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doi:10.15199/48.2019.05.39

# Determination of salient pole synchronous machines electromagnetic parameters from the SSFR test

***Abstract**. Presented article deals with the determination of hydrogenerator electromagnetic parameters from the SSFR test. A method utilized to prepare the results is finite element method based on the module of Steady State AC Magnetic 2D application. Obtained reactances could be determined after an application of own made program used to fit the curves (magnitude and phase characteristic of operator transmittances) to the data coming from the simulation in order to designate the time constants. An impact of saturation effect in stator and rotor steels was researched on obtained reactances in different working states of synchronous machine.*

***Streszczenie.** Prezentowany artykuł przedstawia symulacyjną metodę wyznaczania parametrów elektromagnetycznych hydrogeneratora z testu SSFR (Standstill Frequency Response). Zastosowana metoda obliczeń bazuje na rozkładzie pól sinusoidalnie zmiennych o zadanej zmiennej częstotliwości. Reaktancje hydrogeneratora zostały wyznaczone ze stałych czasowych za pomocą opracowanego programu. Program ten dopasowuje charakterystyki amplitudowe i fazowe do wartości otrzymanych z symulacji. Zbadano wpływ nasycenia obwodu magnetycznego na reaktancje odzwierciedlające zachowanie maszyny w różnych stanach pracy. (**Wyznaczanie parametrów elektromagnetycznych jawnobiegunowych maszyn synchronicznych na podstawie testu SSFR**).*

**Keywords:** hydrogenerator, finite element method, electromagnetic parameters, Standstill Frequency Response test.
**Słowa kluczowe:** hydrogenerator, metoda elementów skończonych, parametry elektromagnetyczne, SSFR test.

## Introduction

The electromagnetic parameters of a synchronous machine are most often determined during running tests from no-load and three phase short circuit tests [1]. These tests are carried out most often at the manufacturer of electrical machines at the test station, which is equipped with a properly selected drive and a constant voltage source. Typically, such equipment is sufficient to test machines with several poles and rated power not exceeding approximately 10 MVA. The problem is encountered when the power is higher and the number of pole pairs exceeds 20-30. Then the measurement of such a machine is difficult due to its dimensions and the lack of a suitable source of DC voltage.

The SSFR (Standstill Frequency Response Test) measuring method [2], which does not require a separate source of direct voltage, can be opposed to these difficulties and can be carried out on the site, eg after being built in a power plant. This method consists in forcing the voltage at a given frequency, at the right position of the rotor (direct and quadrature axis) and with the open or closed excitation circuit. Initially, it was only used to study synchronous machines with a cylindrical rotor (eg turbogenerators), but with its refinement and modification, it was also used in machines with rotor of salient pole [3-6].

Standstill Frequency Response test is used to determine the electromagnetic parameters such as the reactances and the time constants which can be utilized to compute the resistances and the inductances needed to prepare an equivalent machine circuit [1]. In this way new-created equivalent hydrogenerator model allows to predict the dynamic behaviour of the machine during the abnormal operating states.

SSFR test is relatively cheaper than the preparation of no-load and sudden short circuit tests during the running test. The price of the standard test is determined by the auxiliary instruments included during the tests such as the oil and cooling equipments as well as an additional motor driving the tested machine. Additionally the suitable energy has to be ordered in that time in depending on machine type and its terminal quantities.

Elimination of sudden short circuit test reduces a risk regarding an appearance of mechanical stress resulting from the huge stator current during the sudden shorted armature circuit. The resulting stresses can be a few times higher than during rated operation state.

The disadvantage is the visible noise in the measured waveforms and the negative influence of the armature winding resistance during measurements for low frequencies on the course of measurable signals. The research undertaken on the impact of noisy signals on the matching of the characteristics indicates that the obtained results from noisy and "clean" signals are similar [7]. Thus, the obtained electromagnetic parameters are similar to each other.

For low frequencies in the range from 0.001 to 0.01 Hz, a modified SSFR method [8] can be used, which shortens the measurement time by several hours by measuring the resistance of the armature winding before the SSFR test. The value of this resistance is used to estimate low-frequency inductances. This inductivity is then taken into the calculation of synchronous reactance in the d and q axes.

