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Estimation of stator and rotor forms distortions influence on operating parameters of a hydrogenerator

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Estimation of stator and rotor forms distortions influence on operating parameters of a hydrogenerator

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Abstract. The field calculation was carried out using finite element method of the Ansys Maxwell software package and verification in the Matlab Simulink software. It should be noted that there are several regulatory documents that describe criteria for permissible distortion of the rotor shape, where the air gap between the stator and the rotor at diametrically opposite points should not differ from each other by more than ± 20% from the average value equal to their half-sum. In this work, a calculation was carried out covering this interval of diameter change; an analysis was carried out considering change in range of ± 35% of the air gap's width's value. Results of the research showed that a change in a value of the air gap up to 10% would make a significant contribution to magnitude of magnetic field induction, which increases the value of main losses in a core of magnetic circuit of the generator. Also, there is a significant decrease in voltage (from 25 to 50%) of a nominal voltage in nominal power mode, which requires increase in current in field magnetizing coil, leading to ohmic losses' increase in rotor's windings.

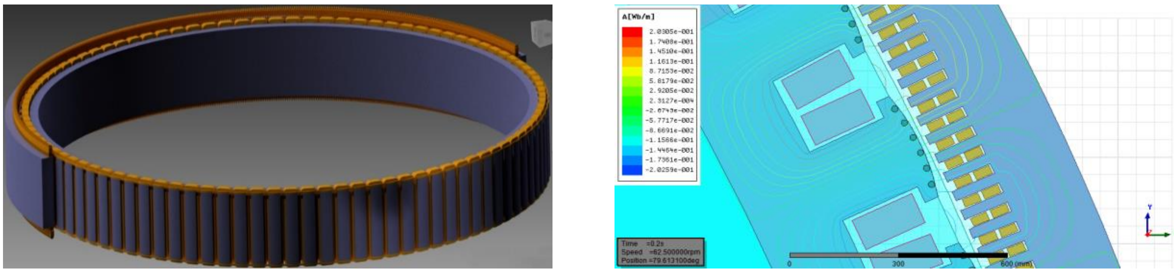
1. Introduction

Modern development of large-scale power engineering is impossible without use of mathematical modeling methods to predict changes in its operating parameters. The article is devoted to study of a synchronous hydrogenator's mathematical model created using finite element method to assess possible consequences when shape of an air gap's geometry is distorted. Both in foreign and in Russian literature, study of deformation's forms of a synchronous machine's rotor of a hydraulic unit has received considerable attention [1-5]. Analysis of the generator's operating parameters during deformation of the generator's symmetrical air gap, which occurs during operation is described in the article. Analysis of the results at rated power and in mode of sudden short circuit was carried out to calculate main and additional losses to determine efficiency. To check initial version of the generator geometry, verification was carried out to determine adequacy of the numerical model with analytical calculation in sudden short circuit mode. Oscillogram of electromagnetic moment's characteristic of the generator was analytically calculated under condition of a symmetrical air gap in the mode of a sudden short circuit and correlated with the results of numerical simulation. During operation of synchronous electric machines, conditions arise for changing the shape of the stator and rotor. The article reflects studies of various types of synchronous hydrogenerator's rotor distortions' influence on operating parameters of a generator.

Gorev-Park and Steinmetz formulas were used for calculating losses in electrical steel were applied [1]. A mathematical model of a synchronous machine was developed from analysis of the machine's geometry on basis of recommendations for design of AC machines (figure 1). To clarify calculation of the number of turns, an analytical calculation based on required flow through a pole in excitation winding was carried out. Magnetic field of a hydrogenerator, like any electric machine, has a spatially periodic distribution with a period equal to double pole division. Magnetic flux through one pole [1]:

$$\Phi = \frac{U_1}{4,44 k_f W_1 f_1 p} \tag{1}$$

where Φ - magnetic flux; U_1 – rated stator voltage; k_f – winding ratio; W_1 - number of turns; f_1 – network frequency, Hz; p – number of poles.



a) b)

Figure 1. The model: a) original synchronous machine; b) The graph of magnetic strength's distribution in the armature of a synchronous machine in nominal power mode.

2. Analysis of the results

Winding ratio is calculated according to formula [3]:

$$k_f = \frac{\sin\left(\frac{\pi}{2m}\nu\right)}{q\sin\left(\frac{\pi}{2mq}\nu\right)}\sin\left(\frac{\pi}{2}\beta\nu\right) \tag{2}$$

where ν - EMF harmonic number; q – number of slots per pole and phase; β – relative winding pitch.

