Electric Power Systems Research 143 (2017) 409–414

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Modelling of steady state and transient performance of the synchronous generator considering harmonic distortions caused by non-uniform saturation of the pole shoe

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ARTICLE INFO

Article history:
Received 30 January 2015
Received in revised form 24 April 2016
Accepted 11 October 2016
Available online 11 November 2016

Keywords:
Air-gap function distribution
Harmonics
Modified winding function approach
Nonlinear
Space distribution

ABSTRACT

In this paper a synchronous generator model is described. This model is developed on the assumption that in loaded and no load conditions the saturation effect affects the pole shoe in a different way. The developed model is based on the multiple saliency model and is formulated using winding function approach in machine variables. The influence of the non-uniform saturation of the pole shoe in load conditions on the performance of the generator is investigated. Simulation results of the model are compared with the measurements on selected salient pole synchronous generator for steady and transient states.

1. Introduction

Nowadays autonomous power generation systems (APGS) requires suitable sophisticated tools. These tools should allow for fast and reliable evaluation of the APGS in steady state (SS) and transient (TRAN) performance. One of the main components of APGS is the electrical energy source. In most systems of this type the source is a synchronous generator (SG). In low power systems such as micro-CHP (Combined Heat and Power) or the aircraft system, SG can be a significant source of voltage and current lower order odd harmonic distortion, especially third harmonic distortion.

Due to requirement of fast and reliable evaluation of the APGS in different SS and TRAN conditions an accurate model of the SG is demanded. This model should include physical phenomena which are main causes of the generated voltage and current harmonic distortion. This is important for validation of the APGS, especially when voltage and current distortions can cause additive loses in system components. This, in effect, can lead to decreased reliability and problems with system optimization in terms of weight reduction.

2. Survey of related works

The accurate representation and analysis of harmonic distortion in APGS and especially in aircraft systems [1–3] is important in terms of reliability studies and design optimization process. The main cause of this distortions is the SG on board [4,5]. This makes the evaluation of the SG performance in APGS a significant part of the design process of modern systems.

FEM models [6] are reliable, however they require high computing power and are too slow for entire system evaluation. These models also require detailed information about every element of the system including the parameters of materials used in system components.

The Winding Function Approach (WFA) [6,7] does not require as much details about the machine as the FEM model. However due to certain limitation of model, like neglecting of tangential airgap flux component [7], it is fairly accurate in small airgap machines.

Magnetic saturation in circuit models [8–10] have been implemented with the assumption of uniform saturation or the differentiation in direct and quadrature axis saturation. These models unfortunately neglect the effects of non-uniform saturation of pole shoe.

Models including permanence or multiple saliences of the airgap geometry spatial distribution [11–15] developed based on the WFA or magnetic permanence modelling represent the behaviour of the SG in APGS in a sufficiently accurate way.

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http://dx.doi.org/10.1016/j.epsr.2016.10.030
0378-7796/

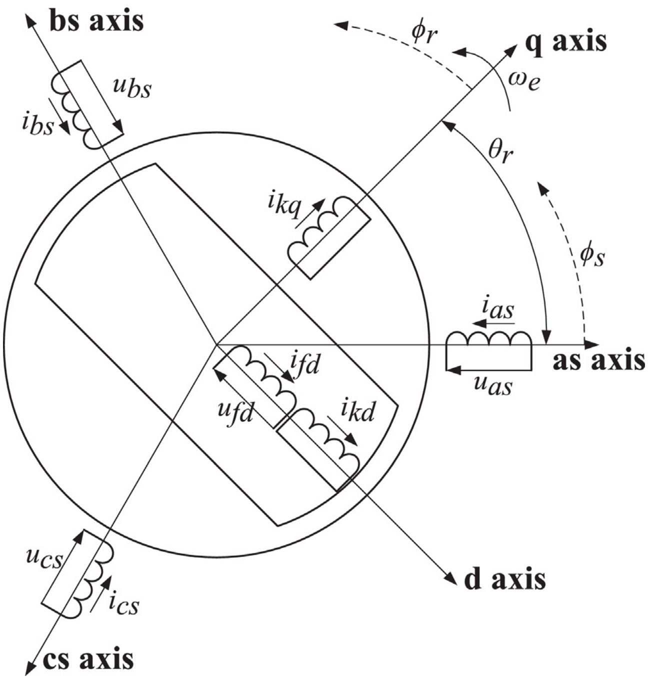

Fig. 1. General structure of SG model.

3. Objectives and scope

The main objective of this paper is the validation of proposed model for evaluation of SS and TRAN performance of the SG in AEPS. One of the main issues in design process of modern APGS is the accurate simulation of entire system. This allows for more cost effective design process. One of the key aspects in APGS and especially aircraft system is the harmonic distortion in system voltage and current. The SG can be a significant source of these distortions. It is important to select the most significant physical phenomena, to be represented by the model, which can cause harmonic distortions. The approach includes winding function space distribution and non-uniform saturation of the pole shoe, models harmonic distortion in an accurate and suitable way to evaluate SS and TRAN performance of SG in APGS.