The SSFR method is primarily used to determine the electromagnetic parameters of a synchronous machine, which can be compared to the values given by the manufacturer or used to set the excitation current regulator and protection devices. The determined time constants and reactances form the basis for creating an equivalent circuit model. The behaviour of synchronous machines in dynamic states is examined almost exclusively by means of Park equations in d and q axes. Simplifications contained in them cause that the obtained results may be imprecise [9].

The purpose of this work is to indicate the possibility of using the SSFR method in large-scale salient pole synchronous machines with static excitation and to demonstrate the effect of saturation of the magnetic circuit on the obtained reactance values.

## Description of hydrogenerator model

An investigated machine is hydrogenerator with salient pole rotor. Main technical data of machine are presented in table 1.

The calculation model consists of two parts: field and circuit. The field model (figure 1) reflects the actual distribution of windings distributed in stator and rotor slots as well as damping circuits in the form of bars.

Table 1. Main data of investigated hydrogenerator

| Name of hydrogenerator data | Value | Unit |
|---|---|---|
| Rated apparent power | 4000 | kVA |
| Terminal voltage | 2400 | V |
| Rated armature current | 962 | A |
| Rated power factor | 0.90 | - |
| Rated speed | 257.14 | rpm |
| Rated frequency | 60 | Hz |

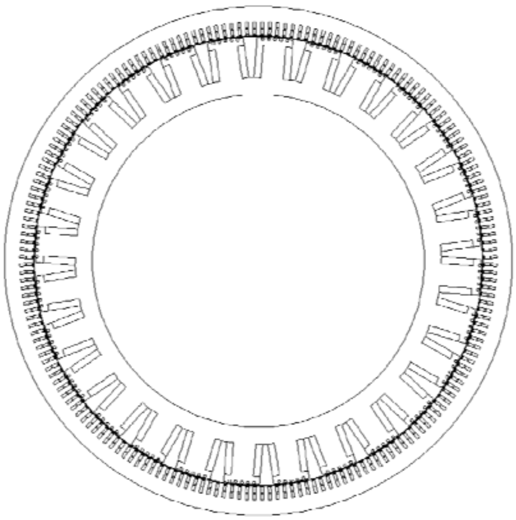

Fig. 1. Field model of investigated synchronous machine

During the calculations, the non-linearity of the magnetization characteristics of the stator and the rotor cores were taken into account as well as the effect of eddy current in the rotor bars. The field model during the calculation is coupled with a circuit model containing focused elements. These elements represent windings and circuits in the field part as well as passive elements that are the end connections of the stator, rotor windings and damping cage.

**SSFR simulation in the Steady State AC Magnetic 2D application**

During the simulation process a module of Steady State AC Magnetic 2D application is utilized. Whereas the name of commercial program used to the calculation is FLUX from CEDRAT. This module can enforce a suitable frequency of signal required in SSFR test. Additionally there is possible to put a lot of different frequencies required by a rule described in [2] in one simulation. Needed range of frequency is from 0.001 to 200 Hz [2].

Presented module allows to use the non-linearity of magnetizing curves. Therefore the saturation effect can be reflected in a proper way. SSFR test on a real machine is performing for very low stator current and this effect is neglected. Whereas this feature can be used to check the synchronous, transient as well as sub-transient reactances at rated load both direct and quadrature axis. Thus short circuit ratio can be computed as inverse of synchronous reactance in direct axis.

Module of Steady State AC Magnetic 2D allows to determine the value of current and voltage (magnitudes and phases) both in stator and rotor windings [10]. In the simulation process the RMS value of voltage source is constant and equals 0.1 V whereas the assumed voltage phase equals to 0 degree in all range of frequencies. In this way the saturation effect was eliminated from the calculation reflecting the real condition during the tests.

During the simulation the rotor and stator winding are connected according to [2]. Only the following two values from the post-processor are read:

- magnitude current of the stator winding,
- phase current of the stator winding.

Above values can be utilized for both direct and quadrature axis and are enough to further analysis to determine the hydrogenerator electromagnetic parameters. Unfortunately above values are not sufficient to obtain all of the needed parameters to create the equivalent circuit of hydrogenerator and that is why another function such as sG(s) has to computed. To calculate this function, the following values from post-processor has to be read only in direct axis:

- magnitude current of the stator winding,
- phase current of the stator winding,
- magnitude current of the rotor winding,
- phase current of the rotor winding.

