Proposals for Improving the Technical State of Turbogenerators in Excess of the Service Life

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***Abstract*—The state of the world economy, the global economic crisis determined that the first priority in making engineering decisions is economic profitability. This affected on the state and development of the electric power industry, in particular, on the operational policy of repairs and the implementation of replacement schedules for turbogenerators that have fulfilled the service life. Therefore, the main worldwide trend of the development of energy systems and turbine generators was not the replacement of equipment that had worked its life, but the extension of the terms of his work.**

Keywords—turbogenerator, reliability, extended life, stator core

I. INTRODUCTION

Economic profitability is a priority in making engineering decisions because of the state of the world economy and the global economic crisis. This was reflected in the state and development of electric power industry, in particular, on the operational policy of the repair and replacement of exhaust performance charts his life turbogenerators (TG). Therefore, the main trend in the development of energy systems and basic generating equipment (turbogenerators) was not to replace the old equipment, but to extend the life of the plant rough to repairs and / or modernization, [1,2].

II. PROBLEM STATEMENT

In modern power systems TG work in difficult conditions: with varying frequency and voltage values, with systematic starts and stops, with changing dynamic effects on the structural elements, with inaccurate synchronization, etc. The exploitation of turbogenerators in non-nominal modes is necessary to maintain the nominal parameters of the network with continuously changing electricity consumption, with "peaks" and "valleys" of load, [1]. However, the exploitation of the turbogenerator in the non-nominal modes causes accelerated wear and emergency trips, serial turbogenerators are not designed for these regimes, [1]. Therefore, during the period of intensive aging of electrical equipment, during modernization and repairs in order to extend the period of its exploitation, it is necessary to ensure:

1) Increase the periods between repairs, reduce maintenance and repair costs;

2) Increase in availability and maneuverability, overload capacity and operational reliability, [2];

3) Use of modern cooling systems. In particular, when upgrading TG with a capacity of 200-300 MW hydrogen should be replaced in the volume of the machine by air, [2,3]. This will require the reconstruction of cooling systems, gas and oil supply systems, will require the use of modern technical solutions: the use of a ventilation scheme with more intensive air circulation, direct cooling of windings, the use of electrical steels with low specific losses and insulation of a higher class of heat resistance;

4) To ensure the possibility of continuous trouble-free operation of TG in non-nominal modes: with active energy production reduced to 60-70%, in the reactive power consumption mode, [3,4];

5) It is necessary to apply a system for monitoring parameters in on-line mode, to perform technical diagnostics of the state of the most stressed nodes and elements, a comprehensive assessment of the state during planned and emergency repairs, [1,4].

III. THE MATERIALS AND THE RESULTS OF THE RESEARCH

It is necessary to repair all the elements of the generator after a significant period of operation, and not only those that determined the need to stop for repairs. The modifications made in the course of repairs, the general aging of equipment and building structures are taken into account when deciding on the extension of the service life. The results of the examinations and test data are used in the evaluation of the generator status, statistics are collected. Defects that cause the most severe consequences: 1) Destruction of individual elements of the rotor (shroud rings, necks of shafts, etc.); 2) Loss of tightness at the outlet of the shaft towards the turbine and excitation system for hydrogen-cooled TG; 3) Destruction of the end packets of the stator core and the frontal parts of the stator winding.

These defects lead to serious accidents, fires, explosions, to long forced downtime. In Table 1 presents data on the total underproduction of electricity due to TG failures with a capacity of 200 (220 MW for TG that have undergone modernization with increasing capacity without changing the dimensions) to 1000 MW (operating data of two-pole TG of Ukrainian NPPs) with various cooling systems.

It has been established that for the TG with water cooling of the rotor (series TZV), the main failures are caused by defects in the rotor elements, and with hydrogen-water cooling (series TGV and TVV), the destructions of the end packages of the laminated stator core and the technical condition of the windings, [4-6]. It was found that the main damage to the stator windings (especially the frontal parts) is caused by the destruction of the ends of the stacked stator pack. Therefore, during modernization and preparation of TG to extend the life of the system, it is necessary to determine and eliminate the causes of systematic damage to the stator windings and cores.