Developed models focus mainly on the magnitude of harmonic distortion in voltage and current of the SG in APGS. For accurate SG performance modelling it should also be noticed that saliency caused by non-uniform saturation of the pole shoe is changing the effective length of the airgap resulting in increase as long as decrease of the airgap length along the pole shoe as it is shown in [16].

Main contribution of the presented research are: the model description, its implementation and simulations in Synopsys/Saber simulator, the validation of the developed model using a case study on selected salient pole generator.

4. Solution

In the proposed solution the airgap geometry spatial distribution function of the WFA method is modified and incorporates the overall saturation of the machine core as well as the non-uniform saturation effect in the pole shoe. Detailed description of the model was presented in [16]. Fig. 1 presents the model in machine variables. Model winding parameters are denoted by *fd* for field winding, *kd* for direct axis damper cage winding, *kq* for quadrature axis damper cage winding, *as*, *bs*, *cs* for armature windings.

Proposed solution for SG model is based on multiple saliences model. However instated of evaluating additional saliences we proposed the different approach. In our research we found that in small SGs the apart from the fundamental component in voltage and current waveforms the presence of the third harmonic can be significant (even over 10% of fundamental component). Based on the winding function approach we concluded that the generated voltage third harmonic is the result of the stator and rotor MMF (magneto motive force) spatial distribution third harmonic and the fundamental harmonic component (not the average value) of the airgap distribution function. Assuming the harmonic components of the machine winding distributions are constant, we proposed a model which describes the relation between non-uniform saturation of the pole shoe and the phase and amplitude of airgap distribution fundamental harmonic component.

4.1. Modeling

General structure of the model is based on the voltage and linkage flux equation and is developed using WFA:

$$\begin{aligned}\mathbf{v}_{abcs} &= -\mathbf{r}_s\mathbf{i}_{abcs} + \frac{\mathrm{d}\boldsymbol{\lambda}_{abcs}}{\mathrm{d}t}\\ \mathbf{v}_{qdr} &= \mathbf{r}_r\mathbf{i}_{qdr} + \frac{\mathrm{d}\boldsymbol{\lambda}_{qdr}}{\mathrm{d}t}\end{aligned} \tag{1}$$

where the flux linkages denoted by $\boldsymbol{\lambda}_{abcs}$ for stator and $\boldsymbol{\lambda}_{qdr}$ for rotor are defined based on current and self and/or mutual inductance [17]:

$$\begin{bmatrix}\boldsymbol{\lambda}_{abcs}\\ \boldsymbol{\lambda}_{qdr}\end{bmatrix} = \begin{bmatrix}\mathbf{L}_s & \mathbf{L}_{sr}\\ (\mathbf{L}_{sr})^T & \mathbf{L}_r\end{bmatrix}\begin{bmatrix}-\mathbf{i}_{abcs}\\ \mathbf{i}_{qdr}\end{bmatrix} \tag{2}$$

Product of current and inductance define the induced voltage waveform. Current is a time dependent variable and its waveform is influenced by the load. The main focus of this paper is the space harmonic distribution of the inductances:

$$L_{xy}(\theta_r) = \frac{L_l + \int_{\phi_{z1}}^{\phi_{z2}} N_x(\phi_z)\int_{\phi_z}^{\phi_z+\pi}\frac{MMF_y(\phi_z)}{\delta(\zeta-\theta_r)}d\zeta d\phi_z}{i_y} \tag{3}$$

where x and y can be substituted with *as*, *bs*, *cs*, *fd*, *kd* or *kq* and z can be substituted with s or r for stator and rotor, respectively. Main causes of harmonic distortion in functions of machine inductances along the airgap are: the spatial distribution of armature and field windings $N(\phi_z)$ and the rotor saliency $\delta(\phi_z-\theta_r)$. The derivative of magneto motive force over current is the winding distribution $N_x(\phi_z) = dMMF((\phi_z)/di_x$. In the proposed model winding distributions have fixed parameters and are defined as:

$$N_x\left(\phi_y\right) = -\frac{N'_x}{2}\sum_{k=0}^{n} kA'_{((2k+1)x)}\sin\left((2k+1)\phi_y\right) \tag{4}$$

where N'_x is equivalent number of winding turns for the fundamental harmonic component. The amplitudes of the distribution are defined in relation to fundamental component $A'_{(2k+1)x} = A_{(2k+1)x}/(-N'_x/2)$. The airgap saliency is described using the average value and the fundamental harmonic component of its length distribution. This function of equivalent airgap geometry spatial distribution (Fig. 2) is defined as:

$$\begin{aligned}&\delta\left(\phi_s-\theta_r, i_m, \rho\right)\\ &= \frac{1}{\alpha_d}\left(\frac{1}{k_{sat2}(\rho)\left(k_{sat1}(i_m)\alpha'_1 - \alpha'_2\cos\left(2\left(\phi_s-\theta_r+\rho\right)\right)\right)}\right)\end{aligned} \tag{5}$$

where α'_1 is the relative average value and α'_2 is the relative amplitude of the fundamental harmonic component of the distribution