Energy Conversion and Management 76 (2013) 910–917

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Rotor current transient analysis of DFIG-based wind turbines during symmetrical voltage faults

Yu Ling [a,b,*], Xu Cai [a,c], Ningbo Wang [d]

[a] WPRC, School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Department of Electrical Engineering, Shanxi Datong University, Datong, Shanxi 037003, China
[c] SKLOE, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[d] Wind Power Research Center, Lanzhou Electric Power Company, Lanzhou, Gansu 730000, China

ARTICLE INFO

Article history:
Received 11 June 2013
Accepted 31 August 2013

Keywords:
Doubly fed induction generator (DFIG)
Protection
Rotor current
Voltage fault
Wind power generation

ABSTRACT

The impact of grid voltage fault on doubly fed induction generators (DFIGs), especially rotor currents, has received much attention. So, in this paper, the rotor currents of based-DFIG wind turbines are considered in a generalized way, which can be widely used to analyze the cases under different levels of voltage symmetrical faults. A direct method based on space vector is proposed to obtain an accurate expression of rotor currents as a function of time for symmetrical voltage faults in the power system. The presented theoretical analysis is simple and easy to understand and especially highlights the accuracy of the expression. Finally, the comparable simulations evaluate this analysis and show that the expression of the rotor currents is sufficient to calculate the maximum fault current, DC and AC components, and especially helps to understand the causes of the problem and as a result, contributes to adapt reasonable approaches to enhance the fault ride through (FRT) capability of DFIG wind turbines during a voltage fault.

1. Introduction

With the fast increasing of wind energy installed capacity over the last two decades, it is playing a vital role in world's energy markets at the present. It is expected that global total wind power generation will supply around 12% of the total world electricity generation at the end of 2020 [1]. Currently a preferred configuration for wind power generation is doubly fed induction generator, which can be seen in Fig. 1. This is due to its advantageous characteristics. In comparison with the fixed speed wind turbine, it can reduce mechanical stresses, and compensate for torque and power pulsations, and as a result improve power quality. In addition, variable speed turbine can maximize the efficiency of the energy conversion, as it can operate at optimal rotational velocity for each given wind speed. It is worth noting, in contrast to the wind turbines with full power converter, that its converter connected between the rotor windings and the grid is in part rating power, with a rating of typically 25% of total system power [2–4].

However, due to the penetration of large scale wind power to the grid, it is becoming significant to study the FRT issue to meet the requirements [5,6] that the turbines should stay connected to the grid for a certain voltage range in case of a grid failure. This is important to enable large-scale integration of wind energy into the grid without compromising system stability. It is worldwide recognized that wind turbines with DFIG are very sensitive to grid voltage due to direct connection of stator windings to the grid. The abrupt large sag in the grid voltage will cause large, oscillatory currents in the rotor windings, which can lead to the destruction of the converter if no protection has been done [7].

A few literatures that have been published investigate the transient behavior of the DFIG during faults by experiment and simulation solutions [8–10]. In fact, it also is important to theoretically analyze the transient of DFIG-based wind turbines during voltage faults. At present, short circuit current behaviors of DFIG are investigated in many literatures [7,11–14] but they usually confine their analysis to a solid symmetrical three-phase short-circuit at the generator terminals. In [7,11] and [12], the interest is only the maximum value of rotor fault currents. The method proposed in [13] and [14] is too complicated for engineering application. In [15], stator and rotor currents are analyzed based on engineering application, in which too many assumptions are needed. In [16], both symmetrical and unsymmetrical faults and voltage dips of any magnitude at the generator terminals are further investigated but the voltages applied to the rotor winding by rotor side converter (RSC) and the differences of the rotor circuit impedance due to different frequency components are still not considered.

So far, only limited information can be gained about the theoretical analysis of variable speed wind turbines with DFIG on rotor currents during voltage faults. In [17], only rotor voltage transient

---

[*] Corresponding author. Address: No. 800, Dongchuan Road, Mulan Building B111, Shanghai 200240, China. Tel.: +86 15525237906.
E-mail address: pleasurely@126.com (Y. Ling).

0196-8904/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.08.050

Nomenclature

$\bar{v}_s, \bar{v}_r$	stator and rotor voltage vectors
$\bar{i}_s, \bar{i}_r$	stator and rotor current vectors
$\bar{\psi}_s, \bar{\psi}_r$	stator and rotor flux linkage vectors
L_s, L_r	stator and rotor self-inductances
R_s, R_r	stator and rotor resistances
L_m	mutual inductance
ω_s, ω_r	synchronous and rotor angular frequency
s	slip of DFIG
τ_s, τ_r	stator time constant and rotor transient time constant
s, r	subscripts denoting stator and rotor
f, n	subscripts denoting the ‘forced’ component and ‘natural’ component
r	superscripts denoting rotor reference frame
DFIG	doubly fed induction generator
FRT	fault ride through
DC	direct current
AC	alternating current
RSC	rotor side converter
EMF	electromotive force

