3-D ANALYSIS OF THERMOMECHANICAL STRESSES IN HYDROGENERATOR'S ROTOR RODS WITH THE APPEARANCE OF THE ECCENRTICITY

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Introduction. Capsule hydrogenerators (HG) with a capacity of 23 MVA type SGK 538/160–70M have been operated for a long time at the Kyivska and Kanivska hydroelectric stations of the Dniprovsky cascade**.**

The accumulated experience of operation of previously mentioned HG shows that one of the most common types of its damage is the separation of the rods of the damping winding (DW) from the segments of short-circuiting rings (SSCR) at the poles of the rotor, which leads to great accidents. One of the major causes of the destruction of the DW may be the uneven distribution of currents and, accordingly, the uneven heating of the rods of the DW, which occurs when the HG is operated in asynchronous operation mode or when appears the eccentricity of the rotor. Especially dangerous for DW is the eccentricity of the rotor. For the HG more common is the static eccentricity (SE) of the rotor, in which the longitudinal axes of the stator and rotor are parallel to each other and are mutually fixed, in contrast to dynamic eccentricity, when the axes of stator and rotor do not coincide, and are parallel to each other, but the rotor axis together with the rotor rotates around the axis of the stator. The appearance of eccentricity can lead to mechanical damage not only in the rods of the DW, but also in the packages of electrical steel of rotor and stator due to friction of the rotor against the stator core. Articles [1, 2] are devoted to the study of the types of the damage in synchronous machines.

Since this damage significantly affects the efficiency of HG, the study of the causes and the results of the destruction of the DW is an urgent scientific and technical task.

The purpose of the research. The purpose of this article is to study the results of thermomechanical stresses modeling in DW and their analysis with the appearence of SE of the rotor using a new 3-D field mathematical model.

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; one-sided air gap under the middle of the pole δ = 6 mm**;**

At each pole of the rotor DW looks like a sector of the "squirrel cage" that consists of 3 copper rods with a diameter of 17,5 mm and a length of 1,653 m. Between the part of the rod located in the slot and the SSCR there is a part of the rod 40 mm long, cooled by air. There are interpolar electrical constructions between the SSCR of each pole of the rotor, i.e. DW has a longitudinal-transverse type of construction. 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. The 3-D field mathematical model is based on a system of differential equations in partial derivatives, which is used to solve stationary problems of structural mechanics. In general, this system of equations has the following form:

$$0 = \nabla \cdot FS + \vec{F}, \qquad F = \nabla u + I,$$

where ∇ – Hamilton's differentiation operator S – effort tensor; F – strain gradient tensor; ∇u – offset gradient; I – moment of inertia, $\vec{F}$ – vector of distributed mass force (centrifugal force during body rotation, gravity, force of thermal deformation).

Von Mises's mechanical stress tensor (MST) was used to analyze the magnitude of mechanical stresses, which characterizes the average value of mechanical stresses occurring per unit volume of material under the influence of the combined action of the different spatial direction and different physical nature forces.

Numerical implementation of the mathematical model is performed by the finite element method in the environment of the software complex Comsol Multiphysics. It was assumed that the HG operates in synchronous operation mode at the nominal load, but has the static eccentricity of the rotor. it was assumed that in the calculations the part of the rod placed in the slot of the pole is movable only in the axial direction.

The value of the SE of the rotor is 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 results of the research. The design of the capsule HG type SGK 538/160-70M in terms of its resistance to the appearance of SE is quite ineffective. Each pole of the rotor of the specified HG contains three rods, and with the appearance of the SE induced currents flow only in the boarder rods, and in the central rod currents are absent. That's why, the central rod remains "cold", and the boarder rods are "hot", it causes the maximum temperature and thermomechanical stresses difference in the elements of the DW.

With the appearance of large values of the SE of the rotor (from ε=0,50 to ε=0,83) appears significant values of the maximum thermomechanical stresses in the SSCR (from 218 to 603 MPa), the largest values of which significantly exceed the yield strength and strength of the copper rods of the rotor of the DW. As a result, there is a significant thermomechanical deformation of the rods and SSCR of the DW, which increases the probability of separation of the rods from the short-circuiting rings of the DW.

Figures 1 – 3 shows in color (purple colors correspond to larger MST values) 3-D distributions of thermomechanical stresses in SSCR and the rods of the DW with the presence of SE of the rotor with the its value ε = 0,83. These figures show hyperbolized (magnified) 300 times thermomechanical deformations of the rods and SSCR of the pole's DW, which clearly reflect the spatial shape of their bending.

