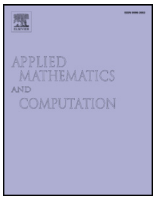
Applied Mathematics and Computation 000 (2017) 1–13

Contents lists available at ScienceDirect

Applied Mathematics and Computation

journal homepage: www.elsevier.com/locate/amc



Determination of high power synchronous generator subtransient reactances based on the waveforms for a steady state two-phase short-circuit

Sebastian Berhausen*, Andrzej Boboń

Institute of Electrical Engineering and Computer Science, Silesian University of Technology, Akademicka 10, 44-100 Gliwice, Poland

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Synchronous generator
Line-to-line short circuit
2D field-circuit model
Fast Fourier transform (FFT)
Least-squares method
Gradient algorithm

ABSTRACT

In the paper, there is presented an analysis of the waveforms at the stator winding terminals of a high power synchronous generator for a steady state two-phase short-circuit. The analysis was performed by the finite element method based on a 2D generator model taking into account higher spatial and time harmonics of the magnetic field as well as the impact of eddy currents in the rotor damping circuits. The used FE model was experimentally verified. For the steady state two-phase short-circuit, the waveforms determined by the FE method were compared with the approximated waveforms calculated using analytical formulas. The analytical formulas were derived from the machine equations written in the stator fixed coordinate system (α, β, 0), using normalized transformation of coordinates and the Heaviside operational calculus. The higher time harmonics obtained based on the FFT analysis of the waveforms of the short-circuit current and open phase voltage were used for determining subtransient reactances in the d and q axes of a 200 MW generator. The thus determined generator reactances were compared with the values determined by other methods.

1. Introduction

Subtransient reactances belong to the standard electromagnetic parameters of a synchronous machine. They characterize the initial electromagnetic state of the machine after the occurrence of a disturbance in operation of the machine. In the initial instants of the transient state, currents flow in all closed electrical circuits of the machine. In the classical circuit model of a synchronous machine containing one equivalent damping circuit in the rotor in the d axis and two damping circuits in the q axis (model of type (2, 2) [1]), transient processes progress from the so-called subtransient state, through the transient state to the steady state to which the subtransient, transient and steady (synchronous) reactances correspond, respectively.

The classical method for determining subtransient reactances is based on measurements at a stationary rotor when forcing in the d and q axes the armature magnetomotive force of frequency greater than or equal to the rated frequency, respectively. The subtransient reactance in the d axis can also be determined at a rotating rotor on the basis of standard tests of a three-phase sudden short-circuit or disconnection of a steady three-phase short-circuit (i.e., at the so-called stator voltage recovery) [2,3].

---

* Corresponding author.
E-mail addresses: sebastian.berhausen@polsl.pl (S. Berhausen), andrzej.bobon@polsl.pl (A. Boboń).

http://dx.doi.org/10.1016/j.amc.2017.06.003
0096-3003/© 2017 Elsevier Inc. All rights reserved.

Please cite this article as: S. Berhausen, A. Boboń, Determination of high power synchronous generator subtransient reactances based on the waveforms for a steady state two-phase short-circuit, Applied Mathematics and Computation (2017), http://dx.doi.org/10.1016/j.amc.2017.06.003

In the paper, there are presented the waveforms at a two-phase short-circuit of a high power synchronous generator stator winding in transient and steady states. It was assumed that prior to a disturbance the generator operated under no-load conditions. The waveforms were calculated when using the two-dimensional field-circuit model of the generator taking into account higher spatial and time harmonics of the magnetic field and the impact of eddy currents in the rotor damping circuits. The developed model of the synchronous generator was experimentally verified.

The waveforms for the two-phase short-circuit in the steady state determined by FEM and the waveforms determined with the use of approximate analytical dependencies were the basis for calculating the subtransient parameters of the synchronous generator in the d and q axes.

The analytical formulas were derived from the machine equations written in the stator fixed coordinate system (α, β, 0), using normalized transformation of coordinates and the Heaviside operational calculus [4].

