uncontrolled variations in load turbogenerator. Graphical method is simple to use, but not imprecise. Especially when the magnitude of the proposed steady-state temperature is judged by the results of the measurements only in the initial stage of the heating process of the stator cores. The proposed method of thermal process on the basis of divergence partly compensates the shortcomings of the above-mentioned methods and allows us to analyze the thermal stresses of the stator winding rod.

Conclusion. Using modern methods of information technology allow the use of graphical method to predict the final temperature of heating turbogenerator stator winding. A dikompozition task analysis of the temperature field of the stator winding rod will expand its understanding of the dynamics of change and improve the accuracy of diagnosis.

Introduction

In the second part of XX century power industry in our country was developing at a brisk pace. Dozens of powerful thermal, atomic and hydroelectric power plants were put into operation, where hundreds of synchronous generators – turbogenerators and hydrotreaters (TH) with capacity up to 1200 MW, produced billions kilowatt-hour of electric power. “Small” energetics was developing rapidly as well. In order to supply electric power to plants producing sugar and alcohol, TH with capacity up to 10 MW were put into operation on Central Heat Stations of practically all Ukrainian plants.

Commissioning of large quantity of TH within relatively small period of time lead to the situation that after 30 years (250000 hours of operation), i.e. today, majority of those machines have exhausted or practically exhausted specified resources. To replace these TH with new machines quickly, without reducing the quality of produced energy, is quite expensive and difficult to implement for any country. Therefore, extension of service life and ensuring reliable work of equipment that has exhausted its resources specified by manufacturing plants, are urgent national problems which can be solved with application of technical diagnostics methods.

Emergency shutdown of TH for repair work causes considerable damage to generating companies. Therefore, electric power producers usually try to “extend” to planned shutdown of TH in course of which all defects detected during diagnostics are removed. However, it is necessary to take into account that in case of wrong assessment of diagnostics results, for example, assessment of development speed or degree of defect hazard, economic damage can be more considerable. In this connection, creation of conditions for exploitation of virtually defective TH becomes main task of their operation management or problem of detected defect development management [1].

Development management of defect detected in course of diagnostics can be realized by means of creation of TH exploitation conditions when defect is not developing completely, is developing at minimum and controlled speed or is removed as a result of implementation of modern accepted and justified solution concerning repair work.

According to statistics, majority of defects and further failures in TH operation consequently occur due to deviation from nominal parameters of thermal processes taking place inside working generator.

Any electric machine, including TH, contains a set of various units (brass stator and rotor winding, steel magnetic conductors, variety of structural details) that require different conditions of cooling and have different values of thermalphysic characteristics (thermal conductivity, thermal capacity). All this leads to inevitable differences in temperature of separate units (parts) in working TH. At the same time it is important that temperature of each unit of machine did not exceed the limit.

It is known that load capacity of TH in most cases is determined by temperature of its windings and cores, namely actual conditions of heat extraction that was produced during operation of TH. Stationary thermal processes take place during continuous electrical load in TH. With increase of load, active power loss increases as well. At the same time, in course of nonsteady thermal process temperature of TH units increases to a certain set value which can exceed allowable value.

Thus, overheating of TH stator and rotor windings – electrical insulation and winding material, may cause interturn closure and even lead to formation of cracks in copper winding. All these conditions lead to considerable decrease of reliability and, consequently, of TH operational life.

At the same time, temperature of separate units and whole TH may increase not only due to increase of electrical load. This may happen due to failures of cooling system that is installed in all modern TH or any other defects occurring inside machine.

Cooling system of modern TH represents technologically composite component of electric power manufacturing system. Depending on performed functions all components in cooling system can be divided into two parts. One part of the system is structural component of TH designed for direct removal of heat produced by electric current. These are ducts in stator winding shafts where liquid coolant is supplied as well as ducts in rotor winding and TH cores for transportation of cooling gas.

Second, larger part of cooling system, is located outside TH. This is a complex of devices that ensure availability of necessary parameters of cooling media and their supply to TH. It is worth noting that temperatures and expenses of liquid and gaseous coolants in cooling systems of TH, as a rule, are not controlled.