of variable speed wind turbines with DFIG has been presented during voltage faults. In [18], based on the method proposed in [17], rotor current transient is further investigated but the focus is rotor short-circuit currents during voltage faults. In [19], the rotor fault current expression is given, but the detailed derivation process is ignored. It is worldwide recognized that rotor currents can influence the capability of FRT of the turbine. It is therefore important and necessary to research how rotor current will be influenced by the parameters and variables of DFIG during voltage faults. This can contribute to understand the transient progress of wind turbines with DFIG during voltage faults and as a result this helps to adapt suitable methods to enhance the capacity of the uninterrupted operation of wind power generation. At the same time, other things can also be done through using the expression of rotor fault current, e.g. calculation of maximum current, calculation of its DC and AC components, even short-circuit calculations for protection relay settings.

The research presented in this paper is to examine the rotor currents transient behavior of wind turbines with DFIG in a generic way both considering the voltages applied to the rotor windings by RSC and the different rotor circuit impedances due to different frequency components during voltage faults. At first, the rotor voltage in terms of stator flux is determined under rotor open-circuit condition based on [17], and the dynamic equation of the rotor current reduces to a first-order differential equation. In turn, by solving the differential equation, the rotor currents after a fault are obtained.

Finally, simulation results are presented based on a DFIG with a rating power of 160 kW. The main goal is to provide a simulation analysis of rotor current, which can be compared with the theoretical analysis proposed in the paper.

2. Rotor modeling of DFIG

The purpose of this section is to present the dynamic model of DFIG rotor in a fixed stator reference frame using a space vector description, which is particularly helpful in following analysis. It is assumed that magnetic circuit is linear. Using the motor convention, the stator and rotor voltages and fluxes in a stationary reference frame are given by Lopez et al. [17]

$$\bar{v}_s = R_s\bar{i}_s + \frac{d\bar{\psi}_s}{dt} \tag{1}$$

$$\bar{v}_r = R_r\bar{i}_r + \frac{d\bar{\psi}_r}{dt} - j\omega_r\bar{\psi}_r \tag{2}$$

$$\bar{\psi}_s = L_s\bar{i}_s + L_m\bar{i}_r \tag{3}$$

$$\bar{\psi}_r = L_m\bar{i}_s + L_r\bar{i}_r \tag{4}$$

For simplicity, in these equations, all rotor variables have been referred to the stator. In terms of these equations, the equivalent circuit of the doubly fed induction generator is shown in Fig. 2. Transient of the machine can be analyzed using these equations, in which the notation “ indicates a space vector. v, i, and ψ represent voltage, current, and flux respectively. Subscripts s and r denote the stator and rotor quantities, respectively. L_s and L_r are the per-phase stator and rotor self-inductances, respectively, and L_m is the per-phase mutual inductance. R_s and R_r are the stator and rotor resistances per-phase, respectively. ω_r is the rotor electrical angular velocity.

Based on Eqs. (3) and (4), the stator current $\bar{i}_s$ can be eliminated and then an expression obtained can be substituted into Eq. (2) and eliminate the rotor flux $\bar{\psi}_r$, the rotor dynamic equation using rotor current vector as state variables is obtained and described as

$$L_{r\sigma}\frac{d\bar{i}_r}{dt} = -R_r\bar{i}_r + L_{r\sigma}j\omega_r\bar{i}_r - \bar{E} + \bar{v}_r \tag{5}$$

where the term $L_{r\sigma}$ is the transient inductance related to the rotor current dynamics, which can be written by the following equations

$$L_{r\sigma} = L_r - L_m^2/L_s \tag{6}$$

In addition, the term E is the back-EMF voltage induced in the rotor winding and reflects the effects of stator dynamics on rotor current dynamics. This term plays an important role on the rotor inrush current, dc-link over voltage and surplus torque during the voltage dip [17]. It is described in terms of stator flux as following

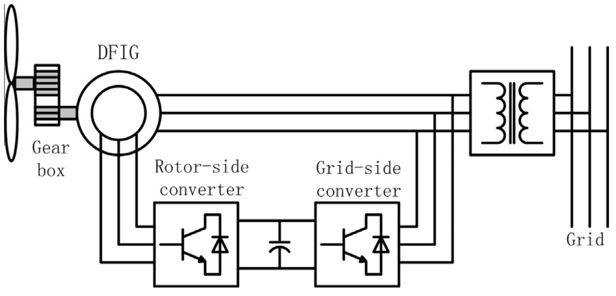

Fig. 1. Schematic of DFIG wind power generation system.

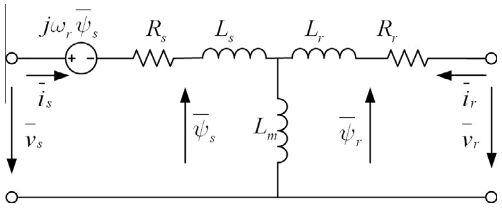

Fig. 2. Equivalent circuit of DFIG in stator reference frame.