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## MEASUREMENT VERIFICATION OF A FIELD-CIRCUIT MODEL OF THE 55.5 MVA HYDROGENERATOR

### WERYFIKACJA POMIAROWA MODELU POŁOWO- -OBWODOWEGO HYDROGENERATORA O MOCY 55,5 MVA

#### Abstract

A two-dimensional, field-circuit model of a 55.5 MVA hydrogenerator is presented in the paper. This model takes into account the fractional-pitch stator winding, the rotor damper squirrel-cage, nonlinear magnetization curves and the rotor motion. Verification of the model has been carried out by the comparison of the no-load and short-circuit characteristics computed using the finite element method with those obtained from measurements.

*Keywords: hydrogenerator, field-circuit model, finite element method*

#### Streszczenie

W pracy przedstawiono dwuwymiarowy połowo-obwodowy model hydrogeneratora o mocy 55,5 MVA. Model uwzględnia uzwojenie ułamkowe w stojanie, klatkę tłumiącą w wirniku, nieliniowe charakterystyki magnesowania rdzeni magnetycznych i ruch obrotowy wirnika. Weryfikację modelu połowo-obwodowego przeprowadzono na podstawie porównania zmierzonych i obliczonych metodą elementów skończonych charakterystyk biegu jałowego i trójfazowego zwarcia.

*Słowa kluczowe: hydrogenerator, model połowo-obwodowy, metoda elementów skończonych*

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## 1. Introduction

Synchronous generators installed in a power system operate under variable load conditions resulting from the need to balance the constantly changing demand for power in the system. Therefore, the monitoring of the current operating conditions of a generator as well as the ability to predict the behavior of a machine under different operating and load conditions becomes more and more important. The majority of scientific research studies addresses high-power turbogenerators. In the literature, much less attention is paid to hydrogenerators [2, 7, 8]. Hydrogenerators, like turbogenerators, are modernized during long-term operation to increase their rating power. There is therefore a need for research of those generators, not only in terms of the possibility of increasing power, but also their influence on the power system operation. Such research is often carried out by simulation programs in which mathematical models of hydrogenerators and turbogenerators are expressed in the  $d-q$  coordinate system.

Due to the large number of starts and stops in a daily cycle, hydrogenerators installed in pumped-storage power plants have to meet high requirements. Such machines must operate as a generator and a motor. This is why the design solutions of their rotors are more complex than those of turbogenerators. The stator windings of hydrogenerators often have a non-integer number of slots per pole and per phase, which is rare in turbogenerators of typical construction.

The field methods for calculating electromagnetic quantities of electrical machines under different operating conditions, using the finite element method (FEM), are currently the most accurate calculation methods, since they enable taking into account the influence of many factors neglected in approximate circuit calculations. In this paper, there is presented the measurement verification of a two-dimensional, field-circuit model of a HV832732/32 hydrogenerator installed in the pumped-storage power plant in Żydowo. The measurement verification was based on the comparison of no-load and three-phase symmetrical short-circuit characteristics determined experimentally with those calculated by FEM.

Calculations of static characteristics were carried out based on the distributions of electromagnetic fields obtained from solving the diffusion equations describing arbitrarily time-varying fields by FEM. Calculations of the generator steady state have to be preceded by calculations of the transient state. Therefore, they are time-consuming, require a large memory and considerable processing power of a computer. The assumed two-dimensional, field-circuit model of the generator takes into account all essential factors affecting the calculated characteristics, among others, the motion of the rotor as well as electromotive forces induced in the windings and damper squirrel-cage by higher harmonics of the magnetic field.

## 2. The field-circuit model of a hydrogenerator

The field-circuit model of a synchronous machine consists of differential equations with partial derivatives describing the distribution of the magnetic field inside the machine and differential equations with ordinary derivatives describing the voltage-current relationships in the electric circuits of the windings [3, 4].

The space-time distribution of the electromagnetic field in the machine is described by the equation for the magnetic vector potential  $\mathbf{A}$ :

$$\operatorname{rot} \frac{1}{\mu} \operatorname{rot} \mathbf{A} = -\gamma \frac{\partial \mathbf{A}}{\partial t} \quad (1)$$

where:

- $\gamma$  – conductivity,  
 $\mu$  – magnetic permeability.