Despite technical complexity of TH cooling system, significant malfunctions in its work and increase of temperature in separate unit of TH may occur due to seemingly not so emergent defects of the system. For example, partial obstruction of shaft ducts through which cooling liquid is transported may cause nonsteady thermal process and increase of temperature in one shaft (group of shafts) of TH stator winding.

Nonsteady thermal processes may have much larger time lag, comparing to electrical transient processes [2]. In its turn, larger part of defects that may cause nonsteady thermal process in TH, as a matter of fact, are defects prone to development in time [3].

For development management of such defects it is essential to not only determine the fact of temperature change, for example of TH unit. It is important to forecast the value of final temperature of nonsteady thermal process as precisely as possible – value of newly fixed temperature of this TH unit, as well as duration of the process – time to newly fixed temperature. Depending on the value of newly fixed temperature of defective TH unit which may appear lower, equal to or higher than allowable temperature, it will be necessary to make decision concerning further TH operation.

Thus, if predictable values of final temperature of TH unit defective condition development appear to be lower than allowable, decision not to change the load of TH may be approved. Otherwise, it shall be necessary to make decision about reducing the load, namely, to what extent and how quickly it will be done, or TH shutdown.

At the same time it is important to determine location of temperature change in TH, the size of which may give evidence about heat exchanging processes inside machine. Thus, in series of modernized TH, stator winding temperature is determined on the basis of results of water temperature measurement at the outlet of each winding shaft. However, more often stator winding temperature is determined on the basis of thermometer readout located over electrical insulation of shafts. It is clear that water temperature at the outlet of the shaft and temperature of electrical insulation of the shaft differ numerically. At the same time, according to our evidence this difference may reach 10K. Under such circumstances, methods of comparison of temperature measurement results with allowable values of TH stator winding temperature shall differ.

Materials and methods

Anticipating the final heating temperature of the stator winding turbogenerator were considered and analyzed the classical method of calculating the final temperature transient thermal process and graphical method for determining the final temperature. Based on the above-mentioned deficiencies identified by developed a new method for calculating the steady-state temperature electrical insulation of the stator winding.

Results and discussion

In essence, final temperature value of nonsteady thermal process may be predicted on the basis of information from expert database which, unfortunately, cannot cover all possible causes of such process in TH or on the basis of result of nonsteady thermal process calculation.

Method of nonsteady thermal process calculation in electric machine mentioned in [2, 4] and series of other publications, without exaggeration, may be considered classical. Object of heating here, namely electric machine, is considered to be uniform solid body. At the same time, meaning of temperature of the object is not used for determination of thermal condition of the object, but surplus temperature of the object (heated machine unit) in respect of temperature of cooling medium or else – superheat temperature.

When TH load increases, that is, heating of TH to a certain higher value of fixed temperature, active power losses ΔP_1 increase as well. As far as one part of thermal energy dQ, which is released in TH stator winding shafts during time $d\tau$ of electric current effect, is expended on temperature increase of shafts $dQ_м$, and second part $dQ_в$ – is removed through cooling system of machine, therefore equation of thermal balance looks the following way:

$$dQ_1 = \Delta P_1 \cdot d\tau = dQ_м + dQ_в = c_м \cdot m_м \cdot d(\Delta T_{1м}) + \alpha \cdot S \cdot \Delta T_{1м} \cdot d\tau$$

where $c_м$ and $m_м$ – are thermal capacity and mass of stator winding shaft material - copper, respectively;
$\Delta T_{1м} = T_{1м} - T_{хв}$ – surplus temperature (overheating) $T_{1м}$ of stator winding shaft in respect of temperature T_{cw} of cooling water at the inlet of TH.
where α and S – heat-transfer coefficient and heat-exchange surface area.

With increase of temperature of winding (value $\Delta T_{1м}$), the portion of heat removed by cooling system is increasing and portion of heat accumulated in TH stator winding shaft is reducing. Therefore, different condition of machine thermal equilibrium (machine unit) will be attained at a certain value of surplus temperature $\Delta T_{1м.к}$.

