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Assessing transient response of DFIG based wind turbines during voltage dips regarding main flux saturation and rotor deep-bar effect

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ABSTRACT

With increasing wind power penetration, transient responses of doubly-fed-induction-generator (DFIG) based wind turbines gain attentive focus. Accurate prediction of transient performance of DFIG under grid faults is required with increasing wind power penetration. Taking into account the main flux saturation and deep-bar effect, this paper concentrates on transient responses and stability of the DFIG system under symmetrical grid faults. Their roles played in the enhancement of system transient stability are clarified. The analyses proposed contribute greatly to proper selection, design and coordination of protection devices and control strategies as well as stability studies.

1. Introduction

Wind industry is becoming one of the world's fastest growing energy sectors nowadays, helping to satisfy global energy demand, offering the best opportunity to unlock a new era of environmental protection, and starting the transition to a global economy based on sustainable energy [1–3]. In recent years, rapid development of wind turbine technology and increasing wind power penetration have resulted in the concern about the stability and reliability of power systems, and thus continuous reformulation of the grid connection requirements for wind turbines [4,5]. This demands that wind turbines remain connected and providing necessary support to the grid during grid faults.

Most wind turbines use induction generators, doubly-fed-induction-generators (DFIG) or permanent magnet synchronous generators (PMSG) [6,7]. Currently, DFIG based wind turbines dominate the world market due to their cost-effective provision of variable-speed operation, as well as the controlling flexibility of electromagnetic torque and reactive power [8,9]. However, since its stator and rotor are both connected to the power system, grid fault ride-through control is difficult for the DFIG, and is a major challenge for wind turbine manufacturers. In the existing literature, there have recently been several papers dealing with this problem, mainly focusing on ride-through controller design and transient response analysis.

With regard to advanced controller design for the improvement of DFIG ride-through capability, a new method was presented by Xiang et al. [10] to control the rotor-side converter so that the rotor current contains components to oppose the DC and negative sequence components in the stator-flux linkage produced by the grid voltage dip. In order to suppress the influence of the back EMF on the DFIG rotor current during grid faults, Peterson et al. [11] designed a general rotor current control law by introducing feed-forward compensation of the back EMF and an active resistance. Sun et al. [12] proposed a control strategy in critical post-fault situations in order to reestablish the voltage at the wind turbine terminal. Field-oriented control based on a unified architecture was introduced in [13] to provide adequate ride-through capability for DFIG. In order to limit the DC-link voltage fluctuation during grid faults, Yao et al. [14] presented an improved control strategy with the instantaneous rotor power feedback.

Some other papers proposed control techniques to deal with both positive- and negative-sequence components in DFIG voltages and currents during unbalanced gird voltage conditions. Xu [15] proposed coordinated control strategies for the rotor-side converter and grid-side converter to provide enhanced control and operation under unbalanced supply. Based on direct power control theory, Martin et al. [16] presented an effective approach during unbalanced voltage dips while providing the possibility of controlling the power and the electromagnetic torque. A control strategy was proposed in [17] by choosing certain current reference values in the positive- and negative-sequences so that the torque and the dc voltage are kept stable during unbalanced sags. Hu et al. [18]

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Nomenclature

v_s, v_r	stator and rotor voltages
i_s, i_r	stator and rotor currents
ψ_s, ψ_r	stator and rotor fluxes
τ_s, τ_r	stator and rotor time constants
$\vec{i}, \vec{v}, \vec{\psi}$	current, voltage and flux vector
L_s, L_r	stator and rotor self-inductances
L_{ls}, L_{lr}	stator and rotor leakage inductances
L_m	mutual inductance
X_s, X_r	stator and rotor reactance
X_m, X_{lr}	magnetizing and rotor leakage reactance
σ	leakage coefficient $\sigma = 1 - L_m^2/L_sL_r$
R_s, R_r	stator and rotor resistances
ω_s, ω_r	synchronous and rotor angular frequency
p	number of pole pairs
J	generator and shaft inertia

Subscripts

d, q	synchronous *dq*-axis
s, r, g	stator, rotor and grid
DC	DC-link
n	rated value
$'$	transient equivalent value

developed PI-R controllers, providing precise control of both positive- and negative-sequence currents under unbalanced conditions.

