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The impact of wind farms with doubly fed induction generators on power system electromechanical oscillations

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A R T I C L E I N F O

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A B S T R A C T

Introduction of large amounts of new wind generation can affect the small signal stability of power systems with three mechanisms: displacing synchronous generators (SGs); reducing SGs power generation; and the dynamics of wind farms (WFs) interacting with the electromechanical mode of SGs. In this paper a novel approach is developed to investigate the impact of the latter mechanism on existing power systems oscillations. In this approach, the dynamic behavior of grid connected WFs is studied independent of the dynamic behavior of system SGs. This approach helps to identify the conditions in which the dynamics of WFs may interact with the electromechanical mode of SGs. Also it helps to foresee the impact of these probable interactions on the frequency and damping of system oscillations. By using this approach in a test system, it was shown that under some circumstances these dynamic interactions considerably decrease the damping of system oscillations but they barely change the frequency of system oscillations. The frequency of system oscillation and the operating point of WF are the two major parameters determine the severity of the decrease in oscillation damping. Comparison of the SG electromechanical eigenvalues calculated before and after the introduction of the WF in the test system, confirmed the prospects of the proposed approach.

1. Introduction

During the last decade, wind power has been the world's fastest growing energy source [1] and many large WFs have been installed and integrated into power systems, caused the share of wind power to reach a considerable level [2].

As long as wind power penetration is insignificant, SGs determine the overall dynamic behavior of power systems, but introduction of large amounts of new wind generation can affect the stability of power systems [3]. These effects in the fields of frequency stability [4,5], transient stability [6], voltage stability [7] and small signal stability have been treated and addressed in recent research efforts. Among them, the small signal stability problem of power systems with high penetration levels of wind power is one of the major challenging fields. Small signal stability is the ability of the power system to maintain synchronism when subjected to small disturbances. In today's power systems, the small signal stability problem is usually the lack of sufficient damping torque for system oscillations [8].

Among the several wind generation technologies developed until now, variable speed wind turbines utilizing DFIGs are the most popular scheme in power system industry [9]. DFIGs do not introduce new electromechanical oscillations in power system but they can affect existing system oscillations by three mechanisms: displacing SGs; reducing SGs power generation; and the dynamics of WFs interacting with the electromechanical mode of SGs.

The impact of DFIG based WFs on the small signal stability of power systems has been the subject of many recent contexts. The impact of large scale DFIG based wind power generation on power system oscillations is investigated in [10]. The dynamics of WFs are not considered and it is supposed that WFs displace existing network generators. In [11] an approach based on the sensitivity of system electromechanical modes with respect to the changes of system inertia is developed with the assumption that WFs replace network generators and thereby decrease system effective inertia. In this study WF dynamics are not considered too. Modal analysis technique is used in [9] [12], and [13] to analyze the impact of DFIG based WFs on power system oscillations.

Up to now in most of the studies devoted to this subject, either WF dynamics have been neglected or their impact on power system oscillations have been investigated with the help of modal analysis technique. Modal analysis technique can afford the identification of dynamic interactions only in the simulated configuration and does not suggest a general pattern.

This work develops a novel approach to investigate the interactions between the dynamics of WFs and the electromechanical

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mode of SGs. The basis of this approach is studying the dynamic behavior of grid connected WFs and system SGs independently. In this regard, first the element of network Jacobian matrix with respect to which the SG electromechanical eigenvalue has the most sensitivity is identified; then by evaluating the influence of the WF dynamics on that element, conditions in which the dynamics of WF may interact with the electromechanical mode of SGs are detected. Also the impact of these probable interactions on the frequency and damping of system oscillations is foreseen.

2. WF model

For power system dynamic simulations, it is common to model WFs as a single equivalent wind turbine [11]. A wind turbine is consisted of the turbine, generator, drive train and converter.

2.1. Turbine

In general, for stability studies, the dynamics related to the turbine, yaw system, and tower can be ignored [14,15]. Therefore wind turbine's input mechanical power is assumed constant in this paper.

2.2. Generator

Equation (1) describes the dynamic behavior of a DFIG. These equations are obtained by transforming the machine three-phase voltage equations into a synchronously rotating frame, referred to as the dq frame.

$$\begin{aligned} v_{sqd} &= -R_s i_{sqd} \pm \omega_s \left(\psi_{sdq}\right) + \frac{1}{\omega_{\mathrm{eb}}}\frac{\mathrm{d}}{\mathrm{d}t}\psi_{sqd} \\ v_{rqd} &= -R_r i_{rqd} \pm (\omega_s - \omega_r)\left(\psi_{rdq}\right) + \frac{1}{\omega_{\mathrm{eb}}}\frac{\mathrm{d}}{\mathrm{d}t}\psi_{rqd} \\ \psi_{sqd} &= -X_{\mathrm{ss}} i_{sqd} - X_m i_{rqd} \\ \psi_{rqd} &= -X_{\mathrm{rr}} i_{rqd} - X_m i_{sqd} \end{aligned} \tag{1}$$

In these equations v, i and ψ represent the voltage, current and flux respectively; ω_s and ω_r are the stator and rotor rotating speeds respectively; ω_{eb} is the rotating speed of the synchronous reference frame and equals $2\pi 60$ rad/s; R is the resistance; X_{ss}, X_{rr} and X_m are the stator, rotor and mutual reactances respectively; and subscripts s, r, d and q stand for the stator, rotor, d-axis and q-axis variables respectively.