In the two-dimensional model, the magnetic vector potential has one component only. The average value of the flux linked with the  $k$ -th winding is expressed by the relationship

$$\Psi_k = \sum_i \frac{l_c}{S_i} \int A_i ds_i \quad (2)$$

where:

- $A_i$  – average value of the potential in the cross-section of the winding conductor,  
 $S_i$  – surface area of the winding conductor,  
 $l_c$  – effective length of the machine.

The Kirchhoff equation describing the electromagnetic state of the  $k$ -th winding is of the form:

$$u_k = R_k i_k + \frac{d\Psi_k}{dt} \quad (3)$$

Where  $u_k, i_k, \Psi_k$  – instantaneous values of the voltage, current and flux linkage of the  $k$ -th winding.

A salient-pole synchronous machine operating in Żydowo Pumped Storage Power Plant was the object of the investigations. The field-circuit calculations were carried out using Transient solver of Ansys Maxwell 2D software [1]. The ratings of the machine for the generator and motor operation are given in Table 1.

Table 1

**Ratings of hydrogenerator HV832732/32**

Quantity	Motor operation	Generator operation
$S_n$	55.5 MVA	71.5 MVA
$P_n$	48.3 MW	61.5 MW
$I_n$	3050 A	3900 A
$I_{fn}$	985 A	995 A
$\cos\varphi_n$	0.87 i	0.95 p
$U_n = 10.5 \text{ kV}, n_n = 187.5 \text{ rpm}$		

The tested hydrogenerator was a salient-pole (32 poles) and low-speed machine. A three-phase two-layer winding of two parallel branches and a non-integer number of slots per pole and phase (fractional winding,  $q = 3.5$ ) is placed in 336 slots of the stator. In salient-pole machines, such a winding provides a lower harmonic content in the induced stator voltage [5, 8]. Due to a different number of slots occupied by the phase bands of the stator winding under successive poles, the region of analysis cannot be divided into symmetrical parts and the sizes of solved equations FEM cannot be reduced [8]. The analysis was performed for the half of the machine cross-section. In the pole shoes of the rotor poles, there are 8 bars of the damper squirrel-cage short-circuited on both sides of the rotor by short-circuiting rings.

In the developed computational model of the hydrogenerator, there was taken into account:

- two-dimensional distribution of the electromagnetic field in the generator cross-section comprising one pole pitch of the machine,
- nonlinear single-valued magnetization characteristics of the stator and rotor cores,
- constant speed of rotor rotation,
- currents induced in the rotor damper-squirrel cage and conducting elements of the rotor,
- influence of the harmonics of saturation, permeance and magnetomotive forces of the windings.

The skin effect in the stator windings and excitation winding was neglected.

The external electric circuits of the hydrogenerator, connected to the modelled windings in the field part, are shown in Fig. 1. They contain the resistances and leakage inductances of stator and excitation winding ends as well as the resistances and leakage inductances of the segments of the short-circuiting rings which short-circuit the bars of the damper squirrel-cage in the rotor. The values of these parameters were determined from the design relationships [9]. The switches ( $W$ ) presented in Fig. 1 were open during the determination of the no-load characteristic and closed during the determination of the three-phase short-circuit characteristic.

The zero Dirichlet boundary condition for the vector magnetic potential was assumed on the outer surface of the stator and the inner surface of the rotor yoke. Symmetry conditions were imposed on the surface separating the two halves of the cross-section.

The rotational motion of the rotor was modeled in Maxwell software by means of the special object 'band' [1] comprising all rotating elements of the rotor. The electromagnetic field was calculated in two separate coordinate systems, motionless in relation to the stator and rotor, respectively.

The considered cross-section of the generator computational model was discretized using triangular finite elements of second order. The computational model contained about 127 000 finite elements. In magnetostatic calculations, the number of finite elements was twice as large since the full machine model was used for investigations. A fragment of the hydrogenerator cross-section and the finite element mesh are presented in Fig. 2.

