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MECHANICAL PROCESSES IN THE TERMINAL PARTS OF THE TURBOGENERATOR STATOR IMBRICATED CORE IN THE PRESENCE OF THE TOOTH AREA PRESSING DEFECTS

Вдосконалено математичну модель та методику розрахунку механічних характеристик в натискних плитах, обумовлених коливанням розпресування зубцевої зони. Реалізація моделі дозволила виявити особливості коливних процесів в механічно з'єднаній системі «зубець-палець-плита» при дефектах пресування осердя статора турбогенератора в зубцевій зоні, зокрема, при різній ступені розвитку дефектів, а саме – відгині різної кількості натискних пальців та зміні геометрії зубця при його частковому розкришенні. Виявлено появу вібрацій певних частот, яких не спостерігалось в умовно бездефектному генераторі, що дає можливість розробки в подальшому способу діагностування стану зубцевих зон магнітопроводу.

Ключові слова: турбогенератор, кінцева зона, зубець, призма, натискний палець, шихтований магнітопровід, механічні характеристики.

Усовершенствована математическая модель и методика расчета механических характеристик в нажимных плитах при распрессовке зубцовой зоны. Реализация модели позволила выявить особенности вибрационных процессов в механически связанной системе «зубец-палец-плита» при дефектах прессовки сердечника статора турбогенератора в зубцовой зоне, в частности, при различной степени развития дефектов, а именно – отгибе различного количества нажимных пальцев, а также изменении геометрии зубца при его частичном раскрашивании. Выявлено появление вибраций определенных частот, которых не наблюдалось в условно бездефектном генераторе, что дает в дальнейшем возможность разработки способа диагностики состояния зубцовых зон магнитопровода.

Ключевые слова: турбогенератор, концевая зона, зубец, призма, нажимной палец, шихтованный магнитопровод, механические характеристики.

A mathematical model and method of calculating the mechanical characteristics of the pressure in the slabs due to fluctuations in the tooth area pressing out was developed. The model implementation allowed identifying the characteristics of oscillatory processes in the mechanically connected "tooth-finger-plate" system in the presence of the turbogenerator stator core pressing defects in the tooth area, particularly with various defect degrees, namely bending of the different number of tooth supports and change in the tooth geometry upon its partial breakage. The vibrations in the fingers and plates at the site of contact were calculated, subject to occurrence of defects in pressing of the core tooth area (bending of the different number of fingers and change in the tooth geometry), as well as numerical values of the tooth vibration frequencies at the beginning of their sudden destruction. It was revealed that depending on the depth of the broken part, the tooth oscillation frequency changes, causing a decrease in the frequency of its transverse vibrations and a sharp increase in the oscillation amplitude, resulting in a growth of strain and stress. These processes greatly intensify the degree of tooth destruction. The emergence of certain vibration frequencies were revealed, which were observed in a relatively defect-free generator, which enables the further development of a method of diagnosing the state of the magnetic duct tooth areas.

Keywords: turbogenerator, terminal zone, tooth, prism, pressure finger, imbricated core, mechanical characteristics.

Introduction. It is known that almost all thermal power plant generating equipment is morally and physically obsolete, since it has worked for more than 200 thousand hours. Reliability of this equipment is reduced. The most problematic unit is the generator stator imbricated core, which has a complicated system of mounting and, in the course of operation, by virtue of thermomechanical forces, the system changes its mechanical condition, weakening or, contrarily, increasing the stator core force of pressing the iron sheets.

The analysis of information on failures and damages to the turbogenerators (TG) units shows that the main causes of damage to the TG stator 160−320 MW is damage to the active steel and windings due to local overheating, active steel pressing weakening, loosening of the grooving wedge and frontal winding part fasteners, as well as their increased vibration [1]. This is also the case for the nuclear power plant TGs 1000 MW.