Table I. Damage from various types of failures and reliability indicators of TG with a capacity from 300 to 1000 MW with various cooling systems

Cooling medium of TG elements	**TG power, MW**	**Average failure rate of TG, units /(TG/year) / average idle time per failure (hours)**	**Possible damage**	
			Specific simple, hours /(TG/year)	**Specific underproduction of electricity, 103 (MW • h) / (TG / year)**
Water - in the stator windings; Hydrogen - in the rotor windings and inside the machine	1000	0,33 / 46,8	17,4	15,5
	800	0,5 / 47,3	16,8	13,2
	200 (220)	0,57 / 65,0	37,0	8,2
Water - in the stator and rotor windings; Air - internal volume of TG	800	1,0 / 170,0	22,4	16,2
	300 (325)	1,5 / 200,0	18,4	9,2
Oil - in the stator winding; Water - in the winding of the rotor; Air - in the volume of TG*	500	2 / 300,0	37,0	8,2

* Data of Russian TPPs

The stator core of the TG undergoes the action of the radial forces of magnetic traction from the electromagnetic forces when operating under load. Under the action of forces, the core deforms and oscillates with a double frequency of the mains voltage. Therefore, at the place where the core is fixed in the body, there are forces that transmit vibration to the body. Vibration leads to the destruction of core packs and can cause contact erosion of the contacting surfaces of the core and rib-wedges. The elastic suspension of the core in the housing is made to reduce the vibration of the housing and increase the flexibility of the fastening elements. For example, the design of the elastic suspension should be used with long longitudinal slots in the area of attachment of the ribs to the hull, Fig. 1, [1,7]. It is practically impossible to repair the cores on the station blocks. It is necessary to attract specialists and technological equipment of the plant - manufacturer. Therefore, the evaluation of the state of the laminated core and the establishment of the causes of its destruction is especially urgent. To increase the operational reliability of cores, in addition to the use of new materials and manufacturing techniques, the use of electrical steel with reduced specific losses, less thickness (0.35 mm), it is necessary to be able to calculate the effort in the blended package and the impact of the quality of the assembly technology. The main factors that determine the quality of assembly technology:

1) The degree of uniformity of the pressure distribution in the core, the determination of the state of the package pressing, and the reliability of gluing the laminated package;

2) Values of temperature coefficients of materials, static and dynamic loads;

3) The state of the insulating coating of the sheets, the layout of the laminated sheets, which determines the resulting bending deformation and the relative movement of the laminated sheets.

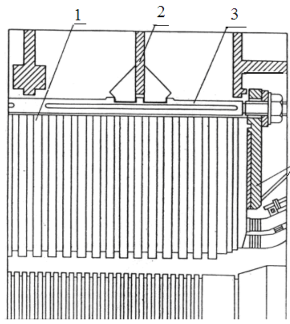
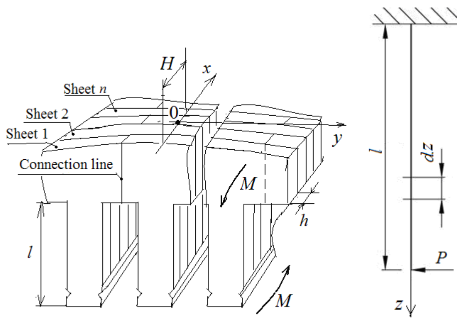


Fig. 1. Elastic suspension of the stator core in the body 1 - stator core; 2 - the hull shelf; 3 - rib of stiffness (rib-wedge); 4 - pressure plate ("pressure finger").

