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Interarea oscillation damping using H-infinity control for the permanent magnet wind generator

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ABSTRACT

This paper investigates the use of the permanent magnet wind generator as a means for damping dynamic interarea oscillations in multi-area power systems. A power modulation controller is proposed based on the H-infinity design methodology. The controller uses as feedback the frequency deviation of the local power system area and applies effective control on the wind generator rotor speed, blade pitch angle and dc link voltage in order to provide sufficient power modulation at the output of the generator to damp interarea oscillations. The paper also investigates the potential use of the energy stored in the dc link capacitance as an auxiliary means to increase the power modulation capability of the generator. The method is applied to a three-area power system that exhibits undamped rotor oscillations. Results presented in the paper demonstrate the effectiveness of the wind generator in increasing considerably the system damping.

1. Introduction

Wind generators can provide the ac grid with many ancillary services, in addition to their main energy conversion function, such as frequency and voltage regulation, peak load shaving, etc. [1]. The fast power modulation capability of wind generators enables them to also provide enhancement of the rotor dynamic stability in multi-machine systems or improve the interarea dynamics in larger interconnected multi-area systems. The two most common types of electric generator used in wind power systems are the doubly-fed induction generator (DFIG) [2] and the permanent magnet synchronous generator (PMSG) [3]. The stator of the DFIG is connected to the grid directly, while the rotor is fed from the grid through an asynchronous controllable dc link; this enables a fast power control [4]. The PMSG, on the other hand, connects to the grid asynchronously through a dc link between the generator stator and the common coupling point with the grid. The controllability of the dc link provides stable operation of the generator and, in addition, fast power modulation capability [5]. Moreover, the stator frequency of the generator is completely independent from the grid frequency minimizing dynamic interactions.

In this paper, a PMSG employed in a wind power system is investigated for its capability to enhance the damping of dynamic oscillations in a multi-area power system. The primary controls of the generator consist of a field-oriented controller (FOC) that regulates the speed for the PMSG and a synchronization controller acting on the grid-side dc–ac inverter that regulates the active and reactive power output to the grid [6]. In [7–9], the design of the controls for the PMSG-based wind power system is concerned with the stability of the inner control loops of the generator and the grid interconnection under the presence of power system dynamics. Additional literature deals with improving the dynamic stability of wind generators by incorporating FACTS devices or utilizing the action of the PSS [10,11]. At high penetration levels, these methods may not be sufficient as there may not be enough power modulation capability to damp oscillations. Recent developments use also the grid frequency feedback in conjunction with the DFIG [12–14]. However, no significant literature addresses the issue of power modulation for damping dynamic interarea oscillations.

Power modulation in PMSG-based wind power systems can be achieved by three methods: according to the first method, the input wind power is modulated by varying the blade pitch angle or the rotor speed. This method, however, is not effective at maximum power point tracking (MPPT) operation as the modulated power can only be negative [15]. A possible solution is to de-load the generator by shifting the MPPT curve down to a suboptimal one [16]. According the second method, the energy stored in the rotating

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parts of the generator can be used to release or absorb power; this is accomplished by controlling the electric torque of the generator [16]. According to the third method, the energy stored in the dc link capacitance is used to release or absorb power from the grid [17,18]. Large values of dc capacitors are common in PMSG-based systems in order to smooth the dc voltage [19]. Small magnitude dynamic modulation of the dc voltage, therefore, can release a significant amount of power.

In this paper, the capability of a permanent magnet wind generator in damping interarea oscillations is investigated. A power modulation controller is proposed based on the H_∞ design. H_∞-based control design has been used in conjunction with wind generators in order to improve the performance of wind turbines under large wind velocity change or under parameter uncertainties [20–24]. In this paper, the controller is designed to use the local frequency signal from the grid in order to modulate the rotor speed, the blade pitch angle and the dc link voltage of the wind generator. The results in the paper demonstrate that the permanent magnet wind generator can provide sufficient power modulation capability to damp interarea oscillations. The results also show that the size of the generator is not critical in achieving the above objective. The paper is organized as follows:

Section 2 describes a suitable dynamic model of the wind generator that can be used in dynamic studies. Section 3 demonstrates the design of the controller for a three area power system with a single wind generation side. Section 4 presents simulated studies. Section 5 provides the conclusion.

2. System dynamic modeling

The configuration of the permanent magnet wind generator with its major control loops is shown in Fig. 1. A back-to-back dc link interconnects the PMSG stator to the ac grid via two dc/ac inverters. The grid-side inverter regulates the ac voltage by injecting reactive power. Real power control is achieved through the action of the same inverter by maintaining the dc link voltage stable and balancing the generated and output powers. On the PMSG side, the rotor speed is regulated through a field-oriented controller (FOC) [6] which acts on the stator d- and q-axis voltages through the corresponding dc–ac inverter.

