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Rotor current dynamics of doubly fed induction generators during grid voltage dip and rise

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A B S T R A C T

The influence of grid voltage dip on doubly fed induction generators (DFIGs), especially rotor current, has received much attention. So, in this paper, the rotor short-circuit current of based-DFIG wind turbines is considered in a generic way, which is suitable to analyze the cases under different levels of both voltage sag and voltage rise. A direct method is proposed to obtain accurate expression of rotor current. Firstly, the rotor open-circuit voltage in terms of stator flux is determined, and the dynamic equation of the rotor current reduces to a first-order differential equation under rotor short-circuit operation condition. Secondly, the expressions of the rotor open-circuit voltage before and after a fault are obtained, respectively. Finally, based on the obtained expression of rotor voltage, the rotor short circuit currents before and after a fault are obtained by solving the first-order differential equation. This analysis contributes to understand the causes of the problem, and as a result, it helps to adapt reasonable approaches to improve the capacity of the uninterrupted operation of wind power generation during a voltage fault. Simulation results evaluate the proposed analysis.

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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 the preferred configuration for wind turbine generation is doubly fed induction generator, which can be seen in Fig. 1. This can be due to their advantageous characteristics. In comparison with the fixed speed wind turbine, they can reduce mechanical stresses, and compensate for torque and power pulsations, and as a result improve power quality. In addition, variable speed turbines can maximize the efficiency of the energy conversion, as they 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 VA 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 low voltage ride through (LVRT) issue to meet the requirements [5] 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. The abrupt large sag in the grid voltage will cause a growth of the current in the rotor windings, which can lead to the destruction of the converter without protection elements. If the current is limited by current-control on the rotor side of the converter, this will lead to high voltages at the terminals, which similarly can destroy the converter [6].

Currently, a possible solution, which is generally used by the manufacturers to protect the converter that is connected between the rotor windings and the power grid is to short circuit the rotor windings of the generator with the so-called active crowbar. It can provide the capacity of keeping the turbine connected to the grid during grid failure, and even can supply reactive power to the grid through a set of by-pass resistors that are connected to the rotor windings [7–9].

A number of literatures that have been published investigate the transient behavior of the DFIG during faults by experiment and simulation solutions [10–13]. However it also is important to theoretically analyze the transient of variable speed wind turbines with DFIG during voltage faults. In [14], rotor voltage transient of variable speed wind turbines with DFIG has been only presented during voltage faults. So far, limited information can be gained about the theoretical analysis of variable speed wind turbines with DFIG on rotor current during voltage faults. In [15], stator and rotor currents are analyzed based on engineering application, in which too many assumptions are needed. In [16], the interest is the

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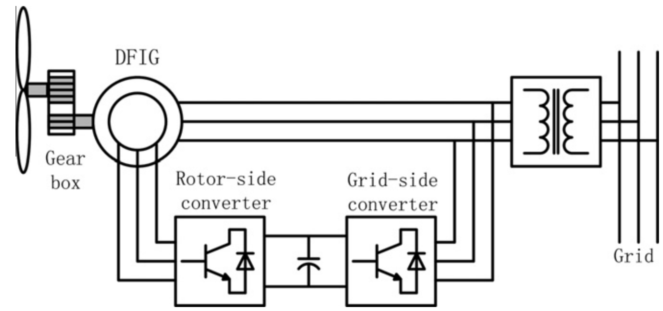

Fig. 1. Schematic of DFIG wind power generation system.

analysis of stator short circuit current, so only the maximum value of rotor current is approximately given. It is worldwide recognized that rotor current can influence the capability of low voltage ride through of the turbine [17]. It is therefore important and necessary to research how both rotor voltage and rotor current will be influenced by the parameters and variables of DFIG during faults. This can contribute to understand the transient progress of wind turbines with DFIG during faults and as a result this helps to adapt suitable methods of enhancing the capacity of the uninterrupted operation of wind power generation.