Imagine a laminated core package, like a glued bar of electrical steel sheets of thickness *h*. Denote the thickness of the insulating coverings δ, Fig. 2, a. We believe that the sheets are laid with overlapping by 1/*n* part of their length. Then it suffices to consider the deformation of the selected section in n layers, since in the remaining layers the picture will be repeated. Normal and tangential stresses appear in the teeth, which are directed from the edge to the edge of the pack. By the law of shear stress, we find that the tangential stresses in the cross section are equal to the tangential stresses that arise in the longitudinal sections. According to Zhuravsky's formula, we determine the tangential stresses during bending that arise at points of the cross-section of the beam from the external force P, located at a distance l (tooth height) from the neutral axis x, Fig. 2,*b*. We assume that the "fastening of the beam" is the transition of the tooth to the back of the core.



a) *b*)

Fig. 2. Laminated core element: *h* - is the thickness of the sheets making up the laminated package; *M* - ithe moment from bending forces; *H* - the width of the packet; *l* - the length of the section under consideration (tooth height); *n* - the number of joints caught in the zone under consideration *a*) places of joints in the core element; *b*) the shear stress model.

Let's write down the value of the tangential stress τ_{zy} in the place of the transition of the tooth to the stator back.:

$$\tau_{zy} = \frac{dM \cdot S_z}{dx \cdot J_z \cdot b} = \frac{Q \cdot S_z}{J_z \cdot b}. \quad (1)$$

Where Q – is the effective transverse elementary force from the bending moment along the length of the fixed element ($Q=dM/dx$). Then the distribution of tangential stresses across the section S_z:

$$S_z = F \cdot y_0 = b \cdot \left(\frac{h}{2}\right) \cdot \left(y + \frac{h/2 - y}{2}\right) = \frac{b}{2} \cdot \left[\left(\frac{h}{2}\right)^2 - y^2\right].$$

We substitute S_z into (1), and, taking into account that the axial moment of inertia for a rectangular cross section is equal $J_z = b \cdot h^3/12$, we determine the tangential stresses in the selected element:

$$\tau_{zy} = \frac{\frac{b}{2}\left[(h/2)^2 - y^2\right] \cdot Q}{\frac{b \cdot h^3}{12} \cdot b} = \frac{6 \cdot Q}{b \cdot h^3} \cdot \left(\frac{h^2}{4} - y^2\right).$$

The calculations showed [6] that the relative compliance of the laminated beam is determined by the longitudinal length and thickness of the sheets, the method of laying, the strength characteristics of the steel, and the thickness of the insulation layer. The tangential stresses in the material above the neutral layer are directly proportional to the transverse force, the static moment of the area of the cross section being considered, inversely proportional to the axial moment of inertia of the section and its width. As the length of the segment (*H*) increases, the compliance decreases, [4]. The maximum tangential stress at the root of the stator tooth is proportional to the maximum bending moment *M*, which is the transverse force from the bending moment along the length of the fixed element (tooth). For the insulation layer, there is no such dependence. If the bundled core packages are not glued, but only pressed with a uniform pressure p_0, the bending forces will lead to the sliding of the steel sheets in the area of the joints (lines joining the laminated sheets along the circumference, Fig. 2).

The performed calculations showed [2,7] that at a compacting pressure $p_0 \geq 1.0$ MPa and at a vibration level with an amplitude of radial oscillations not exceeding 20 μm, the relative slip of the sheets in the laminated core is observed in the joint zone of the sheets at a width of not more than 2 mm. In this case, the effect of the relative slip of the sheets on reducing the flexural rigidity of the cores is negligible and is less than 1%. At $p_0 \geq 1.5$ MPa, the relative slip of the sheets is practically absent in this vibration range. Accordingly, the weakening of the compact in the core leads to an increase in vibration, a decrease in the flexural rigidity, an increase in the zone of relative slip of the sheets (up to ten mm), the deletion of the insulation coating of active steel sheets, the closure of adjacent sheets, fretting corrosion, Steel, heating up to the occurrence of "fire in steel". The relative sliding of the sheets leads to a further reduction in the pressure in the pressed core package. Typically, the reduction of the compacting density of the outer packs is done by locally compressing the packets by installing steel and fiberglass wedges. Bonding of the sheets of the laminated core reduces the effect of this fact. In the tooth, which is weakened by the reduction of the compact, the action of the electrodynamics forces in the axial direction is intensified. This, in turn, leads to the appearance of fatigue cracks in the teeth, to the rash of their fragments; the insulation of the winding could collapse. We evaluate the electrodynamics forces in the axial direction and their effect on the state of the core. The fused core is represented as a set of permanent magnets, and we calculate the forces between the sheets. Magnetic fields from permanent magnets are similar to magnetic fields from electric currents. The definition of the interaction force between plates is reduced to solving the problem of the interaction of surface currents that form on the surface of a rectangular prism and circulate along the surface of the faces around axes that are oriented along one definite direction and create an external field, Fig. 4.