As far as in condition of thermal equilibrium all heat produced in stator winding shafts under electric current is removed through cooling system $c_м \cdot m_м\ d(\Delta T_{1м})=0$, then thermal balance equilibrium looks the following way:

$$c_м \cdot m_м \cdot d(\Delta T_{1м}) = \alpha \cdot S \cdot \Delta T_{1м} \cdot d\tau \,.$$

Taking into account that at the moment of TH loading variation, namely at the beginning of nonsteady thermal process at $\tau=\tau_0=0$, temperature of winding shaft exceeded temperature of cooling medium at the value $\Delta T_{1м.0}$, consequently, with the help of abovementioned solution of differential equation with regard to final fixed temperature we get:

$$\Delta T_{1мк} = \Delta T_{1м} / [(1 - e^{-\tau/K_\tau}) + \Delta T_{1м0} \cdot e^{-\tau/K_\tau}] \,. \tag{1}$$

Value of time constant K_τ – period during which copper shaft of stator winding with mass $m_м$ and thermal capacity $c_м$, will reach surplus temperature $\Delta T_{1мк}$ at heat release power ΔP_1 provided, all that heat is expended exclusively on shaft heating, can be calculated using the following formula:

$$K_\tau = c_м \cdot m_м / (\alpha \cdot S) . \qquad (2)$$

At $\tau=\tau_0=0$ и $T_{1м.0}=0$, namely, when temperature of the shaft equals temperature of cooling medium and TH loading variation took place, on the basis of equation (1) we will get:

$$\Delta T_{1мк} = \Delta T_{1м} / (1 - e^{-\tau / K_\tau}) , \qquad (3)$$

$$(dT_{1м} / d\tau)_{\tau=0} = tg\beta = I_1^2 \cdot \gamma / (\rho_м \cdot c_м \cdot S) . \qquad (4)$$

Figure 1 shows kinetics of object superheat temperatures calculated in accordance with equation (1) – curve 1 and equation (3) – curve 2.

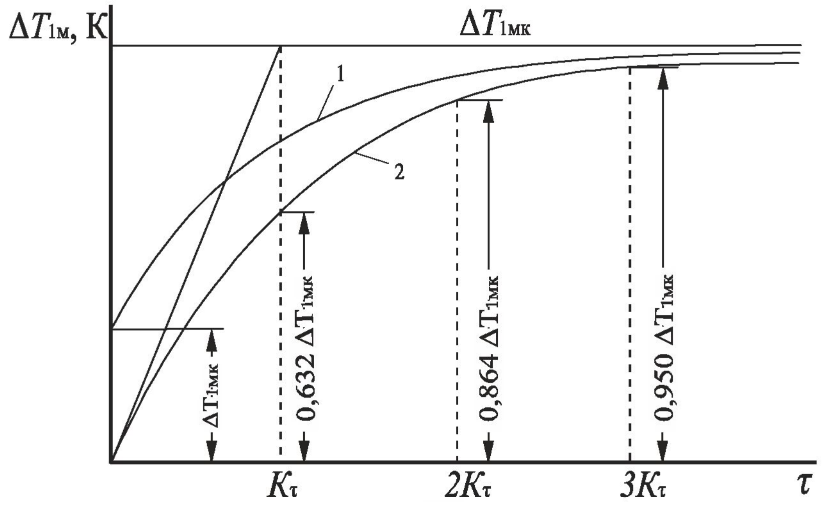

Fig. 1. Calculation results of kinetics of superheat temperature of the stator winding rod

As follows from the results of analysis, the abovementioned method of calculation of nonsteady thermal process final temperature can be used only in cases when TH temperature increase results from change of machine electrical load. At the same time, value of time constant K_τ of nonsteady thermal process does not change, which means that for every specific TH its value may be defined during commissioning or in course of machine testing upon completion of planned repair.

In cases when value of heat-transfer coefficient α, meaning K_τ, changes as a result of defect, the abovementioned method of calculation of nonsteady thermal process final temperature is not quite suitable.

More acceptable for determination of nonsteady thermal process final temperature of TH heating, caused by defect, is the so-called graphical method introduced in the 30s of previous century [5]. To determine final temperature of electrical machine overheating with the help of this method, the following procedures are performed graphically.

