EVALUATION OF AXIAL DEFORMATIONS AND THERMOMECHANICAL STRESSES IN THE RODS OF THE HYDROGENERATOR'S ROTOR WITH THE APPEARANCE OF AN ECCENTRICITY AS A RESULT OF 2-D FIELD CALCULATIONS

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Introduction. Capsule hydrogenerators (HG) with a capacity of 23 MVA, type SGK 538/160–70M, designed for a usage at the hydroelectric power stations of the Dniprovsky cascade in the conditions of a relatively small water level difference from the upper and lower ridges. With the purpose of increasing their capacity, they had been improving and modernizing. Today, previously mentioned hydrogenerators have been operated for a long time at the Kyivska and Kanivska hydroelectric stations, and a significant amount of information about defects during the operation of the damaged parts of the hydrogenerator has been accumulated. A systemic search and an analysis of the reasons of such damage remain an urgent scientific and technical problem.

Articles [2-4] are devoted to the study of eccentricity in electric machines, including HG. Among the typical damage of the capsular HG, which significantly affect its performance and lead to emergency stops, we can highlight the following:

- separation of the rods of the damping winding (DW) at the poles of the rotor from the short-circuiting rings;
- separation of the rods of the damping winding (DW) at the poles of the rotor from the short-circuiting rings;
- burnout and deformation of the sheets of the electrical steel package of the pole due to excess currents in the rods of the DW;
- damage of the rods of the DW and the electrical steel package of the pole due to the eccentricity of the rotor and its friction against the stator core;
- burnout of stator winding insulation due to overheating or short circuit;
- thermal damage of the surface of the contact rings;
- destruction of the holder of the brush holder;
- damage and loss of wedges that fix the stator winding.

It should be noted that in powerful HG the ratio of the height of the air gap under the poles of the rotor to the diameter of the bore of the stator is only 0.1… 0.3%. For capsular HG SGK 538/160 - 70M these dimensions are equal to 6 mm and 6100 mm, respectively. Such features in the design of the HG cause the rapid appearance of the uneven height of the air gap during the operation of the HG. Unevenness can occur due to the appearance of the eccentricity of the rotor or the loss of cylindrical shape of the stator core or rotor. This damage of the HG is quite common because the known technical features to maintain the uniformity of the gap in such structures are not effective enough.

The purpose of the research. To analyze the damage of the capsular hydrogenerator type SGK 538/160–70M with a capacity of 23 MVA, which took place during its operation. Research by the methods of mathematical modeling the heat and axial deformations and thermomechanical stresses in the rods of the studied HG, which occur due to the appearance of static eccentricity (SE) of the rotor.

Research object. The research was carried out on the example of capsular HG SGK 538/160–70M, which has the following data: stator voltage – 6,3 kV; stator current – 2070 A; cosφ = 0,974; efficiency = 96,1%; rotor voltage – 390 V; rotor current – 1040 A; number of poles – 70; speed – 85,7 rpm; number of stator slots – 252; at each pole of the rotor there are 3 DW copper rods with a diameter of 17,5 mm; there are an interpolar electric constructions installed between the rods of the different rotor's poles, so DW have longitudinal and transverse type of construction; rotor length 1,6 m; one-sided air gap under the middle of the pole δ = 6 mm; class of insulation heating of the stator and rotor windings – F (155 ºC), the yield point of the copper rods of the rotor is $\sigma_{пл\_Cu}$=280 MPa, and strength limit is $\sigma_{мц\_Cu}$=390 MPa.

