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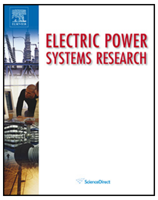

Damping tie-line power oscillations by modulation feedback of wind generators

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ABSTRACT

This paper uses the power modulation capability of wind generators for damping tie-line power oscillations. The type of wind generator investigated is the permanent magnet synchronous generator (PMSG) connected to the power grid through a dc link. First, the paper develops a small-signal aggregate model for the wind generator. Subsequently, three modulation signals are investigated in order to provide effective power modulation: the PMSG speed reference, the rotor blade pitch angle and the dc link voltage. The latter is a novel approach that utilizes the energy stored in the dc link capacitors in order to modulate the power injected into the grid. The paper investigates the relation between the wind turbine and PMSG dynamics and the ability of each modulation loop to provide effective damping. A design method of the feedback loops based on the damping torque concept is demonstrated in the paper. Analytical results on a two-area power system show that wind generation can enhance the system dynamic stability by damping tie-line power oscillations. The analytical results are verified through time-domain simulations of a detailed 3-phase model of the system. The proposed dc link voltage modulation is shown to be a very effective means to provide power modulation in dynamic conditions.

1. Introduction

Wind power generation is a fast rising renewable energy source with a minimum running cost that can be easily embedded in the bulk power grid [1,2]. The most common types of wind generator employed are the permanent magnet synchronous generator (PMSG) and the doubly-fed induction generator (DFIG). Both types interconnect to the grid through a back-to-back dc-link controlled by two voltage-sourced inverters [3]. The basic control scheme applied is vector orientation control through the dc link inverters in order to control the speed or torque of the generator [4]. On the grid side, vector control is used to control the dc link and the ac bus voltages. Additional control loops can be added to each side in order to achieve certain steady state or dynamic objectives such as maximum power tracking [5], damping of torsional oscillations at the wind generator side [6,7], and reducing the impact of wind fluctuation onto the grid [8,9].

A high degree of penetration of wind generation into the power grid is expected to affect both the transient and dynamic stability of the system [10–12]. As the stiffness of the generator shaft is inversely proportional to the pole pairs [13], a PMSG with higher capacity and a high pole number has a soft drive train. This may result in a low frequency oscillation (0.1–8 Hz) injected to the power system which can be excited by the changing weather patterns. This frequency band tends to coincide with frequencies associated with power system inter-area oscillation (0.1–2.5 Hz) [14]. As a result, the power system with high wind power penetrations produced by PMSG wind turbines may experience instability issues. In [15,16], the wind turbine-PMSG system is modeled as two rotating masses connected via the elastic forces of the shaft. This system is shown to be prone to instability due to low damping causing the power output of the PMSG to oscillate. One method proposed to deal with these oscillations is by applying a flexible ac transmission system (FACTS) device at the generator bus in order to add damping [17,18]. Another method, less expensive, is to provide control feedback to the generator in order to modulate the power output [14,19]. In these works, the generator speed oscillations are damped by using either the generator speed error or the generated power output to modulate the electric torque via the action of the ac/dc inverter connected to the generator stator.

The work of this paper focusses on the modulation feedback design between the network frequency and the output power of the wind generator in order to achieve stable operation and enhance the damping of power system oscillations. Fast power modulation of the generator output can be achieved owed to the

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fast operation of the dc link that enables the wind power system to operate essentially as a fast responding controllable power source with the potential to assist the grid in recovering from dynamic and transient disturbances [19]. The paper develops the dynamic small-signal model of a PMSG under field-oriented control. The modeled dynamics include a two-rotating-mass system and the local controls for the generator speed. Three modulation feedback loops were considered: PMSG speed, rotor blade pitch angle and dc link voltage modulation. The latter is a novel approach, which uses the energy stored in the dc link capacitance in order to modulate the output power. The feedback design method used in the paper is based on the damping torque concept. This model is subsequently applied to a lightly damped two-area power system. The limitations imposed by the PMSG inherent dynamics in the bandwidth of the speed and blade pitch angle modulation loops are demonstrated. It is also shown that the dc link voltage modulation has a wider bandwidth which makes it very effective in providing damping.

Section 2 of the paper discusses the small-signal modeling of the wind generator. Section 3 demonstrates the damping of tie-line oscillations in a two-area example system utilizing the feedback provided through the above loops. In the same section, results from time domain simulations of the detailed system using MATLAB are presented. Section 4 provides the conclusions.