From the moment of beginning $\tau_0=0$ of stator winding shaft temperature change over equal intervals $\Delta\tau=(\tau_1-0)=(\tau_2-\tau_1)=(\tau_3-\tau_2)$ superheat temperature is measured in ΔT_1 ΔT_2 ΔT_3, respectively, and on the basis of results of measurement a part of kinetic dependence is built $\Delta T=f(\tau)$ (fig.2). Then, from X-axis from points τ_1, τ_2, τ_3, vertical lines are drawn to intersection with curve $\Delta T=f(\tau)$. Across obtained points on the curve $\Delta T=f(\tau)$, 1, 2, 3, respectively, horizontal lines are drawn, on which, upon intersection with Y-axis, respective changes in superheat temperature of TH stator winding shaft are indicated.

Thus, on horizontal line, drawn from point 1 upon intersection with axis ΔT, section $\Delta T_{10}=\Delta T_1-\Delta T_0$ is indicated which characterizes change of superheat temperature of TH stator winding shaft within time interval from 0 to τ_1. On horizontal lines, drawn from points 2 and 3, left from Y-axis, are indicated intervals $\Delta T_{21}=\Delta T_2-\Delta T_1$, $\Delta T_{32}=\Delta T_3-\Delta T_2$, respectively, that characterize changes of surplus temperature of the shaft within time intervals $\tau_2-\tau_1$ and $\tau_3-\tau_2$.

Following the performance of the above mentioned operations there appear points 1*, 2*, 3*on the left from Y-axis of diagram $\Delta T=f(\tau)$. Axis of intersection of straight line that passes through those points with Y-axis of diagram $\Delta T=f(\tau)$ is the desired final superheat temperature of TH stator winding shaft $\Delta T_{\text{к}}$, namely, which will be fixed in the machine upon completion of nonstedy thermal process.

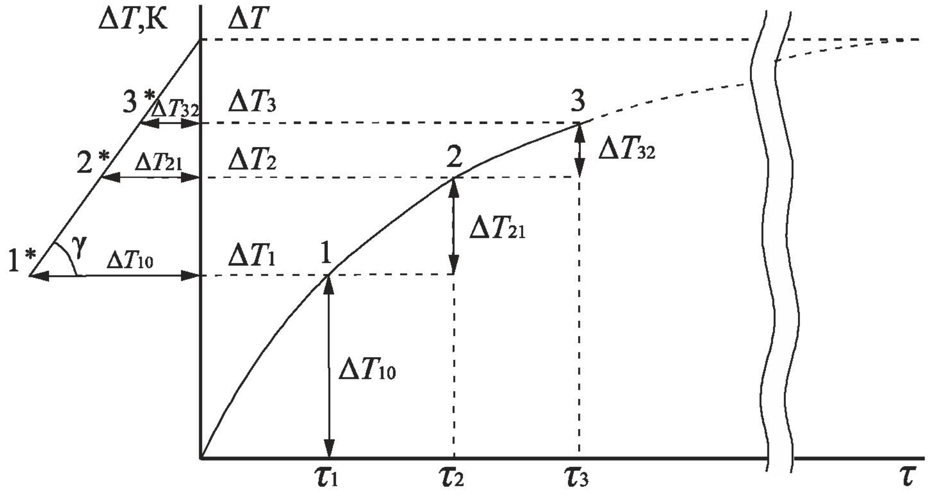

Fig.2. Determination of the final superheat temperature of the stator winding bar graphically

To determine final temperature of nonsteady process, for example heating of stator winding shaft due to defect, it is not difficult to implement auxiliary program into computer program of diagnostics of TH technical state. According to that auxiliary program at the moment of beginning of shaft temperature change $\tau_{\text{н}}$ and further at specified time τ_1 and τ_2, it is necessary to measure shaft superheat temperature: ΔT_0, ΔT_1 and ΔT_2, respectively. Then, final superheat temperature of stator winding shaft with defect may be calculated the following way:

$$\Delta T_{\text{к}} = (\Delta T_1 - \Delta T_0)\cdot tg\gamma + \Delta T_1 = \frac{(\Delta T_1 - \Delta T_0)\cdot(\Delta T_2 - \Delta T_1)}{(\Delta T_1 - \Delta T_0)-(\Delta T_2 - \Delta T_1)} + \Delta T_1 . \qquad (5)$$

Disadvantage of the abovementioned graphic method of determination of TH shaft (unit) final superheat temperature is insufficient accuracy of exponent building $\Delta T=f(\tau)$ and calculation of $\Delta T_{\text{к}}$ according to three points that have small distance from one another in time and distance on the initial section of the exponent. In addition to that, taking into account possibility of continuous measurement of equipment work parameters as well as continuous processing of results of these measurements, graphic method implemented with the help of modern information technologies may be used for forecasting of final temperature of nonsteady thermal processes taking place inside TH.