2.3. Drive train

In general, to model the drive train of a wind turbine, it is enough to consider a two-mass model (one for the turbine, the other for the generator). The following equations are used to model the drive train of the wind turbine,

$$\begin{aligned} 2H_t\frac{\mathrm{d}\omega_t}{\mathrm{d}t} &= T_m - k\theta_{\mathrm{tw}} - c\frac{\mathrm{d}\theta_{\mathrm{tw}}}{\mathrm{d}t} \\ \frac{1}{\omega_{\mathrm{eb}}}\frac{\mathrm{d}\theta_{\mathrm{tw}}}{\mathrm{d}t} &= \omega_t - \omega_r \\ 2H_r\frac{\mathrm{d}\omega_r}{\mathrm{d}t} &= k\theta_{\mathrm{tw}} + c\frac{\mathrm{d}\theta_{\mathrm{tw}}}{\mathrm{d}t} - T_e \\ T_e &= X_m\left(i_{qr}i_{ds} - i_{dr}i_{qs}\right) \end{aligned} \tag{2}$$

where ω_t and ω_r are the turbine and generator rotating speeds respectively; θ_{tw} is the shaft twist angle; H_t and H_r are the turbine and generator inertia constants respectively; T_m and T_e are the mechanical and electrical torques respectively; and k and c are the shaft stiffness and damping coefficients respectively.

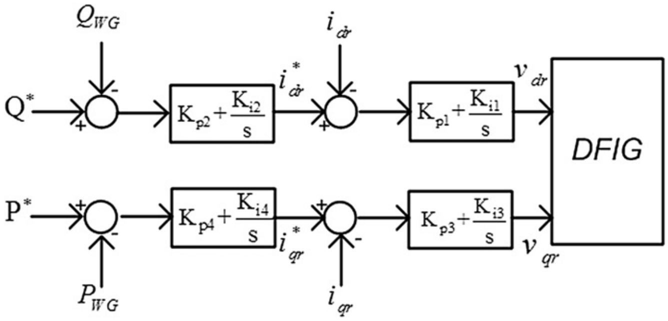

Fig. 1. DFIG controls.

2.4. Converter

In case of DFIGs, a three-phase voltage is injected into the rotor through a back-to-back converter system. This converter is composed of three parts: grid side converter; DC link; and rotor side converter. If the switching frequency is high enough and the switching losses are ignored, for power system stability studies it is possible to neglect the dynamics related to the grid side converter and DC link [16].

To model the rotor side converter, the decoupling control strategy for the active and reactive power generation of DFIGs, that was proposed in [17], is used in this paper. Fig. 1 shows the block diagram of this control strategy. Similar control structures have been used in [16,18], and [19].

In this paper only the voltage control mode is considered for WFs. In this mode the reactive power reference (Q^* in Fig. 1) comes from the simplified equivalent of the supervisory controller of the WF which is depicted in Fig. 2. In this mode, the terminal voltage reference (V^* in Fig. 2) is set by the WF operator. DFIG parameters and WF controller parameters are given in the Appendix.

3. The impact of WFs on system electromechanical oscillations

To investigate the impact of WFs on system electromechanical oscillations, Test system A is developed and used. Fig. 3 depicts the one–line diagram of this test system, where impedances are given in p.u. on a 1000 MVA base. In this paper for the sake of simplicity, only the oscillation of one SG against a strong system (represented as an infinite bus) is considered. The fourth-order model with exponential modeling of magnetic saturation is considered for the SG. Constant mechanical torque input is assumed. The IEEE-type AC4A excitation system model is used. Parameters of the SG are given in the Appendix. The SG supplies a 150 MW load. One half of the load is represented as constant impedance and the other half is modeled as constant power. In Test system B, as depicted in Fig. 4, a 150 MW DFIG based WF is introduced in Test system A. It is assumed that the WF is operating at its rated operating point (rated wind speed).

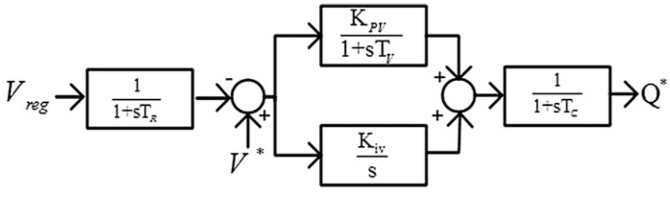

Fig. 2. Voltage control mode.