The research presented in this paper is to examine the transient behavior of the wind turbines with DFIG during voltage faults base on an improved method in the paper. The specific goal of the research is to mainly investigate rotor voltage and rotor current in the worst case, i.e., rotor open-circuit voltage and rotor short-circuit current during voltage faults. This is due to the voltages induced in rotor is lower than rotor open circuit voltage and the current in rotor is lower than rotor short circuit current in any other situation.

At first, the rotor voltage in terms of stator flux is determined under rotor open-circuit condition [14], and the dynamic equation of the rotor current reduces to a first-order differential equation under rotor short-circuit operation condition. In turn, the expressions of rotor open-circuit voltage before and after a fault are obtained, respectively. So, based on the obtained expression of rotor voltage, the rotor short circuit currents before and after a fault are obtained by solving the first-order differential equation.

Finally, simulation evaluation is proposed based on a DFIG with a rating power of 160 kW. The main goal is to provide a qualitative analysis of rotor voltage and current, which can be compared with the theoretical analysis.

2. DFIG modeling

The purpose of this section is to present the dynamic model of DFIG in a fixed reference frame using a space vector description, which is particularly helpful in following analysis [14]. 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

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

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

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

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

For simplicity, in these equations, all rotor variables have been referred to the stator. In terms of these equations, the equivalent circuit

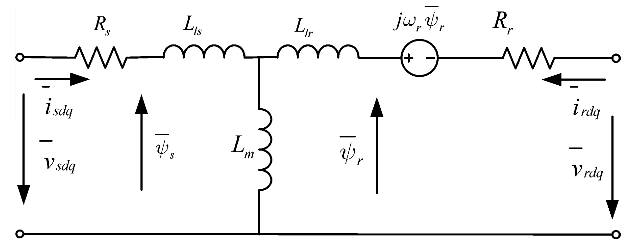

Fig. 2. Equivalent circuit of DFIG model.

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, which is related to the rotational speed of the machine as the expression $\omega_m = \omega_r/p$, where p is the pairs number of machine poles.

Based on (1)–(4), the rotor dynamic equation using rotor current vector as state variables is 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 terms $L_{r\sigma}$ is the transient inductance related to the rotor current dynamics are written by the following equation:

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

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 has important roles on the rotor inrush current, dc-link over voltage and surplus torque during the voltage dip [16]. It is described in terms of stator flux as following

$$\bar{E} = \frac{L_m}{L_s}\left(\frac{d\bar{\psi}_s}{dt} - j\omega_r\bar{\psi}_s\right) \tag{7}$$

By introducing the stator coupling factor $k_s = L_m/L_s$, (7) can further be simplified as

$$\bar{E} = k_s\left(\frac{d\bar{\psi}_s}{dt} - j\omega_r\bar{\psi}_s\right) \tag{8}$$

From (5), it is found that there are two worst situations. One is open-circuit rotor voltage, which is higher than that of any other situation and noting that, meanwhile, rotor current is zero; Another is short-circuit rotor current, which is the highest among any other situation, and meanwhile rotor voltage is zero.

As the analysis above, in open-circuit rotor situation, rotor currents are zero and rotor open-circuit voltage in terms of stator flux can be written by

$$\bar{v}_{ro} = \bar{E} = k_s\left(\frac{d\bar{\psi}_s}{dt} - j\omega_r\bar{\psi}_s\right) \tag{9}$$

According to (9), the voltage is determined by the stator flux.

And, in short-circuit rotor situation, rotor voltages are zero, and so rotor short circuit current is described as following

$$L_{r\sigma}\frac{d\bar{i}_r}{dt} = -R_r\bar{i}_r + L_{r\sigma}j\omega_r\bar{i}_r - \bar{v}_{ro} \tag{10}$$

3. Behavior of DFIG-based wind power during voltage fault

This section analyzes the behavior of the generators in a generic way during a fault. The decision is made so not to focus on a given

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