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## Determination of turbogenerator electromagnetic parameters from the SSFR test in the simulation process

**Abstract.** Presented article deals with the determination of turbogenerator electromagnetic parameters from the SSFR test (Standstill Frequency Response). 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. The achieved results are compared with the data coming from the running test.

**Streszczenie.** Prezentowany artykuł przedstawia symulacyjną metodę wyznaczania parametrów elektromagnetycznych turbogeneratora z testu SSFR (Standstill Frequency Response). Zastosowana metoda obliczeń bazuje na rozkładzie pól sinusoidalnie zmiennych o zadanej zmiennej częstotliwości. Reaktancje turbogeneratora zostały wyznaczone ze stałych czasowych za pomocą opracowanego programu. Program ten dopasowuje charakterystyki amplitudowe i fazowe do wartości otrzymanych z symulacji. Wyniki obliczeń parametrów elektromagnetycznych porównano z wynikami pomiarów. (Symulacyjne wyznaczanie parametrów elektromagnetycznych turbogeneratora z testu SSFR).

**Keywords:** turbogenerator, finite element method, electromagnetic parameters, Standstill Frequency Response test.

**Słowa kluczowe:** turbogenerator, metoda elementów skończonych, parametry elektromagnetyczne, SSFR test.

### Introduction

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]. New-created equivalent turbogenerator model allows to predict the dynamic behaviour of the turbogenerator 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.

SSFR can be performed both in the manufacturing factory and in the power plant. In the factory can be a supplement of standard running test. Whereas in the site can be utilized for a retrofit machine wherein some modifications in the construction were implemented such as new stator main insulation without any changes in stator slot dimensions in order to increase the apparent power or some modification in the rotor. SSFR test in the site is used to check if assumed electromagnetic parameters during the calculation process are confirmed for tested machine and fulfil all grid requirements [2].

This article presents the methodology how to determine the turbogenerator electromagnetic parameters from the simulation of SSFR test both in direct and quadrature axis by using the finite element method. Computed values are compared with the data achieved in the running test from no-load as well as sudden short circuit test.

### Description of turbogenerator model

An investigated turbogenerator possess 2 poles and 2 parallel circuits in the armature winding. The main data are included in table 1.

Table 1. Main data of investigated turbogenerator

Name of turbogenerator data	Value	Unit
Rated apparent power	500	MVA
Terminal voltage	21	kV
Rated armature current	13.75	kA
Rated power factor	0.80	-
Rated field current	4518	A
Number of poles	2	-
Rated torque	1.273	MNm

Created two-dimensional model possess both the field and the circuit part. A cross-section of field part is shown in figure 1. In this place the real distribution of stator and rotor windings as well as the damper windings were reflected. Besides the non-linearity of magnetizing curves for stator and rotor cores are implemented. In addition the model contains the feature of the displacements of current in the rotor wedges and in the solid rotor as well. More information about field-circuit modelling of the turbogenerator can be found in [3]

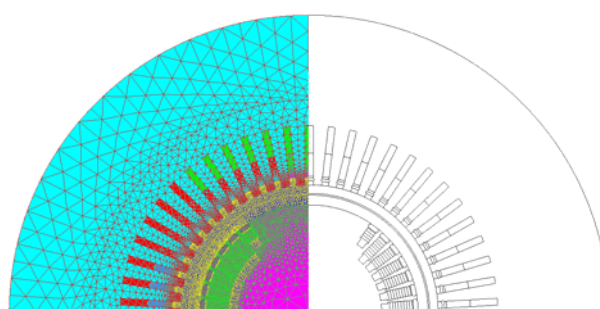


Fig. 1. Half of the field part of investigated turbogenerator

The field model is coupled with a circuit model in where the resistances and the inductances representing the end-windings of stator and rotor are included. The view of modified circuit model utilized to SSFR simulations is presented in figure 2. In this model the voltage source was used but in this case the application of current source can be applied as well. Whereas the current source is required to obtain the electromagnetic parameters existing at rated load e.g. for rated stator current and value of current flow in the stator winding has to be accordant to number of parallel circuits if exist. Presented circuit model was modified to fulfil

all requirements from the rules included in [2] and reflects the same condition as during the real SSFR test.