It was noted earlier that result of measurement of TH stator winding temperature depends on location of thermometer sensing element. Taking into account the fact that electric insulation of machine windings is the most sensitive element of TH to temperature change (increase), apart from graphic method described above, we suggest using our method of calculation of fixed temperature of TH stator winding shafts (electric insulation), theoretical justification of which is described below.

Cross-section (across *x-axis*) of TH stator winding shaft can be represented in the form of double-layer wall which on one side is washed by cooled distilled water (fig.3). Across *Z*-axis here:

1 – Copper layer (Cu) with thickness D_1 (coordinates – $D_1 \geq z \geq 0$) having thermal conductivity coefficient $\lambda_{\text{м}}$, in which electric current is effective *I*, that induces emission of heat with volume density q_v=value of which is proportional I^2/r in the layer with resistance *r*.

2 – Layer of electric insulation with thickness $d=D_2–D_1$ (coordinates – $D_2 \geq z \geq D_1$), having thermal conductivity coefficient $\lambda_{\text{н}}$;

3 – Section, where distilled water (H_2O) is circulating, temperature of which $T_{\text{в}}$ is changing across *x*-axis.

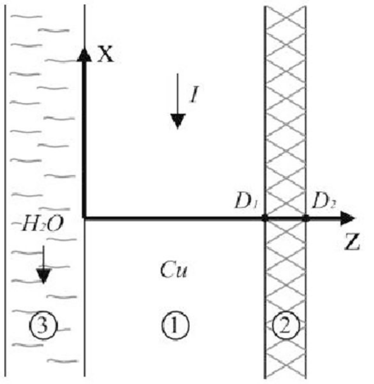

Fig. 3. Model rod windings of the stator.

In one-dimensional statement boundary value problem of calculation of copper part $T_{\text{м}}$ temperature and electric insulation $T_{\text{е}}$ of TH stator winding shaft looks the following way:

$$-\lambda_{\text{м}}(d^2T_{1\text{м}}/dz^2)=q_v \quad -\lambda_{\text{е}}(d^2T_{\text{е}}/dz^2)=0\,, \tag{6}$$
$$-\lambda_{\text{м}}(dT_{1\text{м}}/dz)=\alpha\cdot(T_{\text{в}}-T_{1\text{м}}) \qquad z=0\,,$$

$$T_{1\text{м}}=T_{\text{е}}\,|_{z=D_1} \quad \lambda_{\text{м}}(dT_{1\text{м}}/dz)=\lambda_{\text{е}}(dT_{\text{е}}/dz)\,|_{z=D_1} \qquad z=D_1\,, \tag{7}$$
$$(dT_{\text{е}}/dz)\,|_{z=D_2} \qquad z=D_2\,,$$

where $\alpha_{\text{в}}$ – is heat-transfer coefficient from copper part of the shaft to water.

In the fixed mode temperature of cooling water is increasing across *x*-axis, but in the presence of disturbance is changing across time τ.

Taking into account the fact that temperature of cooling liquid when circulating inside stator winding shaft (across *x*-axis) is changing only from 30°C to maximum 80°C, as well as considerable inertia of thermal processes, when solving practical tasks of calculation of copper part $T_{\text{м}}$ temperature and electric insulation $T_{\text{е}}$ of the shaft using models (6), (7), it is preferred to consider variables *x* and τ as parameters.