Mathematical model takes into account three physical fields of different nature: electromagnetic field, temperature field and field of thermomechanical stresses, that takes into account both heating and centrifugal mechanical stresses during the rotation of the rotor. The electromagnetic field within the cross section of the salient-pole machine with respect to the complex amplitude of the vector magnetic potential $\dot{A}_z$ is described in Cartesian coordinates by a quasi-stationary equation:

$$\frac{\partial^2 \dot{A}_z}{\partial x^2} + \frac{\partial^2 \dot{A}_z}{\partial y^2} - j\omega_1 s\mu\gamma \dot{A}_z = -\mu \dot{J}_{zcm} \quad , \qquad (1)$$

where $\omega_1 = 2\pi f_1$ – is the angular frequency of the stator current, s – is the rotor slip, μ – is the magnetic permeability, γ – is the electrical conductivity, J_{zcm} – is the density of extraneous currents (current density in the stator slots, which is set according to the connection of the winding, current density in the excitation winding). Equation (1) is supplemented by homogeneous boundary conditions of the first kind $A_z|_G$=0 on the line of the outer surface of the stator frame yoke. Equation (1) allows to calculate the electromagnetic field of the machine in constant asynchronous and synchronous operation modes. In synchronous operation mode, accept s = 0.

According to the specified calculation method for each moment of the time within the formed geometry of the calculation area, equation (1) is solved at the corresponding time values of the current density of the stator phases, which are determined by the formulas:

$$\begin{gathered}\dot{J}_{A\,ст} = J_m \cos\alpha_k, \\ \dot{J}_{B\,ст} = J_m\left[\cos\left(\alpha_k + 2\pi/3\right) + j\sin\left(\alpha_k + 2\pi/3\right)\right], \\ \dot{J}_{C\,ст} = J_m\left[\cos\left(\alpha_k + 4\pi/3\right) + j\sin\left(\alpha_k + 4\pi/3\right)\right],\end{gathered} \qquad (2)$$

where $J_m = I_{m1}u_{П1}/S_{П1}$ – is the current density in the phases of the stator winding, $u_{П1}$ – is the number of series-connected conductors in the stator slot; $S_{П1}$ – the cross-sectional area of the stator slot; $\alpha_k = \omega_R t_k$, ω_R – angular speed of the rotor, k=1,…,N – number of steps per time.

The value of μ at each point of the calculation area, where the ferromagnetic materials are located, is determined by the numerical solution of equation (1) by the iterative method according to the given magnetization curves. Electrical conductivity is set only in the slots of the rotor poles, in which the conductive rods of the DW are located. The electrical conductivity in the slots of the stator is assumed to be zero, but the extraneous current density is set in the same slots of the stator according to formulas (2). The current densities in the rotor windings J_2 are set as constant values in accordance with the specified value of the excitation current and the cross-sectional area of the excitation coils.

Equation (1) is supplemented by homogeneous boundary conditions of the first kind $A_z|_G=0$ on the line of the outer surface of the stator frame yoke.

The components of the magnetic induction vector are determined by the relations:

$$\dot{B}_x = \partial \dot{A}_z / \partial y, \qquad \dot{B}_y = \partial \dot{A}_z / \partial x, \tag{3}$$

The current density induced in the electrically conductive rods of the DW is determined on the basis of the first Maxwell's equation by the following expression:

$$\dot{J}_z = (\partial \dot{B}_y / \partial x - \partial \dot{B}_x / \partial y) / \mu. \tag{4}$$

Heat losses in the rods of the DW are determined on the basis of expression (4) as follows:

$$\mathrm{Q}\,(\mathrm{x}, \mathrm{y}) = \left| \dot{J}_z(x, y) \right|^2 / \gamma. \tag{5}$$

Thermal power losses in the stator and rotor windings are counted in the usual way with known active resistances of the windings and the specified values of currents in the windings.

The mathematical model of the temperature field is based on the stationary differential equation of thermal conductivity. In Cartesian coordinates in the 2-D formulation of the equation, it is written as follows:

$$\lambda \left[\frac{\partial^2 \theta(x,y)}{\partial x^2} + \frac{\partial^2 \theta(x,y)}{\partial y^2} \right] = -Q(x, y), \tag{6}$$

where $\theta(x, y)$ – is an unknown distribution function of the temperature; λ – is the coefficient of thermal conductivity; $Q(x, y)$ – volumetric specific heat field sources, W/m^3, which are power losses in the windings (in the excitation winding on the rotor and in the stator winding) when operating in nominal synchronous operation mode, as well as in the rods of DW in asynchronous operation mode of the HG.