Calculation of magnetic field is basis for accurate subsequent calculation of magnetic circuit, characteristics, parameters, and losses of the machine. To increase quality of power generation, configuration a rotor extension width's ratio to a pole pitch width equal to 0.7 was chosen in condition of the maximum width's ratio of an air gap to the minimum within one rotor shoe equal to 1.5. This configuration, based on Wiseman curves, provides an aspect ratio of 1.07, which will reduce higher harmonics' value [2].

Figure 3 shows an oscillogram of excitation current from output voltage of a synchronous generator. In AC devices containing elements with a ferromagnetic core, energy losses occur in cores with a periodic change in the magnetic flux in them. These losses are the sum of the eddy current and hysteresis losses.

Losses in electrical steel are expressed by the following equation [3]:

$$p_v = p_h + p_c + p_e \tag{3}$$

where p_h – hysteresis losses, p_c – eddy current losses, p_e – incremental losses.

Hysteresis losses are proportional to the area of the hysteresis loop.

$$p_h = k_n f B_m^2 \tag{4}$$

where B_m – maximum magnetic flux density in a core, k_n – material dependent factor, f – network frequency.

Eddy current losses:

$$p_c = k_c \left(f B_m \right)^2 \tag{5}$$

where k_c – coefficient depending on grade of electrical steel.
Incremental losses:

$$p_e = k_e \left(f B_m \right)^{1,5} \tag{6}$$

where k_e – incremental loss factor.

Figure 2 shows results of calculating losses in a synchronous generator depending on type of losses. As you can see from the oscillogram, the main losses are in copper windings.

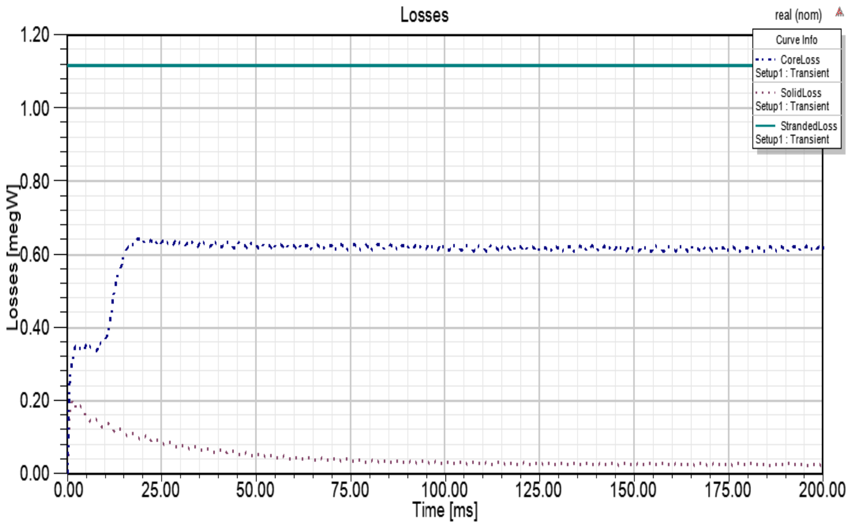


Figure 2. Basic and additional losses in a synchronous generator.

Also, analysis of transient processes during a sudden short circuit was carried out to verify original geometry of a machine with analytical calculation.

Electromagnetic moment [5-8]:

$$M_G = \left(L_q - L_d\right) i_d \cdot i_q + L_{md} \cdot i_{fd} \cdot i_q + L_{md} \cdot i_{kd} \cdot i_q - L_{mq} \cdot i_{kq} \cdot i_d. \tag{7}$$

