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Investigating the Controller Interactions of Distribution Systems with Distributed Generation

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Abstract: This paper investigates the interactions among multiple controllers in distribution systems in the presence of distributed generation (DG). Two doubly fed induction generator (DFIG) type wind turbines are connected to a distribution system to investigate their influence in the system. Simulation results indicate that the parallel operation of DG units and their controllers in the same network in a relatively smaller geographical area have negative interactions giving rise to control mode oscillations. It is also investigated that the coupling of the load dynamics with DG-controllers reduces the damping of the system.

Keywords : control modes, composite loads, doubly fed induction generator (DFIG), distributed generation (DG).

1. INTRODUCTION

Wind power is playing a major role in efforts to increase the share of renewable energy in distributed generation (DG). Following the recent developments in modern power electronics, variable-speed wind turbines equipped with doubly fed induction generators (DFIGs) have drawn increasing attention in contrast to the older constant-speed models with simple squirrel-cage induction generators (SCIGs). Although a variable speed wind turbine has several potential benefits; see Tsourakis et al. (2009), for its successful integration into existing distribution networks, a number of technical challenges related to voltage and power have to be addressed; see Tremblay et al. (2006); Pokharel and Gao (2010).

The stator of a DFIG is directly connected to the power grid while its rotor uses converters which limit the electric current during faults and transients; see Meliopoulos and Cokkinides (2006). A low-inertia of a wind generator may result in larger and faster deviations in voltage and power after occurrence of abrupt variations in generation and system load. Another issue is that the converter model of a DFIG is a multi-input multi-output nonlinear model and the difficulty of controlling it is mainly due to its nonlinear behavior. Conventionally, PI controllers are used for converter control but their response times are usually slow and it is difficult to find appropriate PI parameters in a systematic way for nonlinear systems with switching devices.

With the increasing penetration of wind energy, its impact on a system depends heavily upon the effectiveness of converter control with multiple distributed energy resources (DERs) since distribution networks are divided into subsystems of radial or loop feeders with a number of switches to which commercial, industrial, and residential end-users are connected and impose time-varying load demands; see Su et al. (2011). As the converters have sophisticated feedback control loops, they may interact with the transients of the electric power system and result in unintended modes of oscillations while the nonlinear coupling of load dynamics and power electronics converter control may complicate this problem; see Meliopoulos and Cokkinides (2006).

It is investigated that electromechanical dynamics of a DFIG is more sensitive to the inertia when compared to the dynamics of a synchronous generator and, depending on the operating mode of the DFIG, the network voltage drops significantly that affects the stability and performance of the system; see de Oliveira et al. (2011). Tsourakis et al. (2009) reported that increased wind power penetration results in reduced damping or even instability of either the oscillatory control or electromechanical mode. Usually, high concentration of loads and production in a small area can lead to poorly damped oscillations in a distribution network; see Roy (2013). Although interactions among power system controls for high-voltage transmission systems have been widely investigated; see EPRI (1998); Martins et al. (Status Report of CIGRE Task Force 38.02.16, Brochure No. 166, 2000), very little attention has been paid to analyzing the interactions among multiple DG controllers within distribution systems. In the near future, it is expected that small-scale DG units with sophisticated inverters will be permitted to control the voltage at the point of common coupling (PCC). A massive deployment of converter-interfaced DERs in a distribution system generates additional dynamic interactions with the utility system. Therefore, the aim of this paper is to investigate the interactions of multiple converter connected distributed generators in a distribution network. Both linear and nonlinear simulations are carried out to gather a complete understanding of the problem.

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The rest of the paper is organized as follows. In Section 2, the mathematical model of the system is presented. Both linear and nonlinear analyzes are given in Section 3. The impacts of variations in controller parameters are demonstrated in Section 4. Finally, concluding remarks are given in Section 5.

2. SYSTEM MODEL

2.1 Generator Model

The nonlinear model of DFIG is based on a static model of the aerodynamics, a two mass model of the drive train, a third order model of the generator, the GSC with DC-link capacitor, the pitch controller and the RSC. The rotor of the wind turbine, with radius R_i, converts the energy from the wind to the rotor shaft, rotating at the speed ω_{m_i}. The power from the wind depends on the wind speed, V_{w_i}, the air density, ρ_i, and the swept area, A_{wt_i}. From the available power in the swept area, the power on the rotor is given based on the power coefficient $c_{p_i}(\lambda_{r_i}, \theta_i)$, which depends on the pitch angle of the blade, θ_i, and the ratio between the speed of the blade tip and the wind speed ratio, $\lambda_{r_i} = \frac{\omega_{m_i} R_i}{V_{w_i}}$. The aerodynamic torque applied to the rotor by the effective wind passing through the rotor is given as:

$$T_{ae_i} = \frac{\rho_i}{2\omega_{m_i}} A_{wt_i} c_{p_i}(\lambda_{r_i}, \theta) V_{w_i}^3 \tag{1}$$

A two-mass drive train model of a wind turbine generator system (WTGS) is used in this paper. The drive train attached to the wind turbine converts the aerodynamic torque T_{ae_i} on the rotor into the torque on the low speed-shaft, which is scaled down through the gearbox to the torque on the high-speed shaft. The first mass term stands for the blades, hub and low-speed shaft, while the second mass term stands for the high speed shaft having the inertia constants, H_{m_i} and H_{g_i}. The shafts are interconnected by the gear ratio, N_{g_i}, combined with torsion stiffness, K_{s_i}, and torsion damping, D_{m_i} and D_{g_i} resulting in torsion angle, λ_i. The normal grid frequency is f. The dynamics of the shaft can be represented as follows; see Ackermann (2005):

$$\dot{\omega}_{m_i} = \frac{1}{2H_{m_i}} \left[T_{ae_i} - K_{s_i}\lambda_i - D_{m_i}\omega_{m_i} \right] \tag{2}$$

$$\dot{\omega}_{g_i} = \frac{1}{2H_{g_i}} \left[K_{s_i}\lambda_i - T_{ae_i} - D_{g_i}\omega_{g_i} \right] \tag{3}$$

$$\dot{\lambda}_i = 2\pi f \left(\omega_{m_i} - \frac{1}{N_{g_i}}\omega_{g_i} \right) \tag{4}$$