At the boundary, which is the outer surface of the rotor and on the inner surface of the stator bore, the boundary conditions of the third kind were set:

$$\lambda \frac{\partial \theta}{\partial n} = -\alpha(\theta - \theta_c), \tag{7}$$

where θ_c – is the temperature of the cooling air (θ_c = *40 °C*), α – is the heat transfer coefficient from the stator and rotor surfaces into the cooling air, which has the value α = 30 W/(m^2·K). The following values of thermal conductivity coefficients were set during the calculations: electrical insulation of the stator and rotor windings $\lambda_{\text{із}}$ = 0,25 W/(m·°C); copper conductors λ_{Cu} = 400 W/(m·°C); steel λ_{Fe} = 45,4 W/(m·°C); air $\lambda_{\text{пов}}$ = 0,0235 W/(m·°C).

The main calculation value for the stress-strain analysis is the mechanical stress tensor according to von Mises, which characterizes the average value of mechanical stresses occurring per unit volume of material under the influence of the combined action of force factors of different spatial direction and different physical nature. The increase in the linear dimensions (lengths) of the rods at the pole of the rotor when heated by the value $\Delta\theta_k$ is calculated by the formula:

$$\Delta L_k = \alpha_L \cdot L \cdot \Delta\theta_k,\ k = \overline{1, N}, \tag{9}$$

where N – is the number of rods at the pole; α_L – coefficient of linear expansion (for copper $\alpha_L = 16{,}7 \cdot 10^{-6}$ °C^{-1}); L – is the length of the rod.

If we input a relative increase in length $\varepsilon_k = \Delta L_k / L$, the thermomechanical stresses that occur in the rod due to its heating, are expressed according to Hooke's law by the formula:

$$\sigma_k = E\varepsilon_k, \tag{10}$$

where E – is the Young's modulus (for copper $E = 123 \cdot 10^9$ Pa).

Numerical implementation of the given mathematical model is performed by the finite element method in the environment of the software complex Comsol Multiphysics. The solution of equation (1) that takes into account the actual speed of rotation of the rotor was performed by the method of multiposition calculations described in [1].

The value of the SE of the rotor is conveniently characterized by the coefficient of relative eccentricity.

$$\varepsilon = \frac{\delta_{max} - \delta_{min}}{\delta_{max} + \delta_{min}},$$

where $\delta_{max}, \delta_{min}$ - maximum and minimum values of the air gap.

The coefficient of relative eccentricity varies from 0 ($\delta_{min} = \delta_{max}$ – no eccentricity) to 0,83 ($\delta_{min} = 1\ mm$), as shown in Table 1 [2].

Table 1 – The values of the eccentricity of the HG's rotor

Parameter	Parameter's value					
Δδ, mm	0	1	2	3	4	5
δmax, mm	6,0	7,0	8,0	9,0	10,0	11,0
δmin, mm	6,0	5,0	4,0	3,0	2,0	1,0
ε	0	0,17	0,33	0,50	0,67	0,83

The scheme for the analysis of currents in all elements of DW of a rotor at various size of eccentricity of a rotor of the HG was developed in the program National Instruments Multisim. Scheme is shown in fig. 1 and contains the electrical parameters of the main elements of the DW. The current is closed in the circuit of the DW, which consists of 2 border rods and 2 short-circuiting segments at the pole. This current is caused by pulsations of magnetic flux as a result of SE. In the central rod of the DW, which is located equidistantly from the edges of the pole, currents do not flow.

The results of the research. Fig. 2 shows the current densities occurring in the rods of one pole of the DW as a result of the appearance of static eccentricity of the rotor of the HG in the range ε = 0…0,83. Fig. 3 shows the corresponding temperature distribution of the rods, fig. 4 – longitudinal thermomechanical deformations of the rods, and fig. 5 – thermomechanical stresses in the rods. It should be emphasized that these physical processes are constant, i.e. currents in the rods flow continuously and in synchronous operation modes of the HG, because when the rotor rotates in an uneven air gap, the magnetic flux of the poles pulsates with the frequency of the rotation and induces currents in the DW.