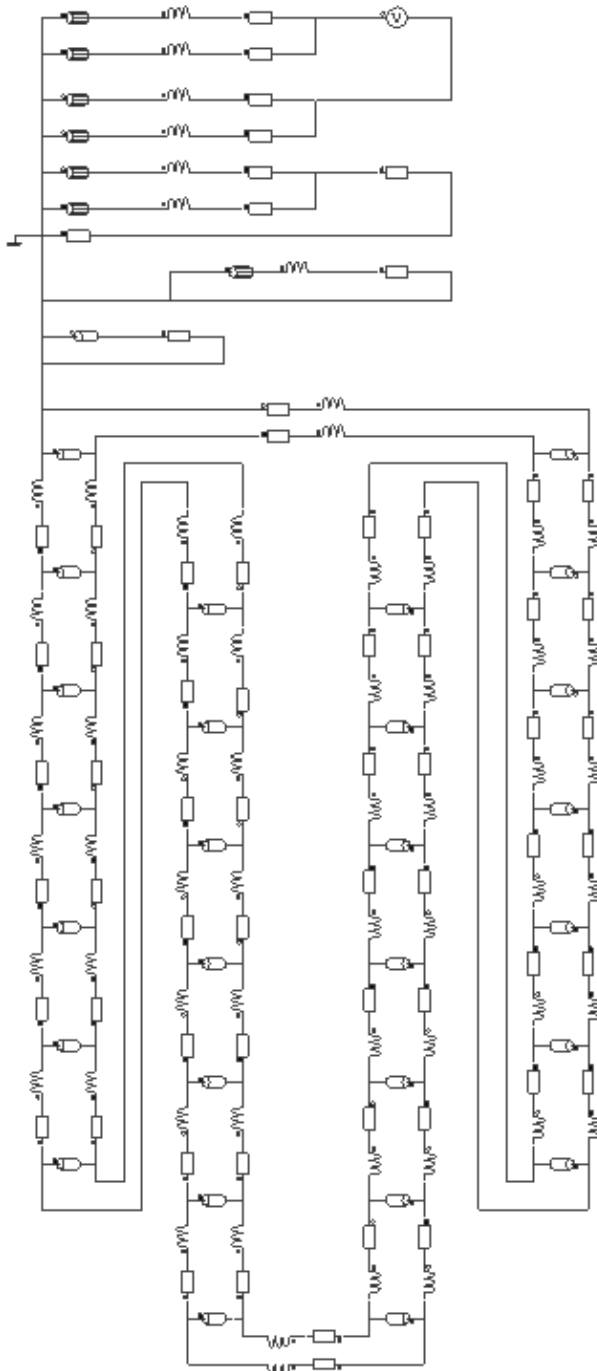


Fig. 2. Modified circuit model of investigated turbogenerator needed to SSFR simulations

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

During the simulation process a module of Steady State AC Magnetic 2D application was 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.

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, sub-synchronous as well as sub-sub-synchronous 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 [4]. 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. Therefore 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 turbogenerator electromagnetic parameters. Unfortunately above values are not sufficient to obtain all of the needed parameters to create the equivalent circuit of turbogenerator and that is why another function such as  $sG(s)$  has to be 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 turbogenerator electromagnetic parameters and  $sG(s)$  function is only mentioned.

Data read directly from the postprocessor is not enough to indicate the turbogenerator 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  $U=const$ .

$$(1) \quad Z_m = \frac{1}{2} \cdot \frac{U_m}{I_m}$$

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

$$(2) \quad \varphi_Z = \varphi_{current} - \varphi_{voltage}$$

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

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

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

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

$$(5) \quad L_m = \sqrt{L_R^2 + L_I^2}$$

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

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 turbogenerator 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 for direct axis

At the beginning of simulation the rotor is situated according to direct axis 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 3-6 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.