As the nuclear power plant share in the total amount of the electricity generated in the country is increased, and a small rated capacity of the pumped storage power plants, the thermal power plant TGs will work in maneuvering, dynamic modes, in which the reliability of the generating equipment is much lower. The frequency of injuries in these modes, according to various estimates, increases 2−7 times. There is a need to develop the means to improve, primarily, the mechanical stability of the generator structural elements to these regimes. This is especially true for the tooth area of the imbricated core, pressed by separate tooth supports. As the load changes, and uneven heating is reduced and increased, they withstand the thermostatic varying forces, under the influence of which they may bend. This results in the local pressing out, mechanical destruction under the influence of electromagnetic forces, leading to severe emergency shutdowns of generators and, consequently, to under-production of electricity.

The pressure plates and tooth supports are the key elements directly supporting the pressing effort at the end of the core. As the pressing of the TG stator core is weakened, primarily the tooth area, a mechanical movement of the stator imbricated core and cracking of the TG stator active iron sheets occurs, provided that the generator runs for some time with the pressed out core. To avoid this, a continuous diagnostics is required [2].

This is a challenge for the experts in all companies globally, producing the powerful TGs, in particular «Electrovazhmash» plant (Kharkiv). However, the use of all methods and measures to increase the mechanical stability, in particular baking of the outer packages of the imbricated core, did not result in the ultimate addressing of this problem. The monitoring and diagnosing of the magnet core technical condition is not implemented, especially in the tooth area, since one side can have about a hundred of tooth supports, and it is unreasonable to install pressure sensors in each of them. Thus, the state of the problem is such that it needs further development and solution.

The objective of this research is to determine the distribution and redistribution of the mechanical forces, torque, linear elongations and deformations in the presence of defects of the tooth area pressing during operation on the basis of the developed mathematical model to calculate the mechanical properties in the terminal part of the TG stator core for further development of improved methods and means of control and diagnostics.

The mathematical model and method of calculating the mechanical properties in the terminal part of the TG stator core in the presence of the tooth area pressing defects during operation was improved. The general equation of static equilibrium is considered, which takes into account the influence of the pressure fingers on the tooth of the TG stator core in view of the tooth defect, in addition to the impact of the tooth supports and shrinking prisms on the stator core.

A mechanical system consisting of a plate, tooth supports, shrinking prisms and teeth was considered. This takes into account the impact of the tooth area defects on the stator core imbricated iron. The model takes into account the change in mechanical properties and parameters in the tooth supports, shrinking prisms, and tooth area over time, provided that the resultant of all forces and all moments is zero [3]. After conversion of static equations into dynamic, a system of two linear ordinary differential equations of the second order with two unknowns is solved. This system is solved using the analytical method by characteristic equations.

Fig. 1 schematically depicts the structure of the pressure plate, tooth support and tooth, and shows the mechanical strength in the tooth area of the stator core (R – means the radius of the circle drawn by the axis of shrinking prisms [m]; r–means the radius of the circle passing through the middle of the contact area of the tooth supports [m]; b –means the distance between the middle of the tooth support contact zone and the shrinking prism [m]; b_f – means a full length of the tooth support [m]).

Let us use a general equation of static equilibrium to describe the mechanical processes, which considers only the effect of the tooth supports and shrinking force of the shrinking prisms on the stator core of a powerful TG TGV-300 [4, 5].

$$\sum_{i=1}^{n}\vec{m}_i + \sum_{I=1}^{N}\vec{M}_I = 0; \quad \sum_{i=1}^{n}\vec{f}_i + \sum_{I=1}^{N}\vec{F}_I = 0, \quad (1)$$

where $\vec{m}_i = \vec{r}_i \times \vec{f}_i$ means the moment of force $\vec{f}_i$ of the i-th finger affecting the pressure plate; $\vec{M}_I = \vec{R}_I \times \vec{F}_I$ means the moment of force of the I-th shrinking prism affecting the pressure plate; N means the number of shrinking prisms in the TG stator; n means the number of the tooth supports in TG stator; $\vec{f}_i$ means the force affecting the i-th tooth support of a synchronous generator stator; $\vec{F}_I$ means the force affecting the I-th shrinking prism of the generator stator (Fig. 1) [3].