In this article the great emphasis is placed only on the determination of hydrogenerator electromagnetic parameters and sG(s) function is only mentioned.

Data read directly from the postprocessor is not enough to indicate the hydrogenerator electromagnetic parameters thus the following equations were used to transform achieved data to useful one. Based on voltage and current magnitudes in the stator, impedance $Z_m$ is computed from an equation (1), where $U$=const.

$$Z_m = \frac{1}{2} \cdot \frac{U_m}{I_m} \tag{1}$$

Whereas phase of this impedance is computed in equation (2) where $\varphi_{voltage}$=const

$$\varphi_Z = \varphi_{current} - \varphi_{voltage} \tag{2}$$

Impedance magnitude and phase can be utilized to compute the inductances in the real $L_R$ and imaginary $L_I$ axis.

$$L_R = \frac{|Z_m| \cdot \sin(\varphi_Z)}{2\omega} \tag{3}$$

$$L_I = \left[ \frac{|Z_m| \cdot \cos(\varphi_Z)}{2} - R_{armature} \right] \cdot \frac{1}{\omega} \tag{4}$$

Obtained the inductances in equations (3) and (4) allow to determine the inductance magnitude (5) and inductance phase (6).

$$L_m = \sqrt{L_R^2 + L_I^2} \tag{5}$$

$$\varphi_L = \frac{a\tan\left(\frac{L_I}{L_R}\right) \cdot 180^o}{\pi} \tag{6}$$

Only equations (1), (2), (5) and (6) are needed to prepare the curves which will be used to determine the electromagnetic parameters in the further activities. For this purpose the program for fit the curves was developed based on the method of minimal square error. This error is between computed value from FEM tool and fitted value for each frequency value. In utilized method, all time constants are changed one by one in small steps around its starting values while other parameters are kept constant. The goal functions are evaluated until reaching minimum – local optimum. Initial values are very important and were taken from the expected values.

Created program is based on 3-order model of the hydrogenerator instead of 2-order for better reflection of electromagnetic parameters. The following equations for characteristics transfer functions are presented for direct and quadrature axis.

$$(7)\quad L_d(s) = L_d(0)\frac{(1+sT_d^{'})(1+sT_d^{''})(1+sT_d^{'''})}{(1+sT_{do}^{'})(1+sT_{do}^{''})(1+sT_{do}^{'''})}$$

$$(8)\quad Z_d(s) = sL_d(s) + R_{armature}$$

$$(9)\quad L_q(s) = L_q(0)\frac{(1+sT_q^{'})(1+sT_q^{''})(1+sT_q^{'''})}{(1+sT_{qo}^{'})(1+sT_{qo}^{''})(1+sT_{qo}^{'''})}$$

$$(10)\quad Z_q(s) = sL_q(s) + R_{armature}$$

$L_d(0)$ is synchronous inductance and is read for $f$=0.001 Hz from direct-axis magnitude inductance. Whereas $R_{armature}$ is set value in the calculation tool but it can be read for $f$=0.001 Hz from direct-axis magnitude impedance.

**Calculation results**

At the beginning of simulation the rotor is situated according to direct and quadrature axes and is fixed. One of the armature winding is disconnected and the current flows by only 2 phases whereas the field winding is shorted. Obtained results in postprocessor are in function of frequencies.

In the figures 2-5 are presented the computed magnitudes and phases of impedance and inductance in all range of frequency as the dots. Whereas the lines are the fitted curves.