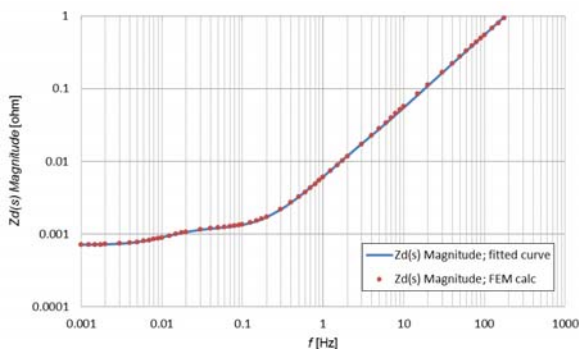


Fig. 3. Direct-axis magnitude impedance

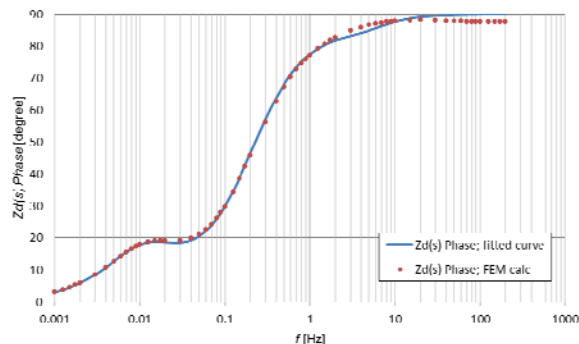


Fig. 4. Direct-axis phase impedance

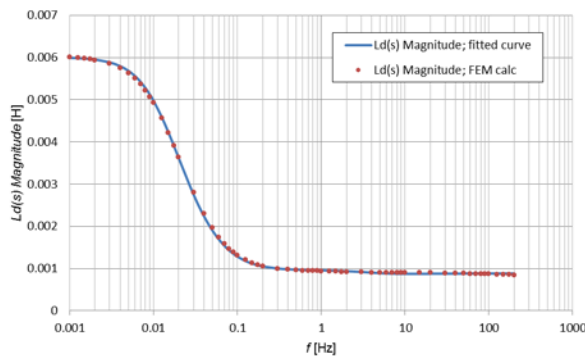


Fig. 5. Direct-axis magnitude inductance

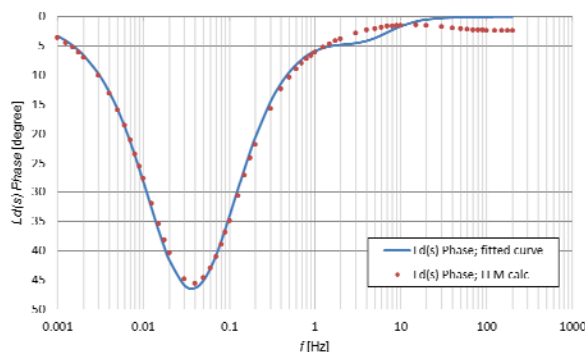


Fig. 6. Direct-axis phase inductance

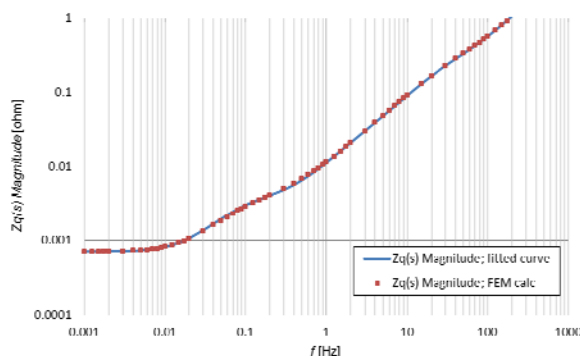


Fig. 7. Quadrature-axis magnitude impedance

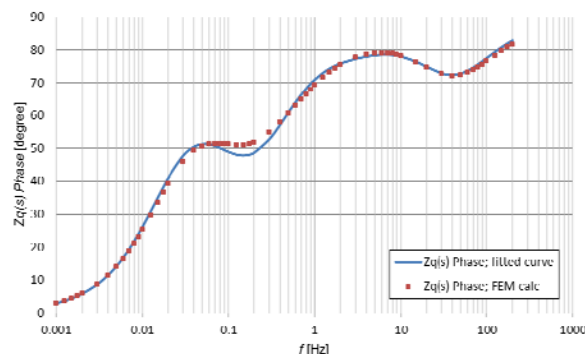


Fig. 8. Quadrature-axis phase impedance

For direct axis good accordance was achieved. Based on the fitted curves it was possible to determine the turbogenerator 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:

$$(11) \quad X'_d = \frac{T'_d}{T_{do}} X_d$$

$$(12) \quad X''_d = \frac{T''_d}{T_{do}} X'_d$$

$$(13) \quad X'''_d = \frac{T'''_d}{T_{do}} X''_d$$

### Calculation results for quadrature axis

In case of quadrature axis, the rotor is situated according to quadrature axis and is fixed. One of the armature winding is disconnected and the current flows by only 2 phases whereas the field winding is shorted the same as in case of direct axis. Obtained results in postprocessor are in function of frequencies. In the figures 7-10 are presented the computed magnitudes and phases of impedance and inductance 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) but for quadrature axis. The methodology is the same as in case of direct axis.