Considering, that vectors of state and input variables, respectively, can be expressed as follows:

$$\begin{cases} \mathbf{x} = [x_1(t)\ \ x_2(t)\ \ x_3(t)\ \ x_4(t)\ \ x_5(t)]^T \equiv \left[i_q\ \ i_d\ \ i_{fd}\ \ i_{kd}\ \ i_{kq}\right]^T \\ \mathbf{u} = \left[u_d\ \ u_q\ \ u_{fd}\ \ 0\ \ 0\right]^T \end{cases}, \tag{8}$$

and the matrix [1]

$$\begin{cases} \mathbf{M} = \begin{bmatrix} L_d & 0 & -L_{md} & -L_{md} & 0 \\ 0 & L_q & 0 & 0 & -L_{mq} \\ L_{md} & 0 & -L_{fd} & -L_{md} & 0 \\ L_{md} & 0 & -L_{md} & -L_{kd} & 0 \\ 0 & L_{mq} & 0 & 0 & -L_{kq} \end{bmatrix} \\ \mathbf{N}(\Omega_h) = \begin{bmatrix} -R_S & \Omega_h L_q & 0 & 0 & -\Omega_h L_{mq} \\ -\Omega_h L_d & -R_S & \Omega_h L_{md} & \Omega_h L_{kd} & 0 \\ 0 & 0 & R_{fd} & 0 & 0 \\ 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & R_{kq} \end{bmatrix}, \end{cases} \tag{9}$$

and then the model of a synchronous generator can be represented as:

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{M}^{-1}\mathbf{N}(\Omega_h) \cdot \mathbf{x} - \mathbf{u} \\ \mathbf{y} \equiv M_G = (L_q - L_d)x_1x_2 + L_{md}x_1x_3 + L_{md}x_1x_4 - L_{mq}x_2x_5 \end{cases}. \tag{10}$$

The equation of motion is similar to the equation 8:

$$\frac{d\Omega_h}{dt} = \frac{1}{J}(M_{mec} - M_G - F\Omega_h), \tag{11}$$

where Ω_h, M_{mec} and J – mean the same values as before; $F -$ constant frictional force.

Figures 3 and 4 show the results of electromagnetic torque's dependences on time in mode of a sudden short circuit. By the type of oscillogram, an aperiodic component is observed, which has a maximum, having a fourfold value in comparison with the nominal torque. The standard model of a synchronous machine in Matlab Simulink software was used as a verification model.

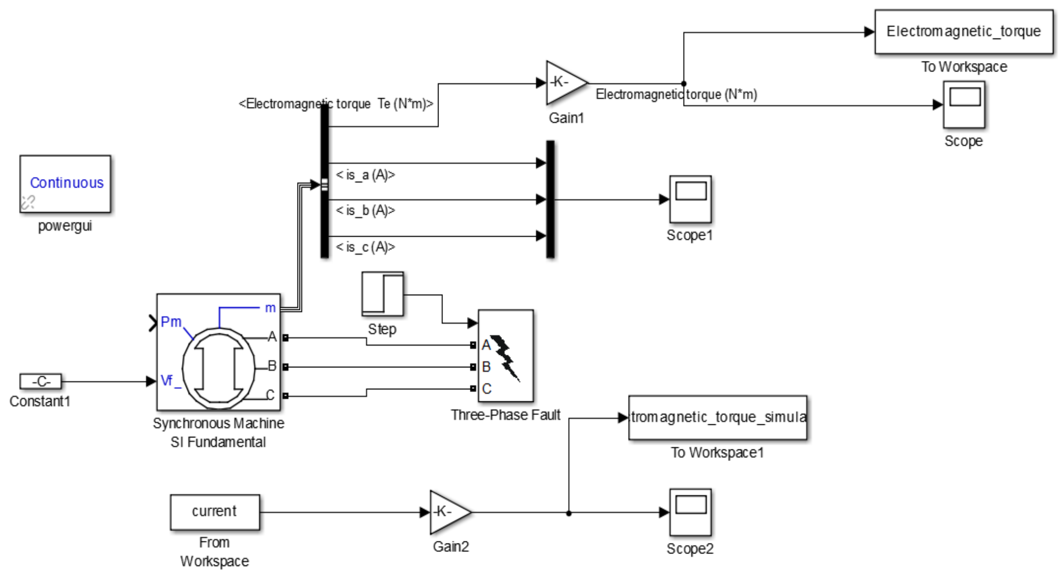


Figure 3. Analytical model of a synchronous machine in a sudden short circuit mode.