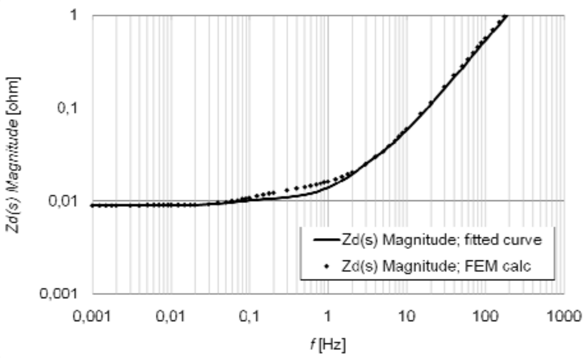

Fig. 2. Direct-axis magnitude impedance

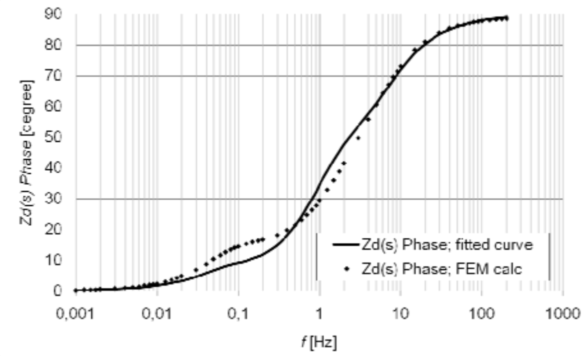

Fig. 3. Direct-axis phase impedance

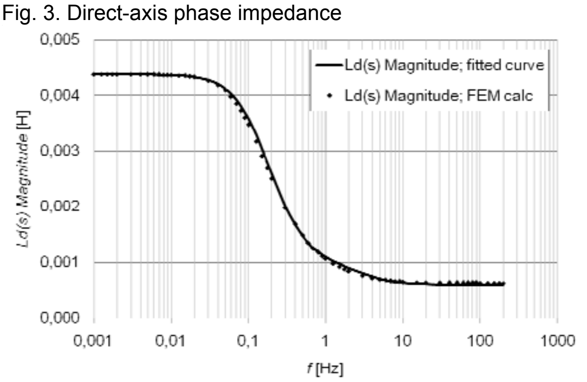

Fig. 4. Direct-axis magnitude inductance

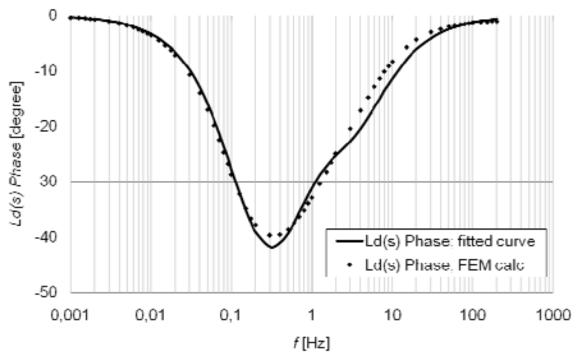

Fig. 5. Direct-axis phase inductance

For direct axis good accordance was achieved. Based on the fitted curves it was possible to determine the hydrogenerator electromagnetic parameters in direct axis which can be found in table 2.

Fitted curves depend on time constants included in equations (7) and (8) for direct axis whereas obtained time constants from the fitting process are used to determine the reactances according to the following equations:

$$(11)\quad X_d^{'} = \frac{T_d^{'}}{T_{do}^{'}} X_d$$

$$(12)\quad X_d^{''} = \frac{T_d^{''}}{T_{do}^{''}} X_d^{'}$$

$$(13)\quad X_d^{'''} = \frac{T_d^{'''}}{T_{do}^{'''}} X_d^{''}$$

In the figures 6-9 are presented the computed magnitudes and phases of impedance and inductance for quadrature axis in all range of frequency as the dots. Whereas the lines come are the fitted curves.

Fitted curves depend on time constants included in equations (9) and (10) for quadrature axis whereas obtained time constants are used to determine the reactances according to the equations (11), (12) and (13) nut for quadrature axis. The methodology is the same as in case of direct axis.

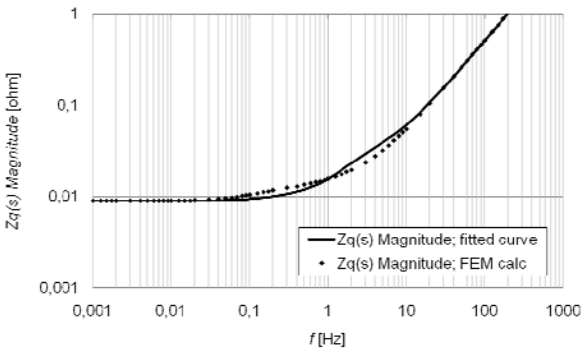

Fig. 6. Quadrature-axis magnitude impedance

As in the case of the d-axis, a satisfactory convergence was achieved in the q-axis. The results are summarized in table 2.