Then let's apply a general equation of static equilibrium to describe the mechanical processes, which considers, besides the impact of the tooth supports and shrinking prisms on the stator core, the impact of the tooth supports and teeth of the stator core TGV-300 in view of the tooth defects:

$$\vec{m}_n^* + \sum_{i=1}^{n}\vec{m}_i + \sum_{I=1}^{N}\vec{M}_I = 0; \quad \vec{f}_n^* + \sum_{i=1}^{n}\vec{f}_i + \sum_{I=1}^{N}\vec{F}_I = 0, \quad (2)$$

where f^*_n, m^*_n – means the force and the moment of force affecting the part of the tooth after the latter is broken.

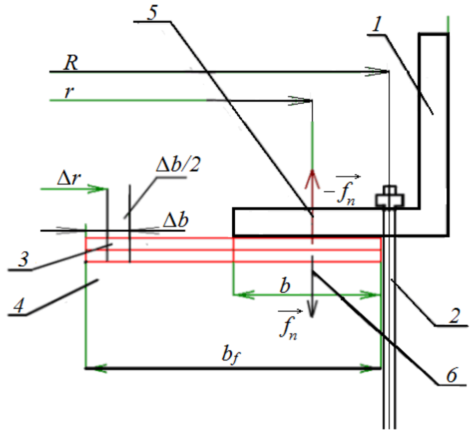

Fig. 1 – Graphic presentation of a mathematical model: *1* – plate, *2* – prism, *3* – finger, *4* – tooth, *5* – force affecting the finger, *6* – force affecting the tooth

Having assumed that the distribution of the mechanical stress of the tooth support on the tooth acts uniformly, then $f^*_n = f_n - \Delta f$, $m^*_n = m_n - \Delta m$.

$$\begin{aligned} & r(f_1\cos(\varphi_1) + \ldots + f_1\cos(\varphi_n)) - R(F_1\cos(\Phi_1) + \ldots + \\ & F_N\cos(\Phi_N)) - \Delta r \Delta f = 0, \\ & F_1 + F_2 + F_3 + \ldots + F_N = f_1 + f_2 + f_3 + \ldots + f_n - \Delta f, \\ & f_1 + f_2 + \ldots + f_n - \Delta f = P - \Delta f, \end{aligned} \quad (3)$$

where F_1, F_2, F_3, … F_N – means the value of mechanical forces in shrinking prisms; f_1, f_2, f_3 , …– f_N means the value of mechanical forces in the tooth supports [N]; φ_i –is the angle of the i-th finger position in the TG stator; Φ_I – means the angle of location of the I-th shrinking prism in the TG stator; P – means the total load of the TG stator pressed iron [N]; Δf – means a change in the force from mechanical action of the tooth on the tooth support after breakage of a single tooth [N]; Δm – means change of the moment of force from mechanical action of the tooth on the tooth support after breakage of a single tooth [N·m]; Δr – means the shoulder of the moment of force from the mechanical action of the tooth on the tooth support after breakage of a single tooth [m].

From a static system of equations (3) after some transformations let is proceed to a dynamic system of equations:

$$\begin{aligned} & \sum_{i=1}^{n} m_i - \sum_{I=1}^{N} M_i = r(f_1\cos(\varphi_1) + \ldots + f_n\cos(\varphi_n)) - \\ & - R(F_1\cos(\Phi_1) + \ldots + F_N\cos(\Phi_N)) = M_y = \varepsilon_y J_y, \\ & f_1 + f_2 + \ldots + f_n - \Delta f = P - \Delta f, \\ & M_y = \varepsilon_y J_y = J_y(a_n - a_{n/2})/2r = J_y 2\ddot{c}/2r = -J_y 2\ddot{c}, \end{aligned} \quad (4)$$

where J_y – means a moment of inertia of the pressing plate; ε_y – means an angular acceleration upon vibration oscillations of the pressure plate around the center of mass; a_n – means the vibration acceleration of the pressure plate at the point above the n-finger; $a_{n/2}$ – means the vibration acceleration of the pressure plate at the point above the n/2-finger; c – means the proportionality factor, which takes into account the uneven distribution of mechanical stress and strength in the fingers of TG stator.

