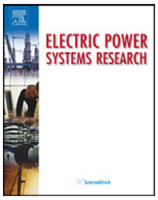
Electric Power Systems Research 81 (2011) 503–509

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr



DFIG rotor voltage control for system dynamic performance enhancement

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ARTICLE INFO

Article history:
Received 20 May 2009
Received in revised form 9 July 2010
Accepted 5 October 2010
Available online 30 October 2010

Keywords:
Wind power generation
Doubly fed induction generator (DFIG)
Converter controls of DFIG
POD controller

ABSTRACT

This article develops a model of a doubly fed induction generator system including the detailed dynamics of the converter circuitry. The order of the converter controls in terms of providing damping to the system is identified through residue principles. Supplementary damping controller has been incorporated so as to compensate for the phase lag introduced by the rotor voltage input, which was observed to have the largest residue contribution at the lightly damped mode. The improvement in damping profile was verified by simulating the system for a number of disturbance conditions. While the power oscillation damping (POD) controller was observed to enhance the system damping generally, it was also able to ride through low voltage conditions arising out of severe fault conditions thus averting total system collapse.

1. Introduction

In the early stage of wind power development, most wind farms were equipped with fixed speed wind turbines and induction generators. The power efficiency of such fixed speed devices is fairly low for most wind speeds. To improve their efficiency, many modern wind generators adopt a variable speed operation in the following ways: direct ac to ac frequency converters, such as the cycloconverter or by using back to back power converters [1], employing synchronous generators provided that a static frequency converter is used to interface the machine to the grid [2]. An alternative approach of using a wound-rotor induction generator fed with variable frequency rotor voltage is receiving increasing attention for wind generation purposes. With changing wind speed, one can adjust the frequency of the injected rotor voltage of the DFIG to obtain a constant-frequency at the stator [3].

The DFIG equipped wind system has many advantages; an important one is that the power electronics equipment carries only a fraction of the total power resulting in reduced cost as well reduced losses in the converters [4]. The other advantages with such a drive system are the possibility to obtain a wide variable speed range with a good performance in terms of active and reactive power control, ability to maximize power extraction, and with the capability of contributing to network support and operation with respect to voltage control, transient performance and damping improvement [5–7].

A good amount of literature is available on modeling and control aspects of DFIG. Ref. [8] demonstrated that a detailed dynamic representation of the converter circuitry is required to investigate the impact of the various controls on the DFIG performance. Vowles [9] reported the performance of the New Zealand system with different wind systems including DFIG. Various solutions have been proposed to achieve decoupled control of active and reactive power and to provide frequency support in emergencies [10,11]. Control of supply side PWM converter for voltage magnitude and phase angle, and control of rotor connected converter for wide speed variation have been proposed in Refs. [12,13]. Through eigenvalue analysis it was observed that there is not much of system degradation because of wind in-feed. Elkinson [14] used eigenvalue analysis of simplified model and observed that while DFIG in-feed can improve damping profile with small disturbance, it has adverse impact when subjected to large disturbances. It is concluded that wind power tends to increase the damping of oscillations of a synchronous generator against a strong system and of inter-area oscillations, while the impact on intra-area oscillations is not significant [15]. In Ref. [16], the advanced control capabilities of the DFIG are used to enhance network damping via an auxiliary power system stabilizer loop. In Ref. [17] it is shown that DFIG penetration increases the damping of oscillations of a synchronous generator against a strong system more significantly if they exercise frequency control. Many of these reported control studies are generally limited to design of PI controllers with local signals without including detailed system dynamics.

Because of the complexity of the wound rotor induction-synchronous doubly fed generator, a detailed analysis of the DFIG including the converter circuit electronics should be carefully carried out. The controls in the converter circuits provide opportu-

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doi:10.1016/j.epsr.2010.10.014

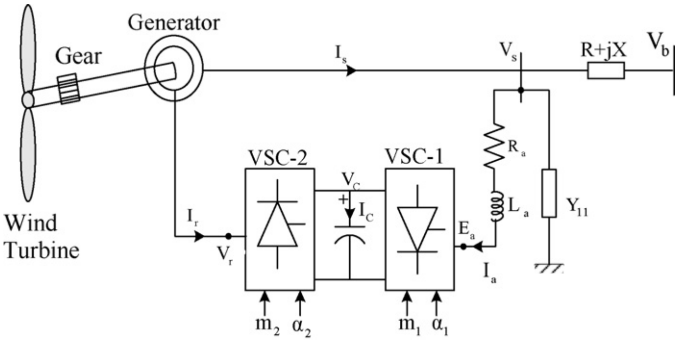

Fig. 1. DFIG system configuration.

nities for possible dynamic performance enhancement and hence, the suitability of these controls should also be examined. This paper presents a detailed dynamic model of the DFIG system including the turbine, generator and converter circuits. A comparison of the effectiveness of the various converter controls in terms of providing damping to the system has been carried out using the residue properties. A power oscillation damping (POD) controller design, which will offset the phase lag introduced in the input circuit, has been included in the simulation studies.