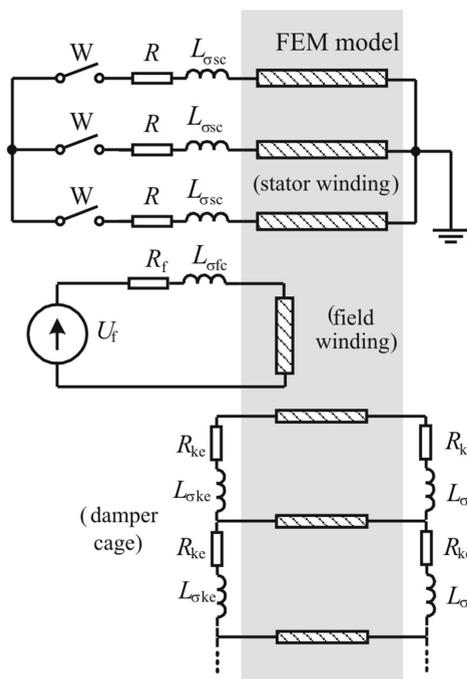


Fig. 1. External circuits connected to the hydrogenerator field model

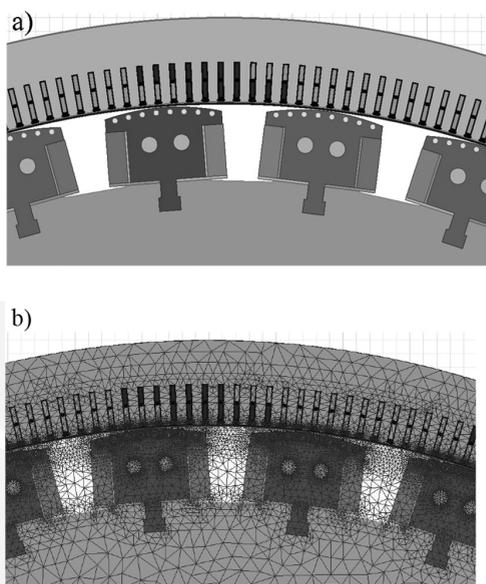


Fig. 2. Fragment of the hydrogenerator cross-section (a) and finite element mesh (b)

### 3. Field calculation results and measurement verification

The developed field-circuit model of the hydrogenerator was used for calculations of the no-load and three-phase symmetrical short-circuit characteristics. Individual points of the characteristics were determined based on instantaneous values of the appropriate voltages, currents and magnetic fluxes in the steady state after finishing the initial transient state.

#### 3.1. The no-load characteristic

The no-load characteristic was determined based on a series of analyses of the electromagnetic field distribution for successive values of the excitation current at the open switch ( $W$ ) of the stator winding (Fig. 1).

Figure 3a) shows the distribution of the magnetic flux density amplitude in the hydrogenerator cross-section in the steady state at no-load at the selected time instant.

In the steady state of a hydrogenerator operating at no-load, the currents induced by higher harmonics of the magnetic field, including subharmonics of the field generated by the fractional winding of the stator, flow in the damping circuits of the rotor [5]. To investigate their influence on the values of the voltages induced in the stator winding, there were calculations carried out whilst taking into account and neglecting the effect of the currents in-

duced in the damper squirrel-cage. Based on the calculations, it was stated that the influence of these currents on the no-load characteristic was negligibly small. The differences in the stator voltage, invisible on the no-load characteristic, are equal to about 40 V on the curved part of the characteristic (Fig. 4). The contents of harmonics in the generator stator voltage is small. Figure 5 shows the amplitudes of higher harmonics, calculated by FEM, in the phase and line-to-line voltage of the generator operating at no-load, related to the amplitude of the first harmonic. The third harmonic of the amplitude equal to 1.76% of the first harmonic amplitude is dominant in the phase voltage. The values of the other harmonics do not exceed 0.25% of the first harmonic amplitude. However, they are uncertain due to the fact that they are comparable with the level of numerical errors. The relative harmonic content of the phase voltage calculated up-to 40-th harmonic from the waveforms of the stator voltage equals [6]:

$$\text{THD} = \frac{\sqrt{\sum_{k=2}^n U_k^2}}{U_1} = \begin{cases} 1.807 & \text{– for the phase voltage} \\ 0.286 & \text{– for the line-to-line voltage} \end{cases} \quad (4)$$

Where  $U_1$ ,  $U_k$  – rms value of the first and  $k$ -th harmonic of the stator voltage.