Fig. 1 shows a DW from the inside (from the core of the pole), and fig. 2 shows the DW and the corresponding thermomechanical stresses from the end of the pole. These figures show a significant difference in the lengths of the boarder and middle rods due to difference in their heating. In general, the rods and SSCR are attached to each other by welding and thermomechanical forces significantly affect the weld. The magnitude of the summary thermomechanical stresses in the rods of the DW is influenced not only by axially directed forces, but also by transverse forces in the short-circuiting ring.

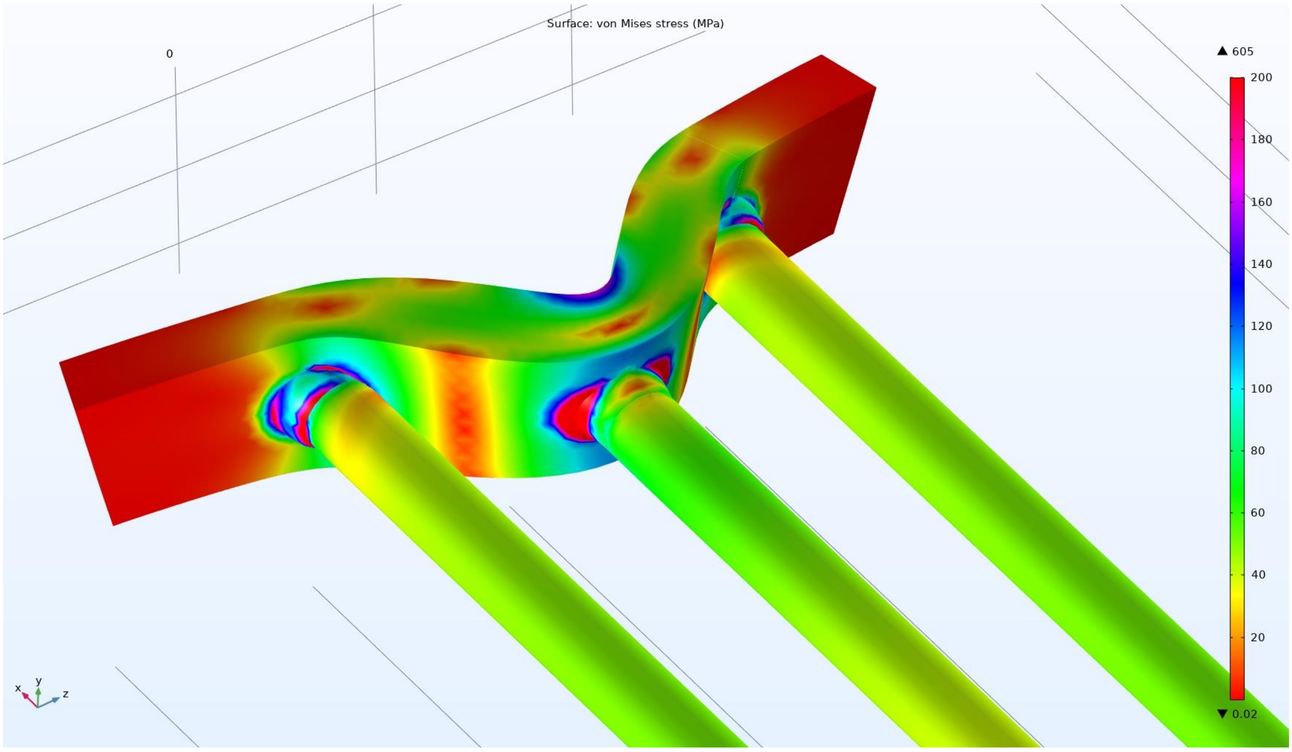

Figure 1 – Distribution of thermomechanical stresses in the SSCR and the rods of the DW with the presence of SE of the rotor ε = 0,83 (view from the core of the pole)

All forces of thermomechanical origin that appears in the rods and SSCR of the DW, can be divided into 3 components:

1) axial force acting on the separation of the central rod from the short-circuiting ring of the DW. This force creates MST component up to 151 MPa at SE ε=0,83, and the mechanical stresses within the cross section of the central rod are distributed relatively evenly. The summary tensile force acting on the central rod is 2.07 tons.