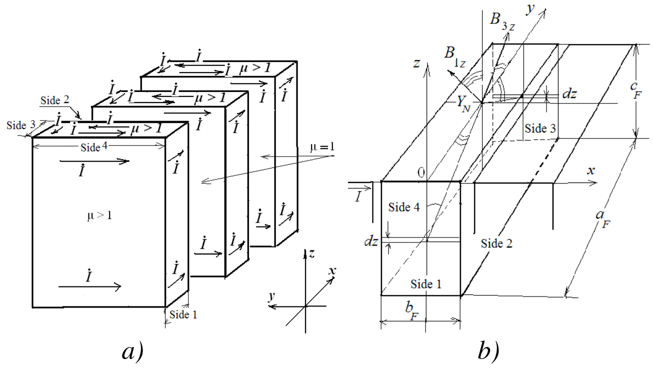


Fig. 4. The model of the system under analysis (*a*) is a model for the formation of surface currents; *b*) - distribution of magnetic fields in the plate of the stator teeth).

Surface currents are formed in planes that are perpendicular to the direction of magnetization along the x axis. The current density does not depend on the value of *x* and is determined by the intensity of the magnetization *M*. The vector potential of the field, which corresponds to the given magnetization *M*, is expressed by:

$$A_M = -\frac{\mu_0 \mu}{4\pi} \cdot \int_V \frac{M \times r}{r^3} \cdot dV = = \frac{\mu_0 \mu}{4\pi} \cdot \int_V \frac{\nabla \times M}{r} \cdot dV + \frac{\mu_0 \mu}{4\pi} \cdot \int_S \frac{M \times n}{r} \cdot dS. \quad \ldots\ldots\ldots(2)$$

Where the volume integrals are taken over the entire volume of the magnet (the sheet element), and the surface integrals are calculated from its surface. For a uniformly magnetized region, i.e. Region where the magnetization M does not change in magnitude and direction within the interior, the second volume integral in expression (2) is zero. Therefore, we calculate the mutual action of the plates only from surface currents.

The magnetic flux is created by two groups of currents, Fig. 4.*a*): 1) currents that are parallel to the *x*-axis; 2) currents that are parallel to the *y*-axis. Consider a group of currents parallel to the *x* axis. Let us consider a group of currents parallel to the *x* axis. For $\delta << b_F$, we can assume that the magnitude of the magnetic induction B_z in the plane z=0 depends only on the flux along the *y* axis. It can be calculated for each of the parties. Let us write the value of the total magnetic induction from the film current along the surface of different faces of one plate of the tooth, (Fig. 4, a), T:

1) for side 1, we can write

$$B_{1z}(Y_N) = \frac{\mu \cdot \mu_0}{2\pi} \cdot \frac{I}{c_F} \cdot \int_{-c_F}^{0} \frac{Y_N \cdot dy}{(Y_N^2 + y^2)} =$$

$$= \frac{\mu \cdot \mu_0}{2\pi} \cdot \frac{I}{c_F} \cdot arctg \frac{c_F}{Y_N};$$

2) for side 3, analogically:

$$B_{3z}(Y_N) = \frac{\mu \cdot \mu_0}{2\pi} \cdot \frac{I}{b_F} \cdot arctg \frac{c_F}{(a_F - Y_N)}.$$