From the comparison of the measured and calculated by FEM no-load characteristics, it follows that the field-circuit model represents the saturation of magnetic cores and higher harmonics of the magnetic field with a strong degree of accuracy.

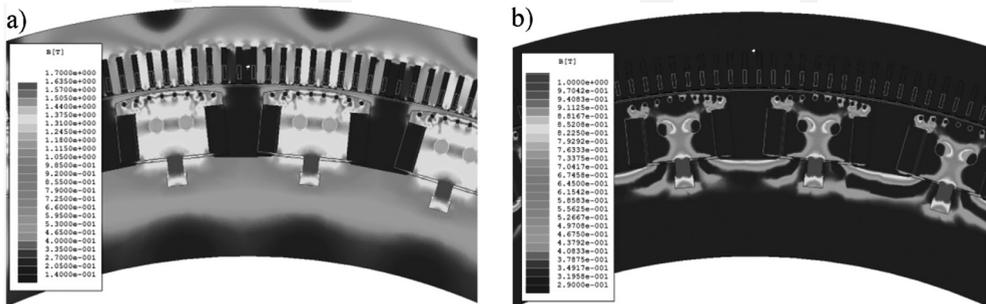


Fig. 3. Distribution of the magnetic flux density amplitude in the hydrogenerator cross-section in steady state at no-load (a) and symmetric short-circuit (b).

To shorten the calculation time, the no-load characteristics are often calculated based on the distributions of magnetostatic fields for given excitation currents. The voltage induced in the stator is calculated with the use of the relationships valid for the circuit model of a mono-harmonic machine. Figure 6 presents the no-load characteristic calculated by means of the magnetostatic solver of Ansys Maxwell. Compared to the calculations based on the generator field-circuit model for transient states, in the magnetostatic calculations the machine model does not take into account the rotational motion of the rotor and electromotive forces induced in the windings and damper squirrel-cage by higher harmonics of the field. The visible differences between the characteristics in the saturation region are equal to about 5%.

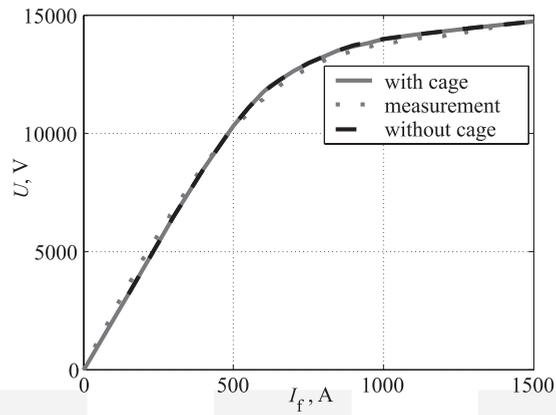


Fig. 4. Comparison of the no-load characteristic when taking into account and neglecting the effect of the damper squirrel-cage with the measured characteristic

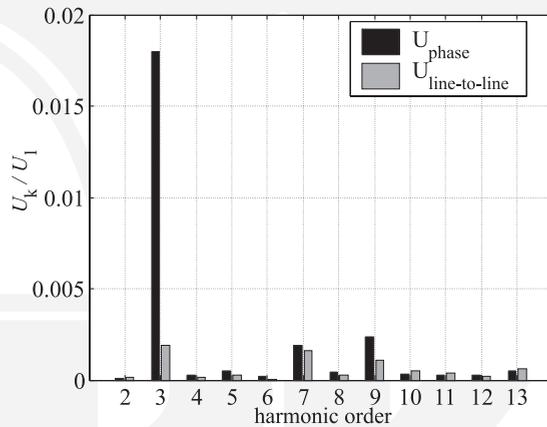


Fig. 5. Amplitudes of higher harmonics of the phase and line-to-line voltage of the stator related to the first harmonic amplitude at no-load