From the results of analysis of heat-exchange process on models (6), (7) it may be seen that, in general, case solution to the boundary-value problem looks the following way:

$$T_{1\text{м}}=A_0z^2+A_1z+A_2\,, \tag{8}$$

$$T_\text{е} = B_1 z + B \;. \tag{9}$$

Therefore, to determine numeric values of copper temperature $T_\text{м}$ of TH stator winding shaft, electric insulation $T_\text{и}$ of the shaft as well as thermal gradients in specific points z=0, z=D_1, z=D_2, it is necessary to define values of coefficients A_0, A_1, A_2, B_1, B_2. It is worth noting that as follows from results of analysis of equations (6) and (8), desired value of coefficient A_0 may be calculated the following way:

$$A_0 = -q_v / (2 \cdot \lambda_\text{м}) \,. \tag{10}$$

It means that values of remaining coefficients A_1, A_2, B_1 и B_2 shall be reasonably calculated using information about value A_0 and value q_v – the main temperature-forming parameter.

In its turn, from the results of analysis of equations (7) and (9) it appears that coefficient B_1=0 and, consequently, $T_\text{е}$=B_2=*const*. It means that temperature of electric insulation across z-axis does not change, that is, temperature gradient in insulation layer equals zero and numeric value of insulation temperature equals temperature of copper shaft in the point of intersection with coordinate z=D_1.

Besides, it appears from condition of continuous heat flow on the boundary surface of materials z=D_1 that $(dT_\text{е}/dz\,)|_{z=\text{D}1}$. It means that stator winding shaft copper reaches maximum temperature in the point of intersection with coordinate z=D_1.

In the result of transformations we get the following equation for calculation of coefficients A_1, A_2, B_1 and B_2 across A_0 and q_v:

$$A_1 = -2 A_0 D_1 = D_1 (q_v / \lambda_\text{м}) \,, \tag{11}$$

$$A_2 = A_1 (\lambda_\text{м} / \alpha_\text{в}) + T_\text{в} = D_1 (q_v / \alpha_\text{в}) + T_\text{в} \,, \tag{12}$$

$$B_2 = A_0 D_1^2 + A_1 D_1 + A_2 = (q_v / \alpha_\text{в}) \cdot D_1 + [q_v / (2 \cdot \lambda_\text{е})] \cdot D_1^2 + T_\text{в} \,. \tag{13}$$

On the basis of results of equation analysis (11)-(13) it appears that difference between maximum $T_\text{м}|_{z=\text{D}1}$=$B_2$ and minimum $T_\text{м}|_{z=0}$=A_2 temperatures of copper layer may be calculated the following way:

$$\Delta T_{1\text{м}} = B_2 - A_2 = [q_v / (2 \cdot \lambda)] \cdot D_1^2 \,.$$

Difference $\Delta T_{\text{м-в}}$ between maximum temperature of shaft copper $T_\text{м}|_{z=\text{D}1}$=$B_2$ and temperature of cooling water $T_\text{в}$ will look the following way:

$$T_{\text{м-в}} = B_2 - T_\text{в} = (q_v / \alpha_\text{в}) \cdot D_1^2 \,.$$

This implies that maximum temperature gradient on the boundary “copper – cooling water” equals A_1=$(q_v/\lambda_\text{м})\cdot D_1$.

Here we shall point out that, as a matter of fact, similar results may be obtained for model which represents hollow cylinder inside of which cooling medium is circulating and on the outside covered with insulation. Similar to examined above, such model may be analysed with or without regard for its heat exchange with environment, for example, by means of natural convection.

As was stated above, in course of nonsteady heat-exchange process temperature of cooling water changes not only during circulation, but in course of time. In that case analytical solution to the problem regarding temperature and temperature gradient in copper part of the shaft, where electric current is effective, which produces volumetric heat emission, may be significantly complicated. Therefore, methods of numeric computation are usually applied for analysis of thermal processes in lead wires [6].