Then the component of the magnetic flux through the end of the plate, determined by currents parallel to the x axis, can be calculated, Web:

$$\hat{O}_{1-3} = \int_{0}^{a_F} \tilde{n}_F \cdot (B_{1Z}(y) + B_{3Z}(y)) \cdot dy =$$

$$= \frac{\mu \cdot \mu_0}{2\pi} \cdot \frac{I}{c_F} \cdot \int_{0}^{a_F} (arctg \frac{c_F}{y} \cdot arctg \frac{c_F}{(a_F - y)} \cdot dy.$$

By the value of the flux, we calculated the value of the force that acts on the core plates in the axial direction, and which could be the cause of the destruction of the core. However, the calculation showed that the magnitude of these forces was insufficient to destroy. But the extreme laminated plate does not have one side of the plate. The forces that act on each extreme tooth of the laminated package are $F_i = p_{magn} \cdot (a_F \cdot c_F)$, where the square of tooth is $(a_F \cdot c_F)$. The total force that acts on the end sheet of the charge core is $F = F_i \bullet N_z$, where N_z is the number of teeth of the stator core. The moment that acts on the extreme plate, *N•m*: $M = F \cdot (c_F/2)$.

When carrying out the calculations, it was accepted: the thickness of the laminated plate is 0.5 mm; Length of the package between ventilation ducts 70-150 mm; the width of the tooth a_z = 20-50 mm, the magnetic permeability of electrical steel μ = 1000-6500, (Table 2). Calculations for the end sections, performed for the turbogenerator ТГВ 325-2А-У3, showed that the action of forces and moments in the end zone can cause the destruction of the tooth zone. After folding the edge sheet, the next sheet becomes the last one.

Table II. Dependence of pressure, force and moment acting on the last tooth of the laminated core stack of the stator, on the value of induction in the air gap of the TG for different values of the width of the tooth with the length of the packet between the ventilation channels of 110 mm and the induction change from 0.2 to 1.2 Tl

Options	**Width of the tooth, a_z, mm**			
	20	30	40	50
Pressing pressure, N/m^2	0,2–2,0	0,3-2,6	0,35-3,6	0,4-4,3
Strength in the blended bag between the core plates, *F*, N	0,5-4,2	1,2-7,0	1,3-10,2	2,0-13,9
The moment acting on the teeth in the axial direction, *M*, N•m	0,02-0,15	0,03-0,25	0,05-0,47	0,08-0,52

There is «a domino» effect. This fact is intensified by the periodicity of the action of forces (100 Hz), metal fatigue and the influence of scattering fluxes.

IV. Conclusions

1) The technical condition of turbogenerators is evaluated in order to determine the possibility of their further operation or establishing the need for maintenance, rehabilitation or full replacement.

2) During long-term operation and, accordingly, with considerable wear and tear, all the elements of the generators are subject to repair, and not only those that determined the necessity of stopping for repairs.

3) When upgrading and preparing the TG to extend the service life, it is necessary to determine and eliminate the causes of systematic damage to the stator windings and cores. The main reasons for the destruction of the bonded cores of TG stators are an increase in vibration due to rigid attachment of the core to the housing and a decrease in the density of the compact. Vibration leads to the destruction of packets of cores and can cause contact erosion of the contacting surfaces of the core and rib-wedges. To reduce the vibration of the housing and increase the flexibility of the fastening elements, the elastic suspension of the core is performed and the stiffness of the frontal parts of the stator windings is reduced, [4,5,8].

4) The choice of the technology for manufacturing the stator core should be maintained taking into account the axial forces that cause its destruction, especially in the end parts. Intuitive reconstruction of the end zones of the stator core does not give positive results. It is necessary to calculate the forces that lead to destruction, for each particular machine, [7-9]. Practical recommendations on the choice of the geometry of the end packets are proposed to exclude their destruction.

5) In the laminated stator core, the forces between adjacent plates in the middle of the laminated package in the axial direction can be neglected.

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