The total value of projections of the force moments in the tooth supports, teeth and shrinking prisms affecting the pressure plate is respect of y axis create an angular acceleration ε_y. The total value of the force in the tooth supports for our mathematical model is always constant and equal to P–Δf.

The total value of the effect of the force moment projections from the tooth supports and teeth in relation to y axis is:

$$\sum_{i=1}^{n} m_i = r((f_0 + ckr\cos(\varphi_1))\cos(\varphi_1) + \ldots + (f_0 + ckr\cos(\varphi_n))\cos(\varphi_n)) - \Delta f \Delta r\cos(\varphi_n) = = 0{,}5ckr^2 n - \Delta f \Delta r, \quad (5)$$

where k – means the average coefficient of elasticity of TG stator tooth support [N/m].

From a system of equations (4), after some transformations and considering the equations (5), we obtain a system of equations:

$$\begin{aligned} &0{,}5ckr^2 n - r\Delta f - 0{,}5R^2 KCN = -J_y \ddot{c}, \\ &nf_0 = P, \end{aligned} \quad (6)$$

where K – means the average coefficient of elasticity of TG stator shrinking prism [N/m]; C – means the coefficient of proportionality, taking into account the uneven distribution of mechanical loads and forces in shrinking prisms of the TG stator.

For further calculations, let us conventionally split the shrinking prism into two halves along the y axis.

$$J_y \ddot{c} + 0{,}5ckr^2 n - \Delta f \Delta r - R^2 KcN = 0, \quad (7)$$

$$\ddot{c} + 0{,}5ckr^2 n / J_y - R^2 KcN / J_y - \Delta f \Delta r / J_y = 0. \quad (8)$$

Given a mechanical defect in the form of a partial tooth breakage, we get:

$$\begin{aligned} \Delta f &= (\Delta S / S)(f_0 + ckr\cos(\varphi_n)) = \\ &= (\Delta S / S)(f_0 + ckr) = (\Delta S / S)(P / n + ckr), \end{aligned} \quad (9)$$

where S – means the area of the tooth contact with the tooth support; ΔS – means the area of the broken tooth part.

After some transformations, we obtain the following expression:

$$\ddot{c} + c\omega^2 - (\Delta S / S)\Delta r P / (nJ_y) = 0, \quad (10)$$

where the value of the square of the angular velocity is:

$$\omega^2 = (0{,}5kr^2 n - R^2 KN - kr(\Delta S / S)\Delta r) / J_y. \quad (11)$$

The general solution of equation (10) will look as follows:

$$\begin{aligned} c(t) &= A\cos(\omega t) + B\sin(\omega t) + \\ &+ ((\Delta S / S)\Delta r P / (nJ_y)) / \omega. \end{aligned} \quad (12)$$

To find the A value we consider that at the initial time t=t_0 before tooth breakage and occurrence of additional vibrations, all tooth supports are all the same conditions, having the same load and the same initial compression. It follows that $c(0)$=0 and

$$A = -((\Delta S / S)\Delta r P / (nJ_y \omega)). \quad (13)$$

Similarly, to find B, given that all tooth supports are in the same conditions, i.e. have the same compression and no extraneous vibration shift of one finger relative to the other, $\dot{c}(0) = 0$ and B=0. Then the solution of equation (10) will look as follows:

$$\begin{aligned} c(t) &= ((\Delta S / S)\Delta r P / (nJ_y \omega)) - \\ &- \cos(\omega t)((\Delta S / S)\Delta r P / (nJ_y \omega)). \end{aligned} \quad (14)$$

The results of calculating the vibration and mechanical characteristics in the terminal part of the TG stator core, in the presence of the tooth area pressing defects. The calculation was carried out for TGV-300 type TG. The numerical value of the total load on all shrinking prisms or on all fingers is P=8829000 N.

