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Modeling and Analysis of High Power Synchronous Generator

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Abstract

This paper proposes a mathematical model of synchronous generator used as an interface between power plant energy sources and the electrical grid. Power electronic converter is then needed to adapt their synchronous speed to the network frequency. Control method is proposed in order to optimize the power factor of synchronous machine. In addition, author presents the performance evaluation of the proposed strategy which allows to improve machine current and voltage quality. Simulation results for different operating points and transitions between them highlight the capabilities of the proposed control model. These include the ability to operate with unity power factor.

Keywords: Synchronous generator, Mathematical model, Power electronic converter, IGBT converter, angle shift, high efficiency.

1. Introduction

High power synchronous machines are principally used as generators in order to convert the mechanical work obtained from steam or water turbine to electrical energy. They are connected to three-phase electrical grid with constant frequency of 50 Hz or 60 Hz [1]. Such generator must have at least one excitation coil [2]. This offers the possibility of controlling the voltage of the electrical grid and then to control the reactive power [3]. The rest of this paper is organized as follows. Section 2 presents a mathematical model of synchronous generator used as an interface between power plant energy sources and the electrical grid. Section 3 describes our proposed power control which is needed to adapt the synchronous generator's speed to the network frequency. The performance evaluation of this strategy is presented in Section 4 and approved by simulation comparative study, these include the ability to operate with unity power factor. Finally, we conclude this letter and give some perspectives to our work in Section 5.

2. Mathematical Model of Synchronous Generator

2.1. Description

This section develops the mathematical model of electrical machine, especially Synchronous Generator (SG). It explains the need for modeling and formulates generalized model as a set of differential and algebraic equations. Actually, Knowledge of the equivalent schemes in steady states and mechanical

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characteristics is required for selecting a machine which would be adequate for a particular application, for designing systems containing electrical machines and for solving the control problems of generators [4].

Figure 1 shows a detailed model of a synchronous machine with round rotor. Indeed, this machine is modeled in the rotor reference frame. It operates as a motor or generator according to the sign of the mechanical torque (positive for motoring, negative for generating). All electrical variables and parameters are viewed from the stator side. In this scheme, d and q are referred to the quantities on the direct and quadrature axis respectively. (m,d) and (m,q) are referred to the magnetizing on the direct and quadrature axis respectively, and f is referred to field on direct axis.

Figure 1: Detailed model of a synchronous machine with round rotor..

2.2. Mathematical representation

Using electrical machines requires mathematical representation of the process of electromechanical conversion. It is necessary to determine equations which correlate the electrical quantities of the machine, such as the voltages and currents, with mechanical quantities such as the speed and torque. These equations provide the link between the electrical access to the machine (terminals of the windings) and the mechanical access to the machine (shaft)[5].

Electrical system:

Stator flux linkages:

$$\phi_d = L_{ls} i_d + L_{m,d} (i_d + i'_f + i'_{k,d}) \quad (2.1)$$

$$\phi_q = L_{ls} i_q + L_{m,q} (i_q + i'_g + i'_{k,q}) \quad (2.2)$$

Electromagnetic torque:

$$T_e = \frac{3}{2}p(\phi_d i_q - \phi_q i_d) \quad (2.3)$$

Mechanical System:

Mechanical rotor speed ω_m :

$$\dot{\omega}_m = \frac{1}{J}(T_e - F\omega_m T_m) \quad \text{with} \quad \dot{\theta}_m = \omega_m \quad (2.4)$$

3. Proposed Power Control

3.1. System parameters calculation

To simplify, and as shown in figure 2, author proposes the equivalent circuit of generator connected to its rectifier via an inductance L_g . The voltage induced by the pole wheel is denoted by V_g and represented by AC voltage source with adjustable amplitude. In a real machine, the amplitude of the induced voltage depends on the machine's excitation. Machine's stator is connected directly to a rectifier which maintains a constant DC Voltage in the intermediate circuit. The stator voltage is therefore designated by V_{red} , its magnitude is imposed by the necessary direct voltage in the intermediate circuit in order to have a desired operation mode [6].

Figure 2: (a) Simple model of generator and rectifier circuit. (b) Schematic Diagram of generator and rectifier voltages.