Alternatively to all known methods and methodologies of calculation of thermal processes in lead wires concept of average temperature may be introduced on the basis of volume of stator winding shaft copper part or its separate components in direction of cooling media flow. This approach is implemented for analytical analysis of thermal processes in TH stator winding by means of transformation of differential equation of nonsteady heat conductivity for shaft copper in partial derivatives:

$$(c\rho)_{\text{м}}\cdot(\partial T_{1\text{м}}/\partial\tau)-\nabla\bullet(\lambda_{\text{м}}\cdot\nabla T_{1\text{м}})=q_v, \qquad (14)$$

where $(c\rho)_{\text{м}}$ – is volumetric thermal capacity of shaft copper as a product of mass thermal capacity to copper density;

$\nabla\bullet$ – divergence;

$\nabla T_{1\text{м}}$ – temperature gradient in copper part of the shaft;

in general differential equation of nonsteady heat conductivity for average volume V of temperature $\bar{T}_{1\text{м}}=V^{-1}\int T_{1\text{м}}dV$ of shaft copper part or any other function related to temperature. Divergence theorem serves as theoretical background for realization of such transfer [7], in accordance with it, to obtain random volume V (рис.4), limited by closed surface S and random vector function $\vec{F}$,the following conditions have to be observed:

$$\oint_s \vec{F}\cdot d\vec{S}=\int_v(\nabla\vec{F})dV. \qquad (15)$$

In equation (15) $d\vec{S}=\vec{n}\,|\,d\vec{S}\,|$ – it is surface element directed to unit norm $\vec{n}$ on the surface S.

As a result of substitution in equation (14) of expression of heat flow density vector resulting from Fourier's law $\vec{q}=-\lambda\nabla T$, by multiplying members of equation by dV and integration according to volume, we will get equation for calculation of average temperature according to volume of copper part of TH stator winding shaft at $(c\rho)_{\text{м}}=const$:

$$(c\rho)_{\text{м}}\cdot(\partial\bar{T}_{1\text{м}}/\partial\tau)=\bar{Q}_v-\bar{Q}_s, \qquad (16)$$

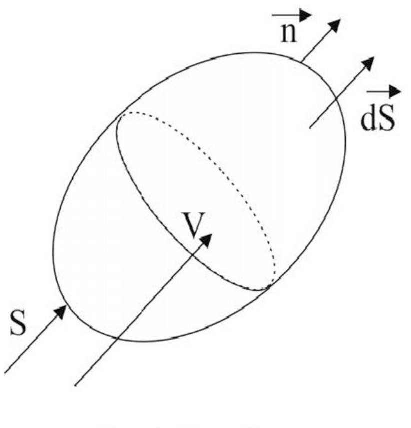

Fig. 4. The divergence theorem.

where $\bar{T}_{1\text{м}}=V^{-1}\int_v T_{1\text{м}}dV$, $\bar{Q}_v=V^{-1}\int_v q_v dV$, $\bar{Q}_s=V^{-1}\oint_s \vec{q}_s\cdot d\vec{S}$ — are, respectively: average volumetric temperature of copper part of TH stator wining shaft, average value of heat emitted in the volume of copper part of the shaft as a result of current effect, average value of heat removed by cooling water from surface S of copper part of the shaft.

In accordance with equation (7) value of heat flow density $\bar{q}_s$ is determined by conditions of heat exchange between copper part of the shaft in which electric current is effective and cooling water. It depends on heat-transfer coefficient $\alpha_{в}$, water temperature $T_{в}$ and temperature of shaft copper $T_{м}|_{z=0}$, which in equation (6) shall be substituted by $\overline{T}_{1м}$.

Taking into account assumptions described above, equation (11) will be the following:

$$(c\rho)_{м} \cdot (d\overline{T}_{1м} / d\tau) = \overline{Q}_v - K(\overline{T}_{1м} - T_{в}) , \tag{17}$$

where K – is coefficient, value of which is proportional to heat-transfer coefficient and water.

In general view, solution to equation (17) regarding changes in the time of average temperature of stator winding copper part can be represented in the form of total of the exponent and straight line, where exponential nature of change $\overline{T}_{1м}$ is determined by complex $K\overline{T}_{1м}$, and linear nature – by complex $(\overline{Q}_v + KT_{в})$. At $d\overline{T}_{1м} / d\tau = 0$, average temperature of stator winding shaft copper part reaches fixed value that equals:

$$\overline{T}_{1мк} = (\overline{Q}_v + KT_{в}) / K . \tag{18}$$

Since integral of solution to equation (16), represented in generalized form –

$$(d\overline{T}_{1м} / d\tau) = f(T_{1м}) = a + b \cdot \overline{T}_{1м} , \tag{19}$$