The disadvantage of the SSFR method is the lack of taking into account during the measurements the influence of the saturation of magnetic circuits on the reactance values. This may result in underestimation of the values of currents occurring during abnormal states during the long-term operation of the machine. In addition, it may be the cause of erroneous analyzes carried out using simplified circuit models built on the basis of data obtained from the

SSFR method. Therefore, the work presents characteristics of synchronous, transient and sub-transient reactances as a function of stator current determined during solving the AC steady state problem, i.e. during the distribution of sinusoidal fields. These characteristics are shown in figures 10, 11 and 12 respectively. A similar solution was used in the case of the turbogenerator [11, 12].

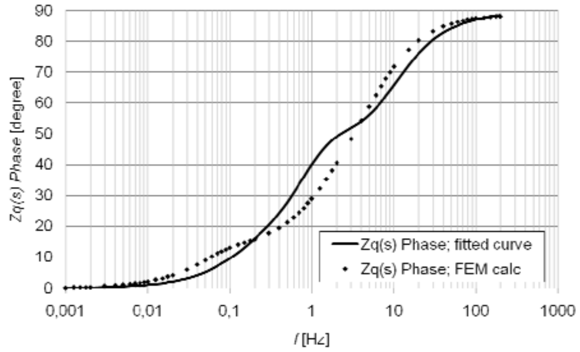


Fig. 7. Quadrature-axis phase impedance

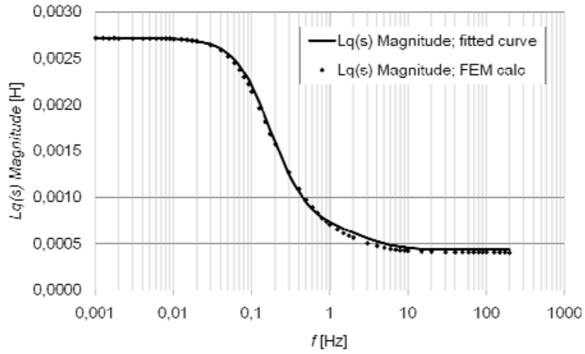


Fig. 8. Quadrature-axis magnitude inductance

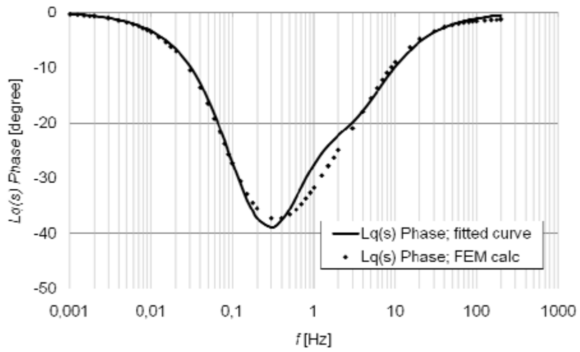


Fig. 9. Quadrature-axis phase inductance

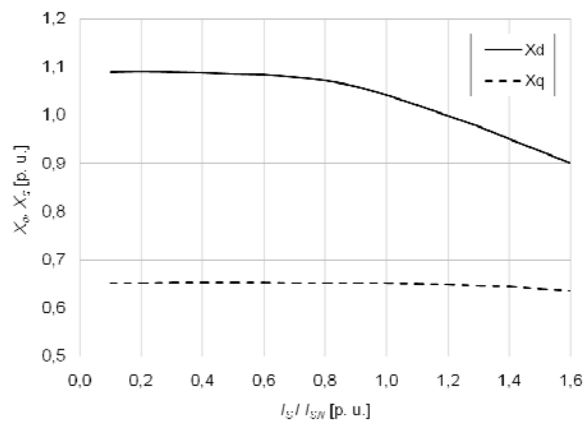


Fig. 10. Dependence synchronous reactances in direct and quadrature axes on stator current