According to schematic diagram in figure 2, active and reactive power can be written, using system parameters, by equations 3.1 and 3.2:

Generator's power:

$$\begin{cases} P_g = \frac{3}{2} V_g I_g \cos \varphi_g = \frac{3}{2 X_g} V_g V_{red} \sin \theta_g \\ Q_g = \frac{3}{2} V_g I_g \sin \varphi_g = \frac{3}{2 X_g} V_g (V_g - V_{red} \cos \theta_g) \end{cases} \quad (3.1)$$

Rectifier's power:

$$\begin{cases} P_{red} = \frac{3}{2} V_{red} I_g \cos \varphi_{red} = \frac{3}{2 X_g} V_{red} V_g \sin \theta_g \\ Q_{red} = \frac{3}{2} V_{red} I_g \sin \varphi_{red} = \frac{3}{2 X_g} V_{red} (V_g \cos \theta_g - V_{red}) \end{cases} \quad (3.2)$$

3.2. System analysis

For the same generator current I_g , two operation modes are possible:

First case when $\cos \phi_g = 1$: operation with machine side reactive power compensation $Q'_g = 0$.

Active power is given in this case by equation 3.3:

$$P'_{red} = P'_g = \frac{3}{2 X_g} V_{red} V'_g \sin \theta'_g \quad (3.3)$$

In addition, voltage V'_g and angle shift θ'_g necessary for this operation mode with $Q'_g = 0$, can be calculated according to equation 3.4:

$$V'_g = \sqrt{V_{red}^2 - (X_g I_g)^2} \text{ and } \theta'_g = \arcsin \left(\frac{X_g I_g}{V_{red}} \right) \quad (3.4)$$

Second case when $\cos \phi_{red} = 1$: operation with rectifier side reactive power compensation $Q''_{red} = 0$. Active power is given in this case by equation 3.5:

$$P''_{red} = P''_g = \frac{3}{2 X_g} V_{red} V''_g \sin \theta''_g \quad (3.5)$$

As for the first case, voltage V''_g and angle shift θ''_g necessary for this operation mode with $Q''_{red} = 0$, can be calculated according to equation 3.6:

$$V''_g = \sqrt{V_{red}^2 + (X_g I_g)^2} \text{ and } \theta''_g = \arctan \left(\frac{X_g I_g}{V_{red}} \right) \quad (3.6)$$

4. Comparative Study by Simulation

4.1. Simulation Model

Figure 3 shows simulation model which is composed of synchronous generator, with adjustable excitation voltage V_f , its stator is connected to a frequency converter with DC intermediate circuit. The whole is connected to the grid via inductors.

In this model, equivalent diagram of the synchronous machine which is shown in figure 1 is used, and its different elements are calculated from the given parameters in section 3. A comparative study is

Figure 3: Simulation model using synchronous generator.

carried out and summarized in this section, to compare the different operation modes, taking into account when $Q'_g = 0$ or when $Q''_{red} = 0$.

The direct voltage in the intermediate circuit is adapted by adjustment of voltage excitation of synchronous machine. Actually, V_f can be expressed as a function of the induced voltage e_g according to equations (4.1-4.4). [7]

$$v_f = \frac{r_f}{x_{md}} e_g \quad (4.1)$$

$$e_g = (v_{red} + \frac{2}{3} x_d \frac{Q_{red}}{v_{red}}) \cos \theta_{gc} + \frac{2}{3} x_d \frac{P_{red}}{v_{red}} \sin \theta_{gc} \quad (4.2)$$

$$V_f = \frac{R_f}{X_{md}} \left((V_{red} + \frac{2}{3} X_d \frac{Q_{red}}{V_{red}}) \cos \theta_{gc} + \frac{2}{3} X_d \frac{P_{red}}{V_{red}} \sin \theta_{gc} \right) \quad (4.3)$$

$$\theta_{gc} = \text{Arctan} \left(\frac{P_{red}}{\frac{3}{2} \frac{v_{red}^2}{x_q} + Q_{red}} \right) \quad (4.4)$$

4.2. Simulation results

For a better presentation of the simulation results, Figure 4 shows the simulated active powers, voltages and currents for different cases. When $Q'_g = 0$, the generator current and voltage are in phase, then the machine side reactive power is compensated.

For the second case, when $Q''_{red} = 0$, the generator current is in phase with the rectifier voltage, in this case rectifier side reactive power is compensated.

The proposed method is then flexible and it is required for selecting the case which would be adequate for a particular application.

5. Conclusion

In this paper modelling and analysis of high power synchronous generator are presented. For a better presentation, a comparative study is carried out and approved by simulation, in order to compare the different operation modes, taking into account when $Q'_g = 0$ and when $Q''_{red} = 0$. The direct voltage in the intermediate circuit is adapted by adjustment of voltage excitation of synchronous machine. Therefore,

Figure 4: Simulated active powers, voltages and currents for different cases.

control method is proposed to optimize the power factor of synchronous machine. These include the ability to operate with unity power factor. As a perspective to this work, author suggests to apply this method to renewable energy. However, sustainable energy generation like hydro, wind and sun are normally not located close to the consumption. It will be very important to find efficient ways to transport large amounts of electricity long distances.

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