The numerical value of mechanical force component f_0, acting on each tooth support, is $f_0 = P/n$ = 8829000/60 = 147150 N.

The numerical value of the mechanical compression of the tooth support Δl_0 in the area of contact of the tooth support and the pressing plate is $\Delta l_0 = f_0/k$ = 147150/(44100000000) = 3,33673 mkm.

The numerical value of the mechanical stress σ_0 for the tooth support in the contact area of the tooth support and the pressing plate is $\sigma_0 = f_0/s$ = 14014285,71 Pa.

The numerical value of the distribution of q_0 mechanical force for the tooth support in the contact area of the tooth support and pressing plate is q_0 = 392,4 kN/m.

The obtained numerical values of the parameters coincide with the defect-free operation mode. The contact area of the tooth and the tooth support is S = 0,027325 m^2.

From the size of the tooth area geometry, the area of the broken part of TG stator core tooth is found using the trapezoid area formula ΔS = (0,02 – 0,005)Δb+tgαΔb^2=(0,02 – 0,005)Δb + 0,053571Δb^2, where Δb – means the depth of the tooth broken part (Fig. 2).

The tangent of the angle α equals tgα = 0,053571429.

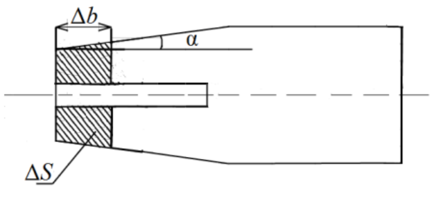

Fig. 2 – General layout of the broken tooth part

The tooth breaking process is seen in the terminal area of the TG stator core.

The numerical values of the tooth oscillation frequency at the beginning of their sudden collapse (at $\Delta b = 0$) and the ratio of this frequency to the 50 Hz electric current is as follows:

$$\omega_0^2 = (0{,}5kr^2 n - R^2 KN)/J_y = 10395225 \text{ s}^{-2},$$

$$\omega_0 = \sqrt{(0{,}5kr^2 n - R^2 KN)}/J_y = 32241{,}628 \text{ s}^{-1},$$

$$\nu_0 = 5131{,}41 \text{ Hz}, \quad \nu_0/50 = 102{,}63.$$

Calculations show that depending on the depth of the broken part, ν_i tooth oscillation frequency changes. There is a decrease in the frequency of its transverse vibrations. This generates a sharp increase in amplitude and, consequently, the growth of strains and stresses, sharply intensifying the tooth destruction process [6].

We will calculate the mechanical characteristics with regard to the tooth defects (the breakage depth is $\Delta b = 0{,}025$ m).

From solution of equations (12), (13) we obtain

$$c(t) = 8{,}84 \cdot 10^{-10} - 8{,}84 \cdot 10^{-10} \cos(32236{,}82t).$$

Then the dependence on the time of mechanical force for the i-th tooth support upon destruction of the n-th wave ($i = n$) ($\Delta b = 0{,}025$ m)

$$f_i(t) = P/n + (A\cos(\omega t) - A)kr\cos(\varphi_i) =$$
$$= P/n - Akr\cos(\varphi_i) + Akr\cos(\varphi_i)\cos(\omega t).$$

Hence

$$f_i = 147{,}15 + 0{,}0439\cos(\varphi_i) - 0{,}0439\cos(\varphi_i)\cos(\omega t) \text{ кN}.$$

It is evident that the forces affecting the finger have a constant component, fluctuating over time, and a component depending on the coordinates (φ_i – determines the angular distance of the i-th finger or tooth to the broken one).