where *a=const, b=const* according to [8] is the following:

$$\int d\overline{T}_{1м} / f(T_{м1}) = b^{-1} \cdot \ln(a + b\overline{T}_{1м}) = \int d\tau , \tag{20}$$

then, calculation of fixed temperature in TH stator winding shaft copper part performed using divergence theorem may cover cases of nonsteady heat exchange. Thus, for practical calculations of typical values of temperature and temperature gradients in copper and electric insulation of TH stator winding shaft that are determining the level of thermal damages in a certain TH unit and the whole TH, block diagram described in fig.5 may be suggested.

Block 1 – variant calculation in accordance with equation (8) with ratios (10)-(13), of temperature distribution across cross-section of TH stator winding shaft.

Block 2 – variant calculation of temperatures in typical points of TH stator winding shaft.

Block 3 – variant calculation in accordance with equation (17) of fixed value of temperature in TH stator winding shaft.

Block 4 – variant calculation in accordance with equation (19) of average temperature change in TH stator winding shaft.

Block 5 – variant calculation in accordance with equation (19) of time to fixed average temperature in TH stator winding shaft.

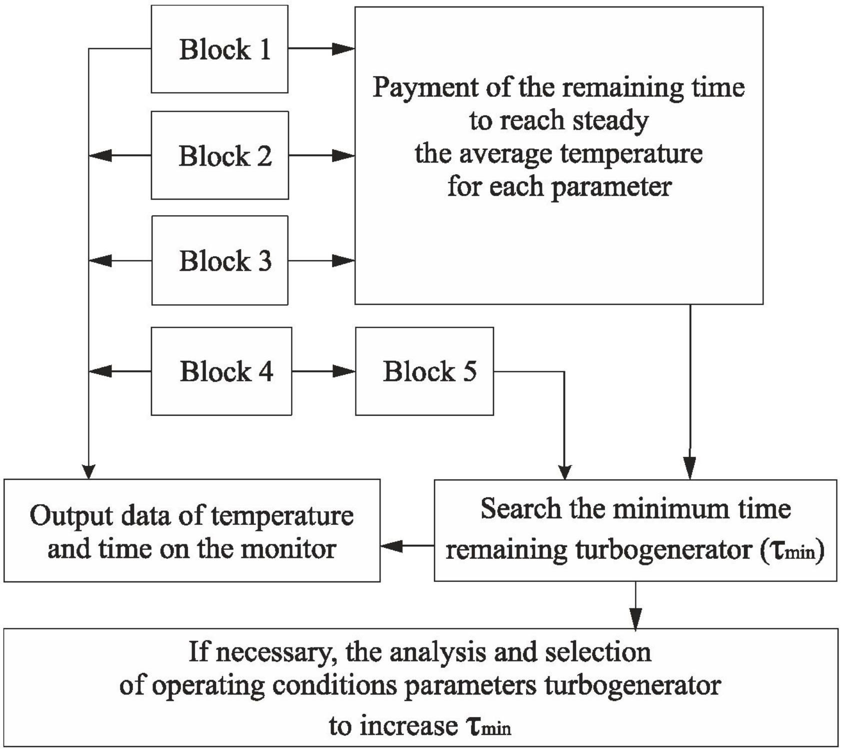

Figure 5. Block diagram of the calculation of the thermal state of a node turbogenerator

Conclusion

- Application of modern methods of information technologies allows usage of graphic method for final temperature determination of induction motor heating in order to predict final heating temperature of turbogenerator stator winding.
- When using decomposition approach, the problem of temperature field analysis of turbogenerator stator winding shaft can be divided into two parts: calculation of temperature distribution across cross-section of the shaft in quasisteady approximation with temperature analysis and temperature gradients in typical points of the shaft; calculation of nonsteady distribution of shaft average temperature with integral ratios of heat supply by electric current and removal by liquid heat-transfer agent.
- Implementation of decomposition approach for temperature field analysis of turbogenerator stator winding shaft allows expanding the notion of dynamics and space variation of temperature field and space variation of stator winding shaft temperature field, increasing reliability of technical state diagnostics of turbogenerator stator winding.

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