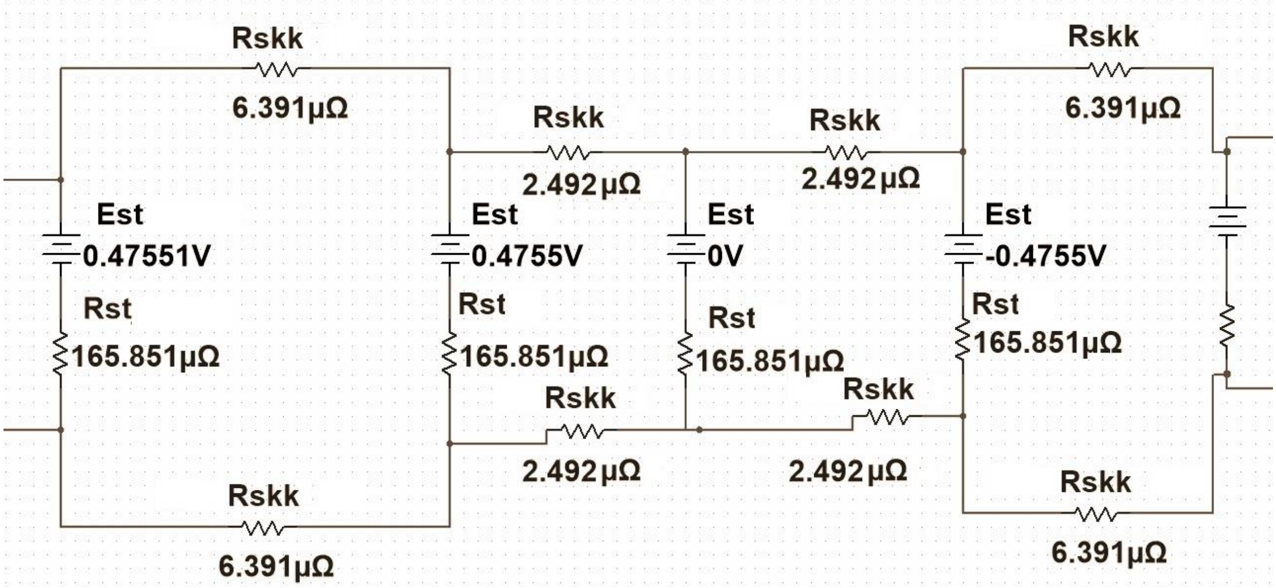

Figure 1 – A fragment of the scheme for calculating currents in the rods of the DW with the presence of SE of the HG's rotor