The induction generator gets the power from the gear box through the stiff shaft. The relationship between the mechanical torque and torsional angle is given by:

$$T_{m_i} = K_{s_i}\lambda_i \tag{5}$$

The mechanical torque depends on torsion stiffness (K_{s_i}), torsion angle (λ_i), rotor speed (ω_{g_i}), etc.

The transient model of a DFIG can be described by the following algebraic-differential equations;; see Ackermann (2005), Nandigam and Chowdhury (2004):

$$\dot{E}'_{rq_i} = -\frac{1}{T'_{o_i}} \left[E'_{rq_i} - (X_i - X'_i) i_{sd_i} + s_i \omega_{s_i} T'_{o_i} E'_{rd_i} \right] - \omega_{s_i} v'_{rd_i} \tag{6}$$

$$\dot{E}'_{rd_i} = -\frac{1}{T'_{o_i}} \left[E'_{rd_i} + (X_i - X'_i) i_{sq_i} - s_i \omega_{s_i} T'_{o_i} E'_{rq_i} \right] + \omega_{s_i} v'_{rq_i} \tag{7}$$

$$\dot{s}_i = \frac{1}{2H_{g_i}} \left(T_{m_i} - T_{e_i} \right) \tag{8}$$

$$\left(v_{sd_i} + j v_{sq_i} \right) = \left(R_{s_i} + jX'_i \right) \left(i_{sd_i} + j i_{sq_i} \right) + j \left(E'_{rq_i} - jE'_{rd_i} \right) \tag{9}$$

here, $X'_i = X_{s_i} + \frac{X_{m_i} X_{r_i}}{X_{m_i} + X_{r_i}}$ is the transient reactance, R_{s_i} is the stator resistance, X_{r_i} is the rotor reactance, X_{m_i} is the magnetizing reactance, $X_i = X_{s_i} + X_{m_i}$ is the rotor open circuit reactance, T'_{o_i} is transient open circuit time constant, T_{m_i} is the mechanical torque, s_i is the slip, $T_{e_i} = E'_{rd_i} i_{sd_i} + E'_{rq_i} i_{sq_i}$ is the electrical torque, E'_{rd_i} and E'_{rq_i} are the direct and quadrature axis transient voltages respectively, i_{sd_i} and i_{sq_i} are the direct and quadrature axis currents respectively, ω_{s_i} is the synchronous speed, $v'_{rd_i} = \frac{v_{rd_i} X_{m_i}}{(X_{m_i} + X_{r_i})}$, and $v'_{rq_i} = \frac{v_{rq_i} X_{m_i}}{(X_{m_i} + X_{r_i})}$.

The DC link dynamic is given by:

$$C_i V_{dc_i} \frac{dV_{dci}}{dt} = -\frac{V_{dc_i}^2}{R_{loss_i}} - P_{r_i}(t) - P_{g_i}(t) \tag{10}$$

where, V_{dc_i} and C_i are the dc-link voltage and capacitance, respectively. Resistor R_{loss_i} represents the total conduction and switching loss of the converter. Also, P_{r_i}(t) is the instantaneous input rotor power and P_{g_i}(t) is the instantaneous output power of the GSC, which are given by:

$$P_{r_i} = v_{rd_i} i_{rd_i} + v_{rq_i} i_{rq_i} \tag{11}$$

$$P_{g_i} = v_{gd_i} i_{gd_i} + v_{gq_i} i_{gq_i} \tag{12}$$

2.2 Load Model

The proper representation of load is important in power system stability studies, but it is a difficult problem because power system loads are composed of different devices; see Morison et al. (2003). A composite load model is used in this paper to represent the dynamic behavior of an aggregate group of small motors, electronic loads and static loads, as shown in Figure 1.

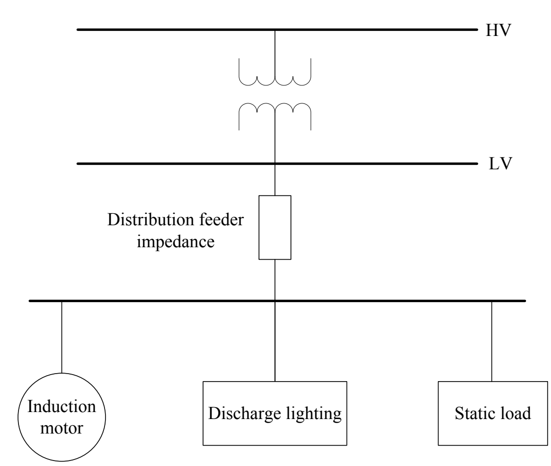

Fig. 1. Example of composite load

Static load: Static load models are relevant to load flow studies as they express active and reactive steady-state powers as functions of the bus voltages (at a given fixed frequency). Common static load models for active and reactive power are expressed in polynomial or exponential forms and can include, if necessary, a frequency dependence term. In this paper, the exponential form is used to represent static load as:

$$P(V) = P_0 \left(\frac{V}{V_0} \right)^a, \tag{13a}$$

$$Q(V) = Q_0 \left(\frac{V}{V_0} \right)^b, \tag{13b}$$