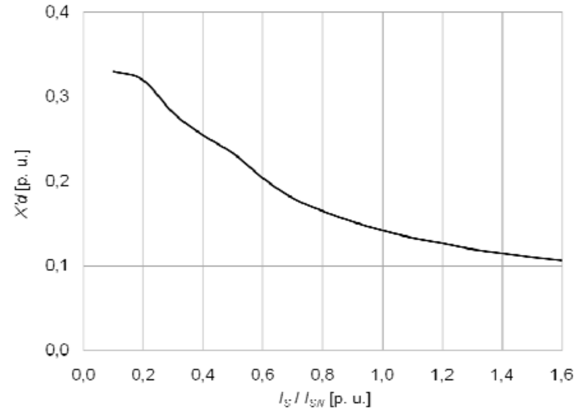


Fig. 11. Dependence transient reactance in direct axis on stator current

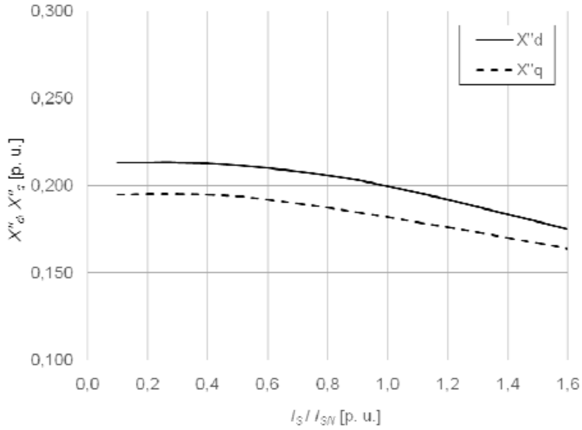


Fig. 12. Dependence sub-transient reactances in direct and quadrature axes on stator current

Figures 13a and 13b presents flux lines and distribution of magnetic induction at $I_S$=$I_{SN}$ (synchronous work) for direct and quadrature axes respectively.

a)

b)

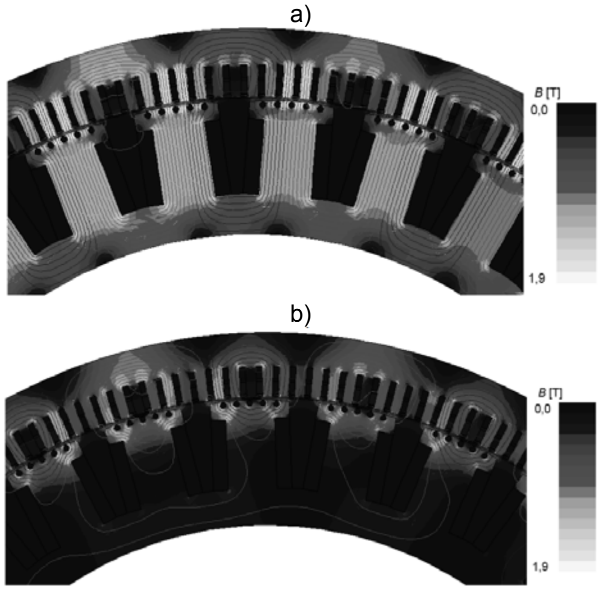


Fig. 13. Flux lines and distribution of magnetic induction at rated synchronous work for direct (a) and quadrature (b) axes

**Conclusion**

The use of the SSFR method in large salient pole synchronous machines is justified. This method allows the determination of electromagnetic parameters with satisfactory accuracy. The accuracy of calculations strongly depends on the curves matching program for the results of FEM calculations or measurements.

The saturation effect in the tested synchronous machine decreased all reactances except the synchronous transient reactance by about 7-8%. For $X'_d$, the above effect is more visible. This reactance is reduced by approx. 57%. Saturation of magnetic circuits does not affect the value of $X_q$.

Table 2. Statement of determined electromagnetic parameters by used SSFR test and from the distribution of sinusoidal fields

| Electromagnetic parameters | Unit | Value from SSFR test | Value from the distribution of sinusoidal fields |
|---|---|---|---|
| $X_d$ | p. u. | 1,128 | 1,120 |
| $X_{dn}$ | p. u. | - | 1,041 |
| $X_q$ | p. u. | 0,660 | 0,652 |
| $X_{qn}$ | p. u. | - | 0,652 |
| $X'_d$ | p. u. | 0,335 | 0,333 |
| $X'_{dn}$ | p. u. | - | 0,142 |
| $X''_d$ | p. u. | 0,211 | 0,213 |
| $X''_{dn}$ | p. u. | - | 0,200 |
| $X''_q$ | p. u. | 0,177 | 0,195 |
| $X''_{qn}$ | p. u. | - | 0,182 |

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