2.1. Mechanical system

The two-rotating inertia dynamic model given in Refs. [25,26] is consider here for the PMSG. The linearized mechanical equations are given by Eqs. (1)–(3).

$$\Delta\dot{\omega}_T = \frac{1}{J_T}\Delta \mathrm{T_w} - \frac{K}{J_T}\Delta\theta \tag{1}$$

$$\Delta\dot{\omega}_g = \frac{K}{J_g}\Delta\theta - \frac{1}{J_g}\Delta \mathrm{T_g} \tag{2}$$

$$\Delta\dot{\theta} = \Delta\omega_T - \Delta\omega_g \tag{3}$$

In the above equations, T_w, T_g, are the wind and electric torques respectively, $\Delta(\cdot)$ denotes variation, J_T, J_g are the moments of inertia of the turbine and PMSG rotors respectively, $K\Delta\theta$ is the elastic torque variation of the shaft.

The electric torque is considered in the next section. The wind torque can be obtained from the coefficient of performance, $C_p(\lambda, \beta)$, according to Eq. (4), where the tip speed ratio is $\lambda = \omega_T R/v_w$, and the blade pitch angle is β (in degrees), and $A = \pi R^2$ is the rotor swept area, ρ is the air mass density, and v_w is the air velocity at the rotor hub [8,29].

Linearizing Eq. (4) around the operating point v_w, ω_T, ω_g, λ, β, one obtains the wind torque variation, ΔT_w, expressed as in Eq. (5), in terms of the wind velocity, blade pitch angle and turbine speed variations, Δv_w, $\Delta\beta$, $\Delta\omega_T$ respectively [27]. K_1, K_2, K_3, are linearization constants.

$$T_w = \frac{\rho A}{2\omega_T} C_p(\lambda, \beta) v_w^3 \tag{4}$$

$$\Delta T_w = K_1\Delta v_w + K_2\Delta\beta + K_3\Delta\omega_T \tag{5}$$

2.2. PMSG electric torque

The dynamic equations of the PMSG in the dq frame of reference are given by Eqs. (6) and (7) [28,29], where R is the stator resistance, L is the stator inductance, p is the magnetic pole pairs; ψ_f is the permanent magnet flux.

$$\Delta\dot{i}_{gd} = -\frac{R}{L}\Delta i_{gd} + p\omega_g\Delta i_{gq} + p i_{gq}\Delta\omega_g - \frac{1}{L}\Delta v_{gd} \tag{6}$$

$$\Delta\dot{i}_{gq} = -\frac{R}{L}\Delta i_{gq} - p\omega_g\Delta i_{gd} + p\left(\frac{\psi_f}{L} - \mathrm{i_{gd}}\right)\Delta\omega_g - \frac{1}{L}\Delta v_{gq} \tag{7}$$

With reference to Fig. 1, the PI speed controller determines the q-axis stator voltage. The state equation of this controller is given by Eq. (8) and its output by Eq. (9). In the same figure, another fast PI controller controls stator current, i_{gd}, to zero for unity power factor operation by acting on the d-axis stator voltage. Since the response

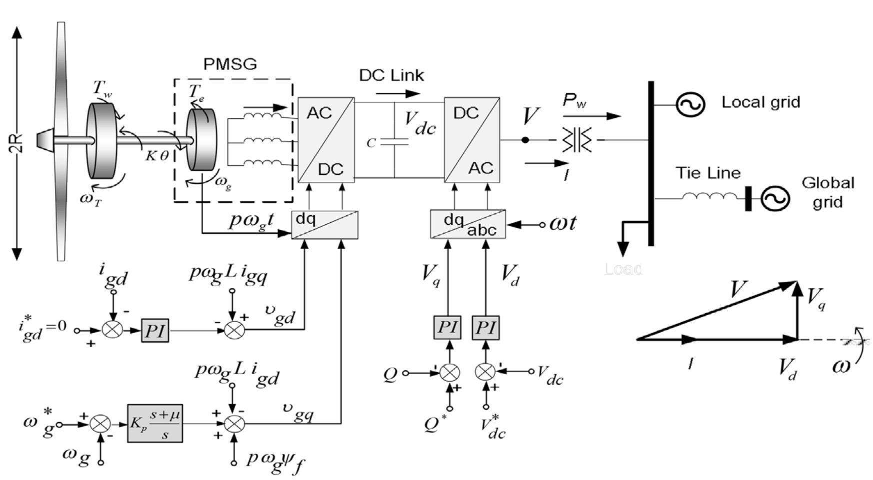

Fig. 1. Configuration of the PM wind generator: generator and DC link controls.