In the paper, the subtransient parameters were determined by two methods. The first method is based on higher time harmonics determined based on the FFT analysis [5] of the waveforms of the short-circuit current and open phase voltage in the steady state [6] calculated by FEM. In this method, there were used the analytical relationships between the subtransient reactances in both axes and the amplitudes of higher harmonics.

The second method is based on the use of the optimization method. In this method, the searched parameters are selected in such a way as to minimize an appropriate objective function defined by deviations (determined at individual time instants) between the waveforms calculated by FEM and those calculated from analytical dependencies. The gradient algorithm available in Mathcad software was used to minimize the objective function. The calculation results of the parameters obtained by both methods were compared with each other.

The possibility of determining both subtransient reactances based on only one test of steady two-phase short-circuit is the advantage of the presented methods. Standard tests performed on machines at standstill require setting the rotor in appropriate positions, which can be difficult in the case of large machines. Whereas the tests of a three-phase sudden short-circuit or a voltage recovery enable determining the parameters only in the d axis.

2. The synchronous generator model used for investigations

Field-circuit models are often used for the analysis of electrodynamic states of electrical machines [7]. Using these models one can simultaneously solve the equations of the magnetic field, the Kirchhoff equations describing the electromagnetic state of individual windings of the machine and the equation of the rotational motion of the rotor. The reliability of the materials and construction data of the analyzed machine is a decisive factor determining the accuracy of calculations carried out with the use of field-circuit models. That is why the developed for simulations two-dimensional field-circuit model of the synchronous generator was verified by measurements. It was made by comparison of the measured and calculated waveforms of the stator voltage at step changes of the voltage regulator reference voltage of the generator operating under no-load conditions as well as on the basis of the measured and calculated by FEM no-load and three-phase short-circuit characteristics. The thus verified model of the synchronous generator was used for calculations of the waveforms for a two-phase short-circuit of the stator winding.

2.1. The synchronous generator field-circuit model

The differential equations with partial derivatives describing the distribution of the magnetic field inside the machine and the differential equations with ordinary derivatives describing voltage–current dependencies in electrical circuits of the windings are the field-circuit model of a three-phase synchronous generator.

In the developed field-circuit model of a synchronous generator, there were taken into account [8]:

- two-dimensional magnetic field distribution in the cross-section. The consequence of this assumption is the omission of end winding leakage inductances in the machine mathematical model as well as the phenomena occurring in the generator end region resulting from the finite length of magnetic cores. The end winding leakage inductances can be calculated e.g., based on the analysis of the magnetic field distribution in the generator end region (this analysis requires developing a 3D model) or based on approximate design dependencies [9],
- nonlinear magnetization characteristics of stator and rotor cores,
- currents induced in the solid block and slot wedges of the rotor,
- impact of saturation, permeance and winding magnetomotive force field harmonics,
- constant rotational speed of the rotor.

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

Given the above assumptions, the space–time distribution of the electromagnetic field can be expressed by using the magnetic vector potential $\boldsymbol{A}$ which in the considered two-dimensional model has only one component directed perpendicular to the plane of the area in question $\boldsymbol{A} = \mathbf{1}_z A$:

$$\mathrm{curl}\frac{1}{\mu}\mathrm{curl}\mathbf{A} = -\gamma\frac{\partial \mathbf{A}}{\partial t} - \gamma\,\mathrm{grad}V + \gamma\,\boldsymbol{v}\times\mathrm{curl}\mathbf{A}, \tag{1}$$

where: μ – magnetic permeability, γ – electrical conductivity, V – scalar electric potential, $\boldsymbol{v}$ – velocity vector of the moving system.

Please cite this article as: S. Berhausen, A. Boboń, Determination of high power synchronous generator subtransient reactances based on the waveforms for a steady state two-phase short-circuit, Applied Mathematics and Computation (2017), http://dx.doi.org/10.1016/j.amc.2017.06.003