The mean value of the $\sigma_i(t)$ mechanical stress dependence on time for the i-th tooth support, taking into account the tooth defect ($\Delta b = 0{,}025$ m) is as follows:

$$\sigma_i = 14014{,}286 + 4{,}184\cos(\varphi_i) - 4{,}184\cos(\varphi_i)\cos(\omega t) =$$
$$= 13808{,}8 - 4{,}121\cos(\omega t) \text{ кPa}.$$

The mean value of the $\Delta l_i(t)$ mechanical shift dependence on time for the i-th tooth support, taking into account the tooth defect ($\Delta b = 0{,}025$ m) is as follows

$$\Delta l_i(t) = P/(kn) - Ar\cos(\varphi_i) + Ar\cos(\varphi_i)\cos(\omega t) =$$
$$= 3{,}33673 \cdot 10^{-6} + 9{,}96168 \cdot 10^{-10}\cos(\varphi_i) -$$
$$- 9{,}96168 \cdot 10^{-10}\cos(\varphi_i)\cos(\omega t) \text{ m}.$$

Let us find the dependence of the $q_i(t)$ mean mechanical power distribution (mechanical force vs length ratio) from the time when the tooth is broken ($\Delta b = 0{,}025$ m):

$$q_i(t) = 392{,}4 + 0{,}117\cos(\varphi_i) - 0{,}117\cos(\varphi_i)\cos(\omega t) \text{ N/m}.$$

The results of the estimated studies are shown in fig. 3 and tabl. 1.

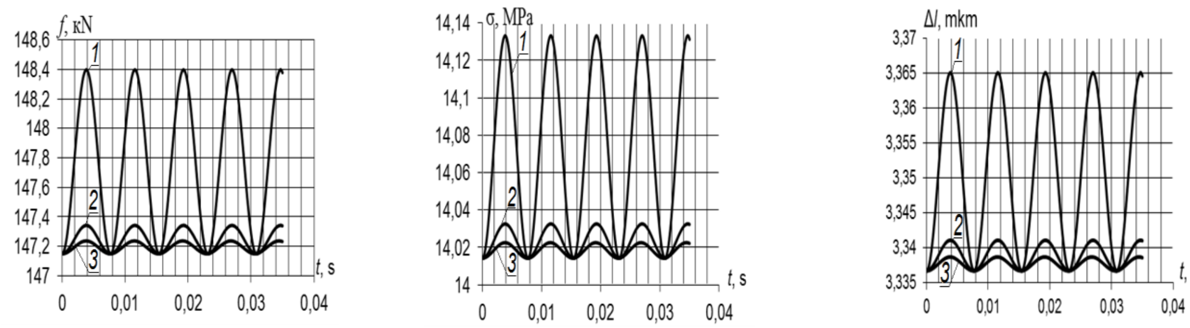

Fig. 3 – Dependence of the mechanical force, stress and shift from time affecting the 1-st and 59-th tooth support at the initial moment of tooth destruction under the 60-th finger (for 3 breakage options):
1 – at $\Delta b = 0{,}2$ m, *2* – at $\Delta b = 0{,}05$ m, *3* – at $\Delta b = 0{,}025$ m

Tabl. 1 shows the mechanical properties in the contact area of the fingers and plate stator of the TG 300 MW for varying degrees of the tooth breakage and, for comparison, when the tooth area pressing zone is normal and when one to five fingers are bent, and upon normal pressing of the stator core in the tooth area. The mechanical characteristics are presented in the table for the set mode.

Calculations of mechanical properties in the mechanically connected "tooth-finger-plate" system upon analysis of the dynamic process show that to monitor the same, it is sufficient to install only one sensor anywhere in a circle within the contact area of the plate and tooth supports. It is thus possible to monitor the changes in these characteristics, regardless of the sensor site. However, there are difficulties associated with the need to install the highly sensitive sensors, as well as change in mechanical forces and stresses are negligible (tabl. 1).