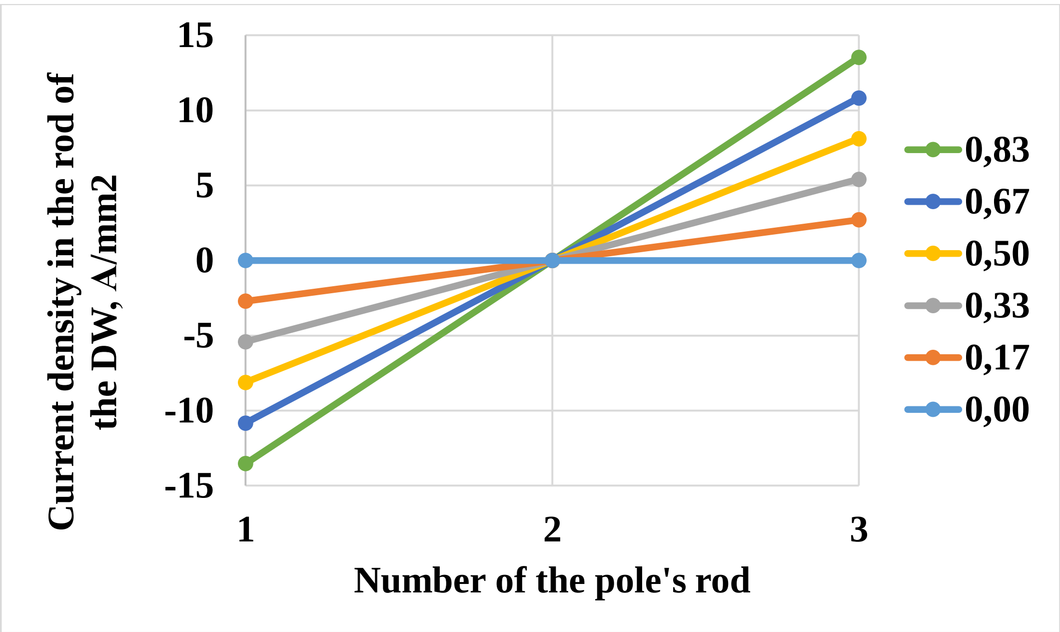

Figure 2 – Distribution of current densities in the rods of the DW with the presence of SE of the HG's rotor

Fig. 2 shows that even at insignificant values of the SE of the rotor there are significant current densities in the rods of the DW (to 13,5 A/mm^2), that significantly exceeds the calculated value of the current density of the DW (2,37 A/mm^2). As a result, there is a burnout and deformation of the sheets of the electrical steel package of the pole due to significant currents in the border rods of the DW. Due to the flow of significant currents, the border rods of the DW can be heated up to 213 °C at ε=0,67 and up to 307 °C at ε=0,81 (fig. 3).

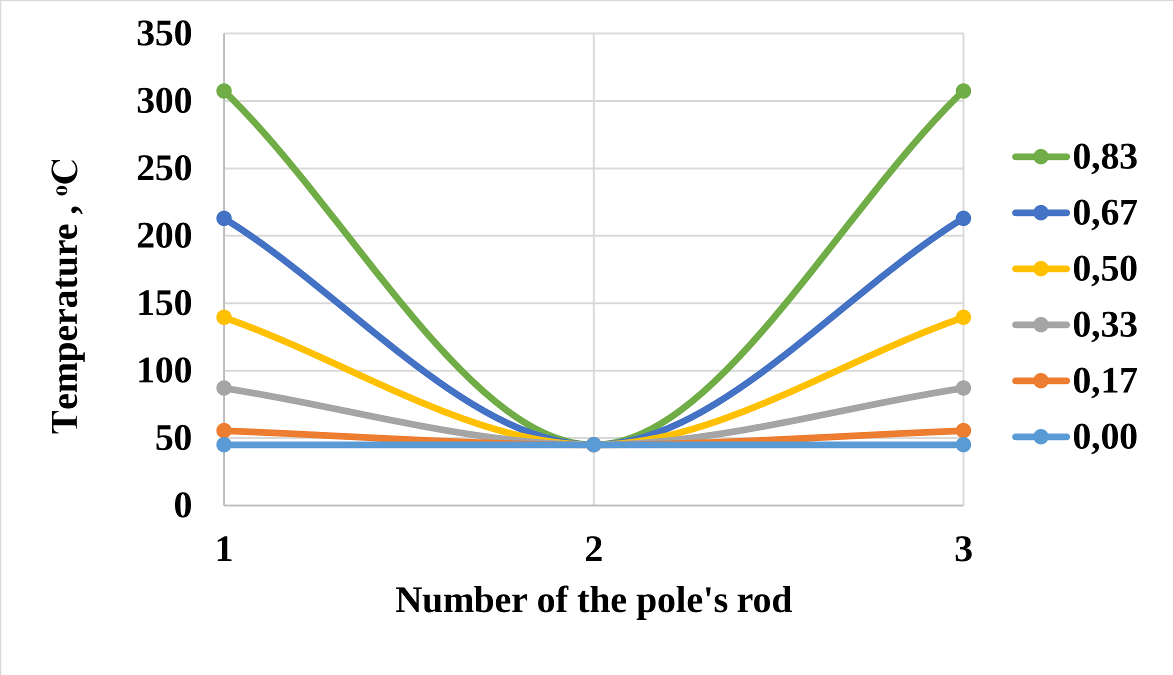

Figure 3 – Temperature distribution in the rods of the DW with the presence of SE of the HG's rotor