2) axial compression force applied to the boarder rods that are elongated due to their temperature heating. This force at SE ε=0,83 in each of the boarder rods creates local maximum of thermomechanical stresses up to 297 MPa, which are almost 2 times higher than the MST in the central rod, but distributed along the cross section of the boarder rods significantly unevenly. Although the integral force acting on each of the boarder rods is about 2 times less than the integral force applied to the central rod, but

due to the greater value of the local MST in some parts of the boarder rods, the destruction of the material of the DW begins from them.

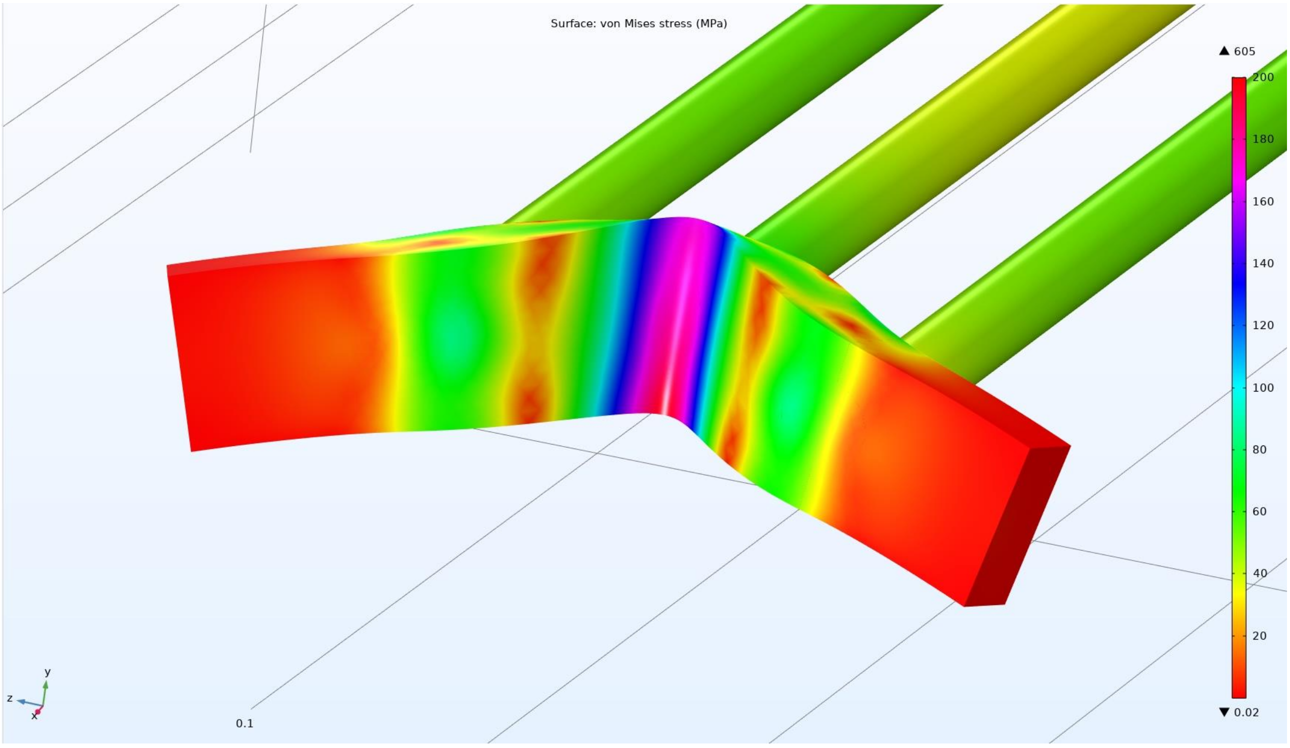

Figure 2 – Distribution of thermomechanical stresses in SSCR and DW rods with the presence of SE of the rotor ε = 0,83 (view from the end of the pole)

3) the tensile force of the SSCR due to the different elongation of all pole rods, which acts in the direction of the arc of the sector of the short-circuiting ring of the DW and leads to the bending of the SSCR that are welded to the ends of all rods of the DW. This force tensiles the SSCR and also is an important factor in the destruction of the DW, because increases the probability rods damage.

The combined action of all three forces in different directions in space leads to a complex thermomechanical process of damage to the DW of the HG due to the appearance of large local values of MST in the rods and in SSCR.