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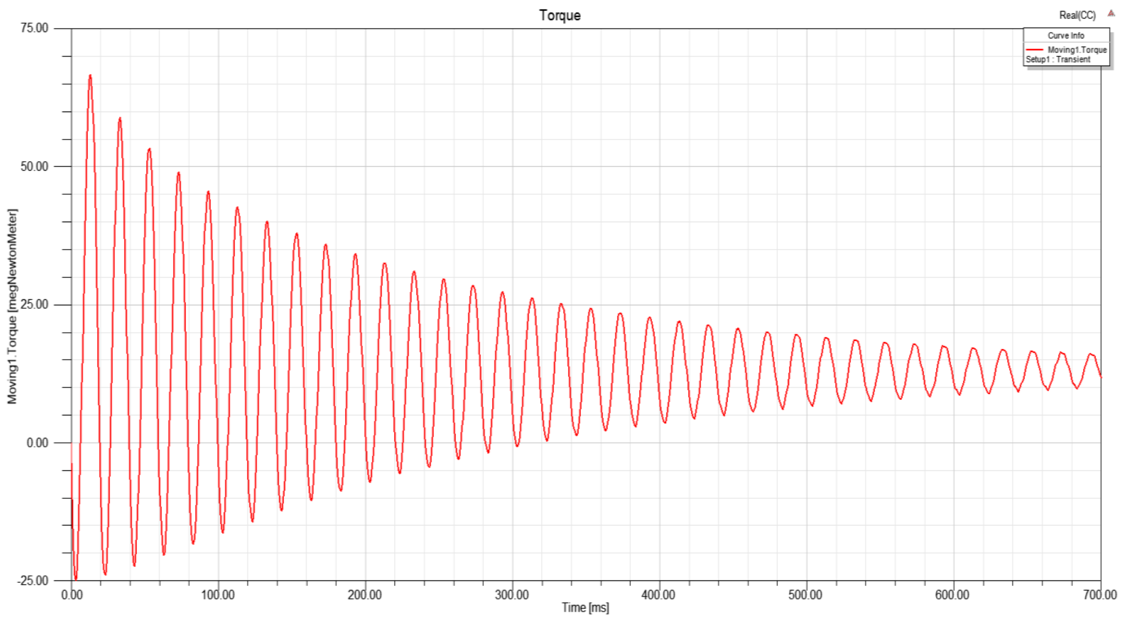

Figure 4. Calculation of the transient electromagnetic moment in mode of sudden short circuit with symmetrical geometry.

Simulation of a synchronous generator is performed under the same simplifying assumptions as for a permanent magnet synchronous generator [6].

The model is based on classical representation of a generator as a synchronous machine with three stator windings, one field magnetizing coil and two damping windings [3], described using the following variables and parameters: i_d, i_q – currents along the axes in coordinates $d - q$; u_d, u_q – voltages along the axes in coordinates d - q; i_{fd}, u_{fd} – exciting current and voltage; i_{kd}, i_{kq} – damping currents along the axes $d - q$; R_S – active resistance of a stator winding; R_{fd} – active resistance of a field magnetizing coil; R_{kd}, R_{kq}– active resistance of a damper winding; L_d, L_q – inductance of a stator windings along the axes d – q; L_{fd} – inductance of a field magnetizing coil; L_{kd}, L_{kq} – inductance of a damper winding; L_{md}, L_{mq} – magnetizing inductance along the axes d – q.

Figures 5 and 6 show the results of the mathematical model's studies of a synchronous generator in the form of current and voltage oscillograms. The results of idle mode were used as the initial results.

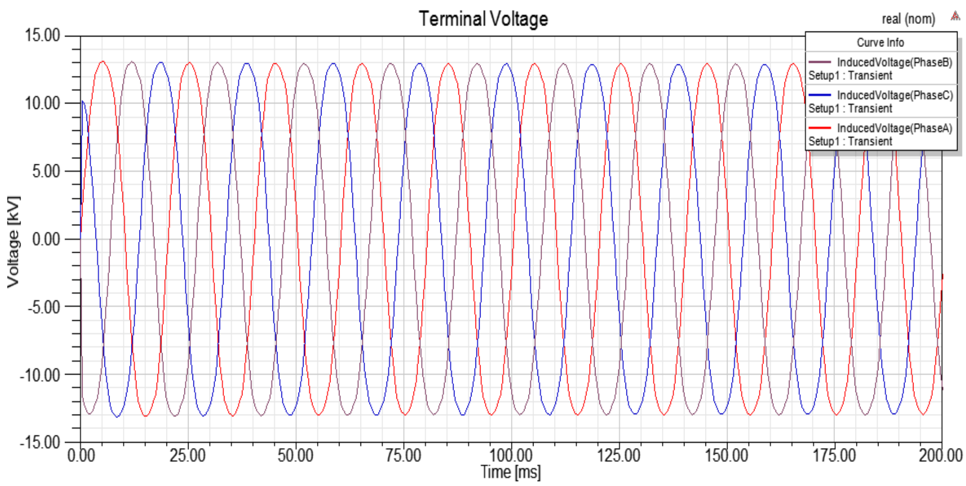

Figure 5. Graph of voltage at the output of a synchronous generator.