Significant heating of the rods of the DW leads to significant within the length of the pole of the rotor temperature elongations of the rods in the axial direction (up to 5,9 mm at ε=0,67 and up to 8,5 mm at ε=0,83, fig. 4) and the corresponding longitudinal mechanical stresses (up to 391 MPa at ε=0,67 and up to 565 MPa at ε=0,83, fig. 5). This increases the probability of separation of the rods from the short-circuiting rings of the damping winding, because the values of the longitudinal mechanical stresses in the rods of the DW reach values close to the strength limit of the copper rods of the DW.

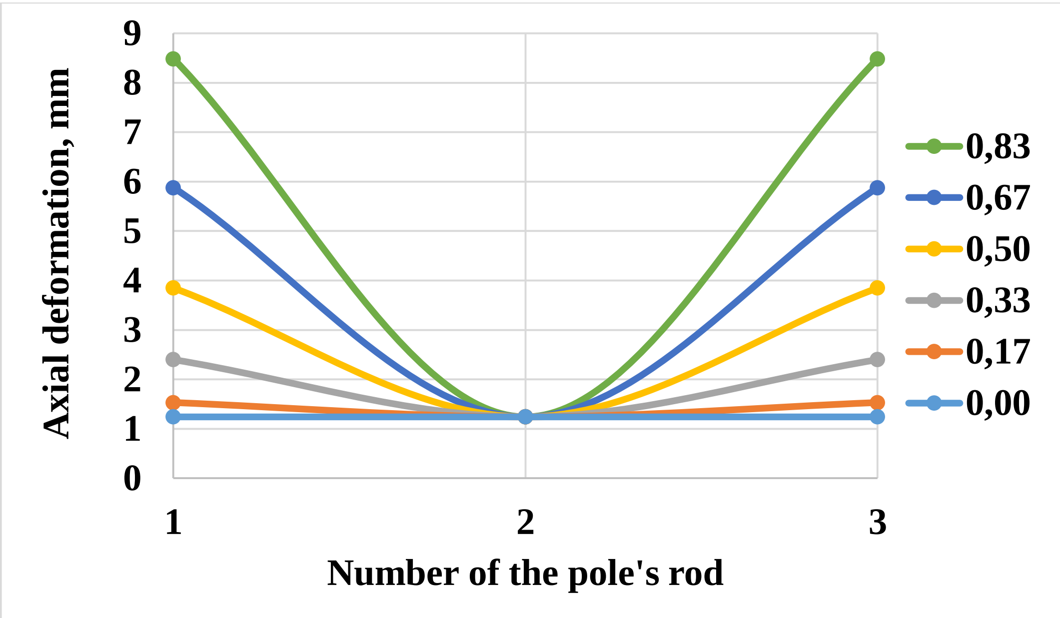

Figure 4 – Distribution of longitudinal thermomechanical deformations in the rods of the DW with the presence of SE of the HG's rotor

It is obvious that there is a significant difference between the values of thermomechanical deformations and stresses between the central and border rods of the DW at the pole, which leads to bending and destruction of short-circuiting segments of the DW of the rotor. Thus, the appearance and development of the SE of the rotor is one of the most significant reasons of emergency damage and failure of the HG.