The research based on monitoring the mechanical characteristics in the contact area of the plate and finger as the defects of the tooth area pressing develop also showed the emergence of certain vibration frequencies not observed in a "relatively defect-free" generator. Based on this phenomenon, we might further develop an effective way to monitor and diagnose the pressing out of the tooth area of a powerful TG stator.

Table 1 – Mechanical characteristics in the area of contact of the tooth supports and plate with varying degrees of tooth defects (Δb=0,025 m; 0,05 m; 0,2 m*)* and the normal compression of the stator core in the tooth area (a relatively defect-free state) and when one to five fingers are bent, and upon normal pressing of the stator core in the tooth area

№ finger	«Defect-free»			Δb=0,025 m			Δb=0,05 m			Δb=0,2 m		
	σ_i, MPa	f_i, kN	Δl_i, mkm	σ_i, MPa	f_i, kN	Δl_i, mkm	σ_i, MPa	f_i, kN	Δl_i, mkm	σ_i, MPa	f_i, kN	Δl_i, mkm
1	14,0143	147,15	3,337	14,0184	147,193	3,3377	14,0235	147,246	3,3389	14,0737	147,774	3,3509
2	14,0143	147,15	3,337	14,0184	147,193	3,3377	14,0233	147,244	3,3389	14,0727	147,763	3,3507
3	14,0143	147,15	3,337	14,0183	147,191	3,3377	14,0231	147,242	3,3388	14,0711	147,746	3,3503
…	….	….	….	….	….	….	….	….	….	….	….	….
58	14,0143	147,15	3,337	14,0184	147,193	3,3377	14,0233	147,244	3,3389	14,0727	147,763	3,3507
59	14,0143	147,15	3,337	14,0184	147,193	3,3377	14,0235	147,246	3,3389	14,0737	147,774	3,3509
60	14,0143	147,15	3,337	13,8088	144,993	3,2878	13,5696	142,480	3,2309	11,4160	119,868	2,7181

№ finger	1 finger is bent			3 fingers are bent			5 fingers are bent		
	σ_i, MPa	f_i, kN	Δl_i, mkm	σ_i, MPa	f_i, kN	Δl_i, mkm	σ_i, MPa	f_i, kN	Δl_i, mkm
1	14,74	154,80	3,510	0	0	0	0	0	0
2	14,73	154,72	3,508	15,36	161,83	3,76	0	0	0
3	14,72	154,58	3,5052	15,32	161,36	3,75	16,22	167,30	3,83
4	14,70	154,38	3,5007	15,26	160,71	3,71	16,10	166,08	3,8
….	….	….	….	….	….	….	….	….	….
57	14,72	154,58	3,5051	15,32	161,36	3,75	16,22	167,30	3,83
58	14,73	154,72	3,5083	15,36	161,83	3,76	0	0	0
59	14,74	154,80	3,5102	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0

Conclusions.

1. A mathematical model and method of calculating the mechanical characteristics of the pressure plates due to fluctuations of the tooth area pressing out was improved. The model takes into account both the impact of the tooth supports and shrinking prisms, and the impact of the tooth supports and shrinking prisms of the TG stator core, considering the tooth defects, and allows calculating the mechanical properties at the beginning of the oscillation process and during static equilibrium, without inclusion of relaxation processes.

2. These characteristics were studied in a mechanically connected "tooth-finger-plate" system, provided the appearance of pressing defects in the core tooth area, particularly when a different number of tooth supports is bent, and the tooth geometry is changed. It was determined that changes in mechanical forces and stresses when 1 to 7 fingers are bent made up no more than 10 %, while a single finger was broken, these changes were even smaller, about 1 %. Therefore, to monitor the pressing status, it is required to use highly sensitive measuring equipment. Thus, the work was carried out in two ways, by controlling the mechanical characteristics on the pressure plates and vibrations caused by development of defects regarding the change of the tooth geometry and the number of bent tooth supports, the frequency of which varies depending on the relevant pressing state.

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