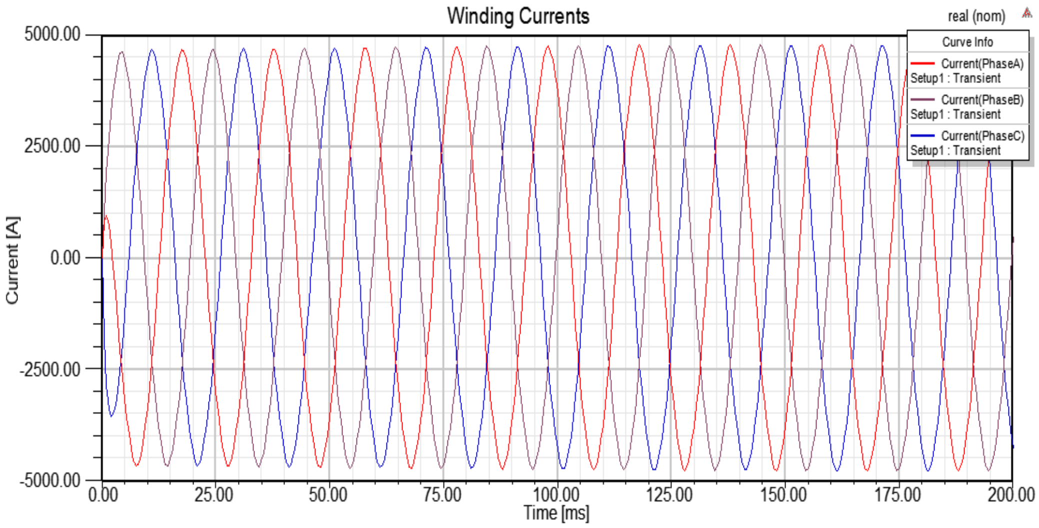

Figure 6. Graph of current at the output of the synchronous generator in the nominal power mode.

The result of the study is analysis of comparison of changes in operating parameters depending on distortion of a rotor shape and a size of an air gap. Table 1 shows operating parameters of an air gap calculated by finite element method. Table 2 shows operating parameters of an electrical network, which affects change in an air gap. The results obtained using finite element method make it possible to predict corresponding change in operating parameters of a synchronous generator and give appropriate recommendations to regulatory documents.

Table 1. Nominal power mode of synchronous generator.

№	Change of an air gap between rotor and stator, %	The maximum magnetic field induction in the air gap, T	The minimum magnetic field induction in the air gap, T	A ratio of the rated voltage to voltage at the generator outputs	Current ratio to rated current	Efficiency, %
1	+20	0.797	0.76	4.00	1.89	99.10
2	+35	0.847	0.65	4.60	2.03	99.16
3	-10	0.885	0.713	3.94	1.93	97.23
4	-20	0.741	0.101	3.68	1.87	95.10
5	-35	0.741	0.101	3.73	1.93	91.12

Table 2. Sudden short circuit mode of the synchronous generator

№	Deformation of the rotor in relation to the stator, %	The maximum torque to rated torque ratio, M_{max}/M_{nom}	Maximum current to steady state curent ratio $I_{max.aper}/I_{max}$	The ratio of the rated voltage to voltage at the generator outputs
1	+20	5.50	2.50	1.73
2	+35	5.28	2.50	1.92
3	-10	5.78	2.37	1.86
4	-20	5.89	2.33	1.86
5	-35	5.56	2.33	1.86

3. Conclusion

Research was carried out that shows how a change in size of an air gap affects operating parameters of a generator. The results obtained in the study reflect possibility of obtaining operating parameters with possible changes in geometry of an air gap. Undoubtedly, development of finite element methods, considering dynamics of the object under study, makes it possible to obtain trends in changing modes of a hydrogenerator, as one of the most expensive elements of a hydro power station. Based on the formulas described above, analytical verification of electromagnetic moment was made in mode of sudden short circuit (VSC) in case of a symmetrical air gap.

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