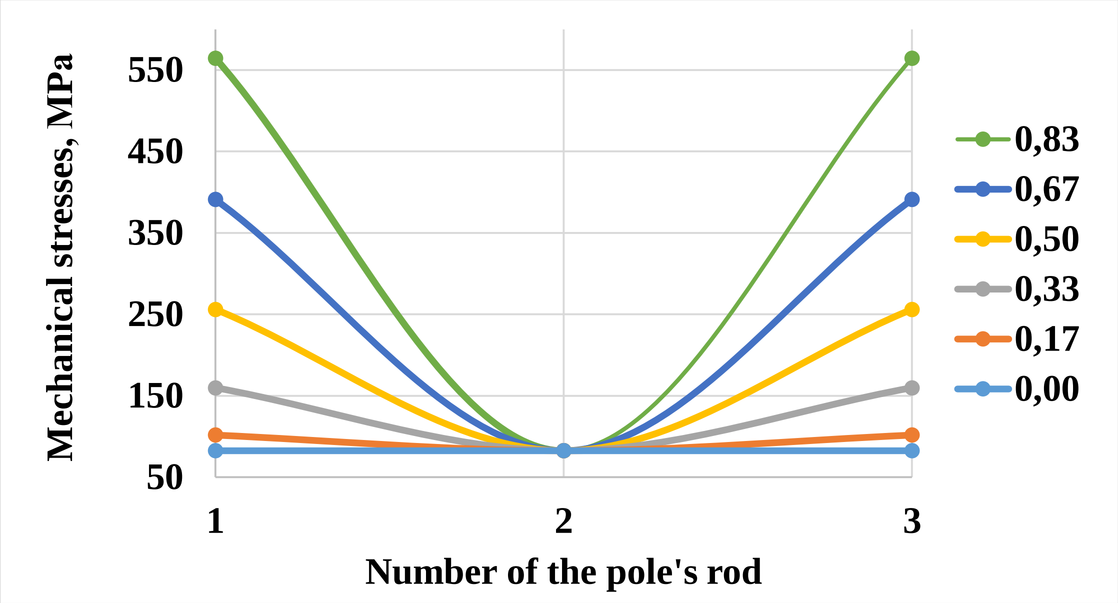

Figure 5 – Distribution of longitudinal thermomechanical stresses in the rods of the DW with the presence of SE of the HG's rotor

Conclusions. Damage of the SGK 538/160–70M capsule hydrogenerator with a capacity of 23 MVA, which took place during its operation, was analyzed.

The heat and mechanical stresses in the rods of HG, which occur due to the appearance of the SE of the rotor have been researched with use of he methods of mathematical modeling.

It is shown that in real conditions of HG operation, which are characterized by a significant value of SE, asymmetric thermomechanical deformations of DW rods are dangerous and can cause an emergency stop of HG.

References

1. Васьковский Ю.Н. Вибровозмущающие электромагнитные силы в короткозамкнутых асинхронных двигателях при наличии повреждения их конструкции / Васьковский Ю.Н., Гераскин А.А. // Технічна електродинаміка № 5, 2010, с.31-38.

2. Вібродіагностика ексцентриситету ротора асинхронних машин на основі аналізу вібрuзбуджуючих сил / Ю.М. Васьковський, О.А. Гераскін // Вісник НТУ «ХПІ». Тематичний випуск «Електричні машини та електромеханічне перетворення енергії». – Харків: НТУ «ХПІ», 2014. – № 38 – С52-62.

3. Васьковський Ю.М. Діагностика кутового ексцентриситету ротора асинхронних двигунів на основі аналізу вібрuзбуджуючих сил / Ю.М. Васьковський, О.А. Гераскін, Н.В. Беленок // Вісник Національного технічного університету «ХПІ». Збірник наукових праць. Серія: Електричні машини та електромеханічне перетворення енергії. – Харків: НТУ «ХПІ». – 2016. – № 11 (1183). – С. 30-35.

4. Васьковський Ю.М. Електромагнітні процеси у демпферній системі роторів гідрогенераторів при нерівномірності повітряного проміжку / Ю.М. Васьковський, С.С. Цивінський, О.І. Титко // Технічна електродинаміка. – 2015. – № 1. – С. 65–71.