In addition, some researchers are addressing the issue from different perspectives, focusing on detailed analysis of DFIG transient characteristics and the evolution of electrical variables during grid faults. Theoretical studies were proposed in [19–22] for understanding the causes of the overcurrents that appear during the grid faults. Mei and Pal [23] analyzed the influence of crowbar resistance on the rotor peak current and on the reactive power demand of the generator during grid faults. Smith et al. [24] studied the effects of turbine parameter and operating points on the transient stability of the system. These studies and related papers come to a common understanding that accurate prediction of DFIG transient performance under grid faults is important for proper selection, design and coordination of protection devices as well as stability studies.

In order to increase the accuracy of performance prediction, the influence of magnetic saturation and deep-bar effect has to be taken in account. Deep-bar effect, in particular, may bring about effects on transient characteristics of induction motor drive systems where large slips are present in normal operation, such as DFIG. Main flux saturation and deep-bar effect on DFIG transient responses have been tackled to a certain extent in previous published reports [25,26]. It is shown that the model with both saturation and deep-bar effect provides better prediction of the behavior of DFIG during grid faults. However, their respective influence on transient operation of DFIG and the corresponding theoretical analysis have not been illustrated.

Taking into account the main flux saturation and deep-bar effect, this paper concentrates on transient responses and stability of the DFIG system under symmetrical grid faults. The following part of the paper is organized in this way: Section 2 firstly illustrates the system modeling. Control schemes of DFIG wind turbines are then described briefly in Section 3. Influence of main flux saturation on transient performance of DFIG as well as the theoretical analysis is presented in Section 4, while Section 5 illustrates the role played by deep-bar effect in system transient operation. Finally, conclusions are summarized in Section 6.

2. DFIG system modeling

A doubly-fed-induction-generator is basically a wound-rotor induction machine with the stator windings directly connected to the three-phase grid and with the rotor windings connected to a back-to-back partial scale frequency converter, which consists of two independent converters connected to a common DC bus, namely the rotor-side converter and the grid-side converter, as shown in Fig. 1 [9].

The behavior of the doubly-fed-induction-generator is governed by these converters and their controllers both under normal and fault conditions. The converters control the rotor voltage in magnitude and phase angle, and are therefore, used for active and reactive power control.

2.1. Generator model

A favored way of representing a DFIG for the purpose of analysis, simulation and control is in terms of direct (d) and quadrature (q) axes [15]. Using the motor convention and considering the transients of the stator-flux linkage, the voltage equations for DFIG are given below, where rotor variables and parameters are referred to the stator.

$$\begin{cases} v_{sq} = R_s i_{sq} + \frac{d}{dt}\psi_{sq} + \omega_s \psi_{sd} \\ v_{sd} = R_s i_{sd} + \frac{d}{dt}\psi_{sd} - \omega_s \psi_{sq} \end{cases} \tag{1}$$

$$\begin{cases} v_{rq} = R_r i_{rq} + \frac{d}{dt}\psi_{rq} + (\omega_s - \omega_r)\psi_{rd} \\ v_{rd} = R_r i_{rd} + \frac{d}{dt}\psi_{rd} - (\omega_s - \omega_r)\psi_{rq} \end{cases} \tag{2}$$

The stator and rotor fluxes are given by

$$\begin{cases} \psi_{sq} = L_s i_{sq} + L_m i_{rq} \\ \psi_{sd} = L_s i_{sd} + L_m i_{rd} \end{cases} \tag{3}$$

$$\begin{cases} \psi_{rq} = L_r i_{rq} + L_m i_{sq} \\ \psi_{rd} = L_s i_{rd} + L_m i_{sd} \end{cases} \tag{4}$$

where

$$\begin{cases} L_s = L_{ls} + L_m \\ L_r = L_{lr} + L_m \end{cases} \tag{5}$$

The electromagnetic torque is calculated using

$$T_e = 1.5p(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}) \tag{6}$$

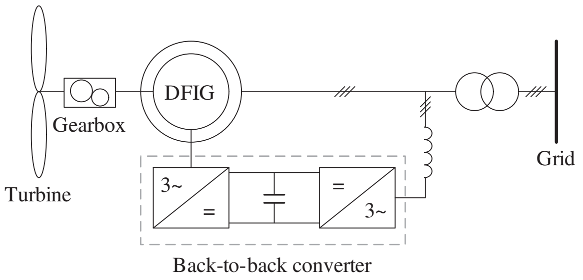

Fig. 1. Schematic diagram of wind turbines based on DFIG.