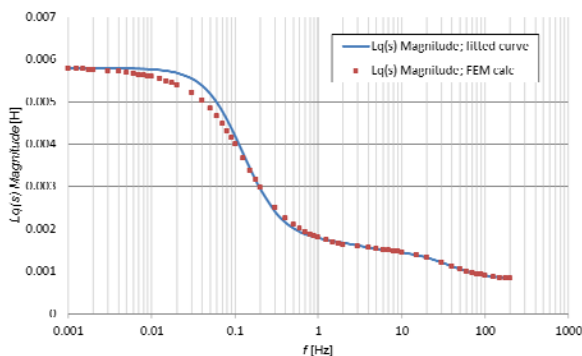


Fig. 9. Quadrature-axis magnitude inductance

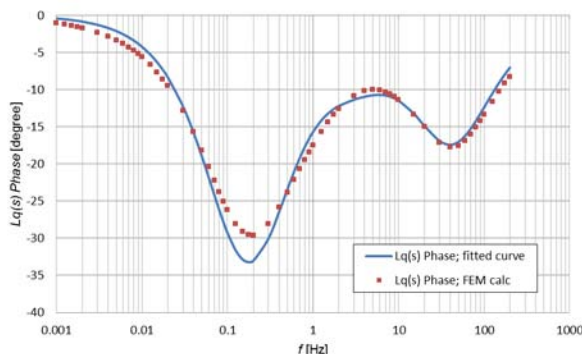


Fig. 10. Quadrature-axis phase inductance

Based on the fitted curves it is possible to determine the turbogenerator electromagnetic parameters in quadrature axis which can be found in table 3.

### Conclusion

Achieved results from the FEM computations and created program allow to determine the turbogenerator electromagnetic parameters. These values are located in tables 2 and 3 for direct and quadrature axis respectively.

The comparison shows that the values of reactances are very similar to measured values during the standard

running test. Unfortunately the time constants are significantly different despite the fact that computed reactances depend directly from these time constants, see equations (11), (12) and (13).

Better solution to determine turbogenerator electromagnetic parameters is usage of a method presented in [5] where the reactances are computed from the flux values in active part and taking into account the leakage flux value in end-winding. The method in [5] bases on the sinusoidal field distribution for transient and sub-transient parameters and bases on the magneto-static state in case of the synchronous reactances.

An advantage of Steady State AC Magnetic 2D application is low simulation time even in case of reflection of saturation effect. Whereas disadvantage is a need of the program used to fit the curves in order to determine the time constants.

Table 2. Comparison of turbogenerator electromagnetic parameters coming from SSFR test and from the running test for direct axis

Electromagnetic parameters	Unit	Value from SSFR test	Value from the running test
$T'_d$	s	1.755	1.250
$T''_d$	s	0.031	0.058
$T'''_d$	s	0.021	-
$T'_{do}$	s	10.976	8.100
$T''_{do}$	s	0.038	-
$T'''_{do}$	s	0.019	-
$X_d$	p. u.	2.139	2.112
$X'_d$	p. u.	0.342	0.345
$X''_d$	p. u.	0.279	0.275
$X'''_d$	p. u.	0.313	-

Table 3. Statement of the results for quadrature axis

Electromagnetic parameters	Unit	Value from SSFR test
$T'_q$	s	0.504
$T''_q$	s	0.047
$T'''_q$	s	0.003
$T'_{qo}$	s	1.676
$T''_{qo}$	s	0.055
$T'''_{qo}$	s	0.005
$X_q$	p. u.	2.065
$X'_q$	p. u.	0.620
$X''_q$	p. u.	0.524
$X'''_q$	p. u.	0.294

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