2. System modeling

The configuration of a wind power generation system based on the PMSG is shown in Fig. 1. Wind power is converted through a wind turbine-PMSG and it is injected to the grid through a back-to-back dc link [5,24]. With reference to the figure, the inverter on the grid side regulates the dc link voltage by balancing the link power flow, and supplies reactive power to the grid. The inverter on the PMSG side regulates the generator speed by controlling the generator torque through the stator q-axis current and also keeps the stator power factor at unity by controlling the stator d-axis current to zero [5,24].

A suitable dynamic model of the above system is shown in Fig. 2a. The model represents the speed controller of the PMSG and the dc link voltage controller at the ac-side inverter. The PMSG speed reference derives from the output of the maximum power point tracking (MPPT) loop and it is considered constant in this analysis, since the MPPT response involves very low frequencies in the rage 0.1–0.2 Hz [25], whereas the dynamics associated with the PMSG speed and tie-line power oscillations have frequencies in the range of 1–2 Hz.

2.1. Wind turbine-PMSG rotating mass system

The wind turbine-PMSG system behaves as two rotating masses connected via the elastic forces of the shaft. The variational equations of the system in the s-domain are described by (1) [7,21,28].

$$\Delta\omega_T = \frac{\Delta T_w - K\Delta\theta}{sJ_T} \tag{1a}$$

$$\Delta\omega_g = \frac{K\Delta\theta - \Delta T_g}{sJ_g} \tag{1b}$$

$$\Delta\theta = \frac{\Delta\omega_T - \Delta\omega_g}{s} \tag{1c}$$

In the above equations, $\Delta(\cdot)$ 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 wind torque equation is given by (2), where $C_p(\lambda, \beta)$ represents the coefficient of performance as a function of the tip speed ratio, $\lambda = \omega_T R/v_w$, and the blade pitch angle β (in°), $A = \pi R^2$ is the rotor swept area, ρ is the air mass density, and v_w is the air velocity at the rotor hub [8,27,29].

After linearizing (2), the wind torque variation, ΔT_w, can be expressed as in (3) in terms of the wind velocity, blade pitch angle and turbine speed variations, Δv_w, $\Delta\beta$, $\Delta\omega_T$, respectively,

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

$$\Delta T_w = K_1\,\Delta v_w + K_2\,\Delta\beta + K_3\,\Delta\omega_T \tag{3}$$

The gains in (3) are computed around the operating point $v_w, \omega_T, \omega_g, \lambda, \beta$ by (4a)–(4c):

$$K_1 = \frac{\partial T_w}{\partial v_w} = \frac{v_w^2 \rho A}{2\omega_T}\left[3C_p(\lambda, \beta) + \lambda\omega_T \frac{\partial C_p(\lambda, \beta)}{\partial \lambda}\right] \tag{4a}$$

$$K_2 = \frac{\partial T_w}{\partial \beta} = \frac{v_w^3 \rho A}{2\omega_T}\left[\frac{\partial C_p(\lambda, \beta)}{\partial \beta}\right] \tag{4b}$$

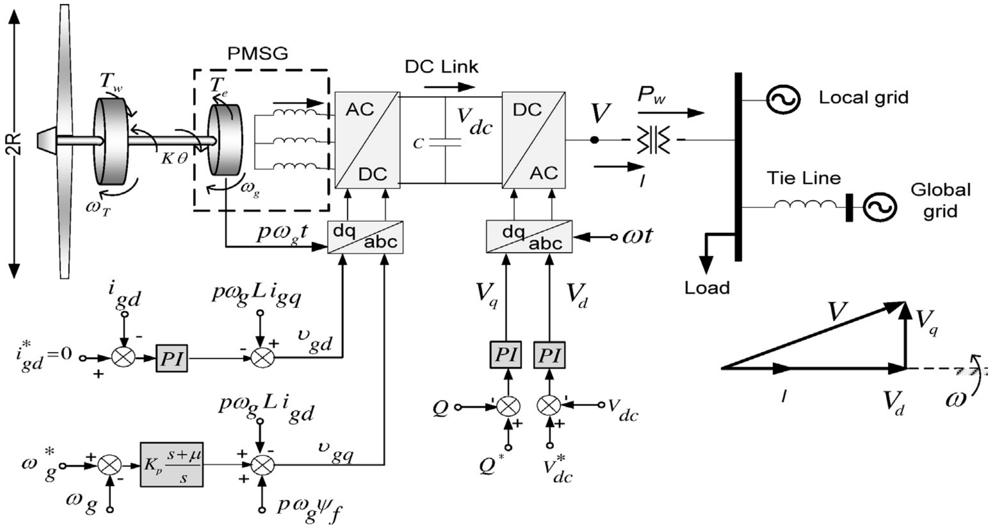

Fig. 1. Interconnected wind power system with major control loops.

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