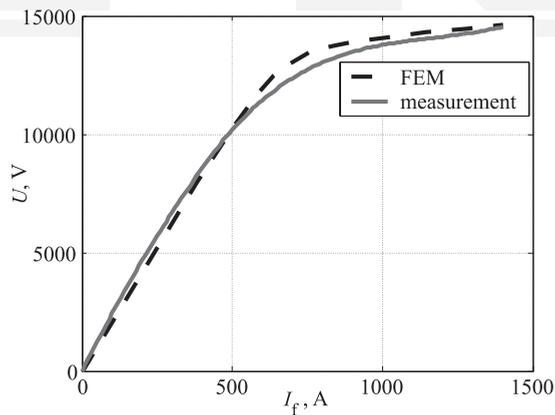


Fig. 6. Comparison of the no-load characteristic determined based on calculations of magnetostatic fields (FEM) and measurements

### 3.2. The three-phase symmetrical short-circuit characteristic

The three-phase symmetrical short-circuit characteristic was determined on the basis of a series of analyses of the electromagnetic field for successive values of the excitation current at the short-circuited stator winding. The computational model of the machine contains the circuit of three star-connected phases of the stator windings, short-circuited at terminals, connected to the field model FEM (Fig. 1). Figure 3b) shows the distribution of the magnetic flux density amplitude in the hydrogenerator cross-section at the steady-state symmetrical short-circuit at selected time instant. The comparison of the short-circuit characteristic calculated by FEM with that measured in Żydowo Power Plant is presented in Fig. 7.

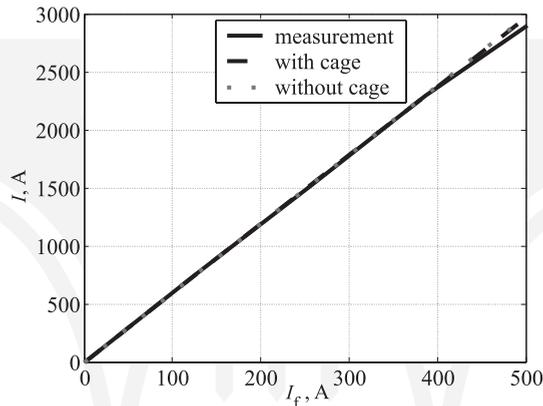


Fig. 7. Comparison of the calculated and measured three-phase symmetrical short-circuit characteristic of the hydrogenerator

From the carried out FEM calculations, it follows that the influence of the damper squirrel-cage on the rms values of the short-circuit currents is negligibly small under the analyzed operating conditions of the turbogenerator (Fig. 7).

The comparison of the calculated and measured characteristics recorded in Żydowo Power Plant proves the correctness of the modelled stator winding and rotor electric circuits.

## 4. Remarks and conclusions

The presented two-dimensional field-circuit hydrogenerator model with a non-integer number of slots per pole and per phase in the stator includes all essential factors influencing the calculation accuracy. These factors are: nonlinearity of magnetization characteristics of magnetic cores; higher space and time harmonics of the magnetic field; rotational motion of the rotor; effect of currents induced in the damper squirrel-cage; conducting elements of the rotor.

The investigated hydrogenerator is a multipolar machine with a fractional pole pitch stator winding. To use the symmetry conditions enabling a reduction of the size of the solved system of equations FEM, the computational model should not comprise one pole pitch only, which is possible in machines with an integer number of slots per pole and per phase. This model should contain a greater number of pole pitches, dependent on the kind of a fractional winding.

The comparison of the no-load and short-circuit characteristics calculated based on this model with the measured characteristics proved the usefulness of the model for analyses of different states of generator operation. In particular, the agreement of the calculated and measured no-load characteristics confirms the correctness of modelling the phenomenon of saturation of magnetic cores and higher harmonics of the magnetic field. Whereas the agreement of the calculated and measured short-circuit characteristics confirms the correctness of modelling the stator winding and the electric circuits of the rotor.

The calculations of the no-load characteristic based on the distributions of the magnetostatic field can be loaded with a few percent error resulting from neglecting the effect of higher harmonics induced in the stator winding.

In the model, there are solved the diffusion equations, which is time-consuming, especially when the purpose of calculations is to determine the quantities in the steady state.

The field-circuit model of the hydrogenerator verified by measurements will be used for determining the parameters of circuit models of synchronous generators in further works by the authors of this paper.

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