2. Dynamic model

Fig. 1 illustrates the DFIG wind power generation system consisting of a wound rotor induction generator and a back-to-back converter between the rotor slip rings and the grid. A so-called crowbar is inserted between the rotor slip rings and the rotor-side converter, which short-circuits the rotor windings in case a large external grid voltage sag or swell, to protect the converter from over voltage and over current [18]. The wound-rotor induction generator is grid-connected at the stator terminals, but the rotor terminals are fed with variable frequency voltage through a set of voltage source controllers (VSC-1 and VSC-2). This allows fixed-frequency electric power to be extracted from the generator stator. The system model, given in the following, includes the wind turbine, the wind system, the induction generator, and the converter circuits, the transmission line and load.

2.1. Wind turbine and the wind system

The mechanical power output of a wind turbine is related to the wind speed V_ω by Abdin and Xu [19],

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta) V_\omega^3 \tag{1}$$

Here, ρ is the air density and A is the swept area by the turbine blades. The power coefficient C_p is expressed as a function of tip speed ratio λ and the blade pitch angle β through [20],

$$\begin{aligned} C_p(\lambda, \beta) &= 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-21/\lambda_i} + 0.0068\lambda \\ \frac{1}{\lambda_i} &= \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \end{aligned} \tag{2}$$

Fig. 2 shows the variation of turbine power output for different wind speeds. The blade pitch angle β was considered to be zero in all these cases. Wind speed changes continuously and its magnitude are random over any interval. The average wind speed is usually considered constant for some intervals. The fluctuations during such intervals can be considered to be combination of constant and sinusoidal variation around the mean speed, V_m. A typical formula is [21],

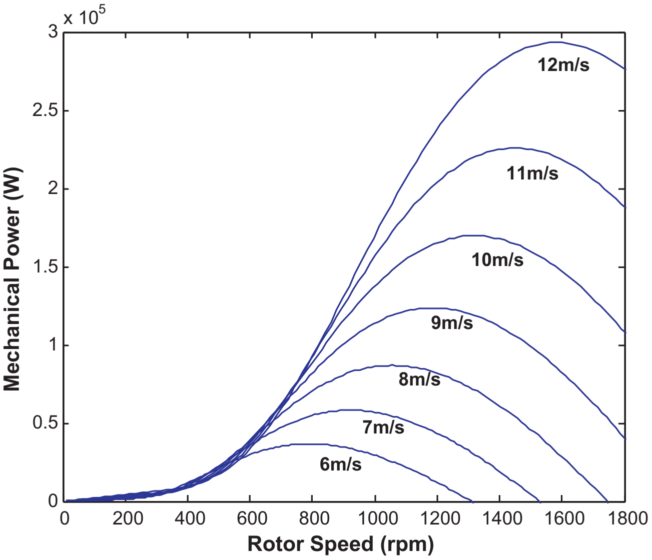

Fig. 2. Generator rotor speed vs. power output characteristics for different wind speeds.

$$V_\omega = V_m\left[1 - 0.2 \quad \cos\left(\frac{2\pi t}{20}\right) - 0.5 \quad \cos\left(\frac{2\pi t}{600}\right)\right] \tag{3}$$

The wind gust can be simulated by varying the magnitude and frequency of the sinusoidal fluctuation.

2.2. The induction machine model

The induction generator model can be derived from the generalized induction motor model of Krause [22]. The voltage current relations along the *d–q* axes of the stator and rotor circuits, respectively, are:

$$\begin{aligned} \frac{1}{\omega_0}\dot{\psi}_{ds} - \frac{\omega_e}{\omega_0}\psi_{qs} + R_s i_{ds} &= v_{ds} \\ \frac{1}{\omega_0}\dot{\psi}_{qs} + \frac{\omega_e}{\omega_0}\psi_{ds} + R_s i_{qs} &= v_{qs} \end{aligned} \tag{4}$$

$$\begin{aligned} \frac{1}{\omega_0}\dot{\psi}_{dr} - s\psi_{qr} + R_r i_{dr} &= v_{dr} \\ \frac{1}{\omega_0}\dot{\psi}_{qr} + s\psi_{dr} + R_r i_{qr} &= v_{qr} \end{aligned} \tag{5}$$

The stator and rotor flux linkages and currents are related through,

$$\begin{aligned} \psi_{ds} &= x_s i_{ds} + x_m i_{dr} \\ \psi_{qs} &= x_s i_{qs} + x_m i_{qr} \end{aligned} \tag{6}$$

$$\begin{aligned} \psi_{dr} &= x_r i_{dr} + x_m i_{ds} \\ \psi_{qr} &= x_r i_{qr} + x_m i_{qs} \end{aligned} \tag{7}$$

In the doubly fed mode, active power is always supplied from the stator terminals to the power grid, independent of the value of generator rotor slip. At super synchronous speed rotor circuit supplies power to the grid, while under sub synchronous operation the grid supplies the rotor. The rotor motion of the machine, considering positive for motor operation, is expressed through the following slip equation:

$$(2H)\Delta\dot{s} = P_e - P_m - D\Delta s \tag{8}$$