As was already mentioned, the cause of such damage is, on the one hand, the appearance of the SE of the HG’s rotor, and on the other hand - an ineffective design of the DW of HG type SGK 538/160-70M, because the presence of an odd (three) number of rods at the pole in this design leads to the conditions of rapid destruction of the DW.

It is known that the choice of the DW parameters depends not only on the number of rods, but also on other factors, such as the electromagnetic moment that can give DW in asynchronous operation mode, but this factor must be taken into account while creating DW resistant to SE. For example, the number of the rods of the DW at the pole can be equal to not only two but also four, but, in general, in any design, their number should be even to avoid the presence of the rod located in the center of the pole.

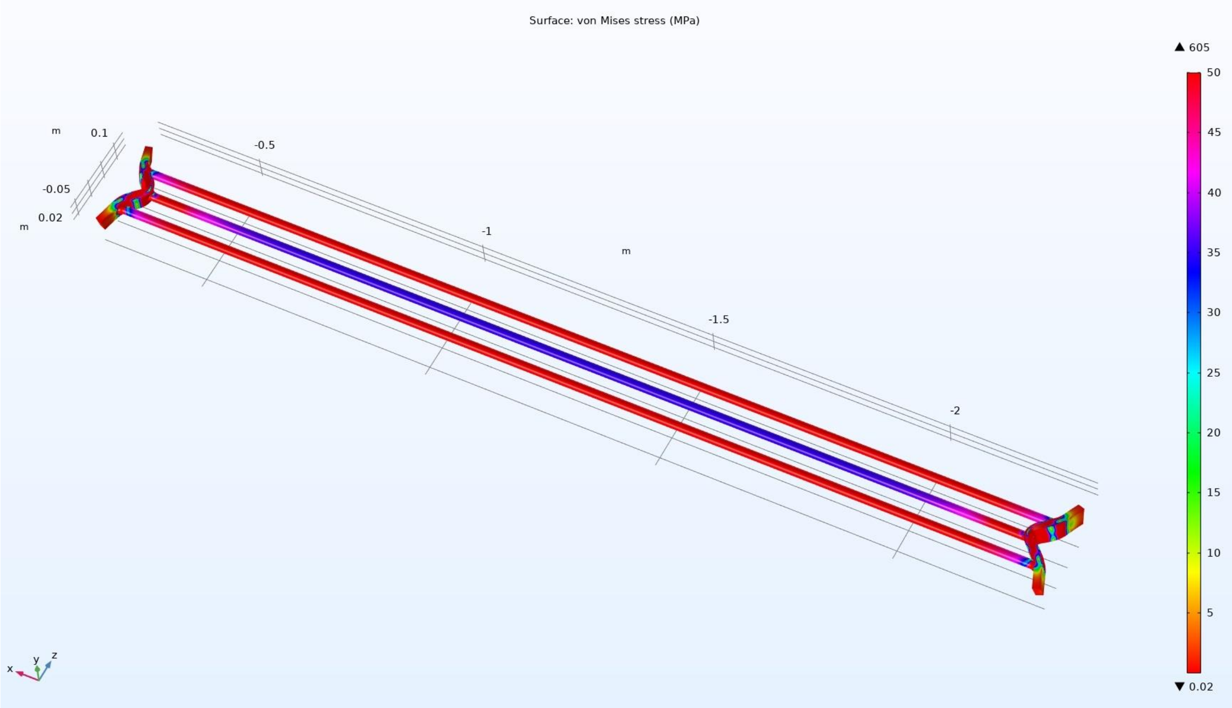

Figure 3 – Distribution of thermomechanical stresses in DW rods with the presence of SE of the rotor ε=0,83

Fig. 3 shows that in the middle of the central rod MST values are larger than in the boarder rods, due to the fact that no currents flow in the central rod.

Thus, 3-D mathematical modeling of thermomechanical stresses in the elements of the DW allows to research in details the causes and mechanism of the destruction of the DW with the appearance of the SE of the rotor. 3-D model allows to identify the areas with the highest values of MST and to offer the design and technical solutions to prevent the destruction of the pole's rods.

Conclusions. During this research 3-D mathematical model of the stress-strain state of the DW of the SGK 538/160–70M capsule hydrogenerator has been developed, which allows to determine the thermomechanical deformations of the DW, which appear due to the appearance of the SE of the HG's rotor. It is shown that the presence of three rods at the pole of the rotor of this HG causes the damage of the DW. That's why the modernization of the construction of the DW should be aimed onto creating an even number of rods at each pole.

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