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Short-circuit current of doubly fed induction generator under partial and asymmetrical voltage drop

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ABSTRACT

The doubly fed wind turbine is the main equipment of wind generators. The fault transient characteristics of doubly fed induction generators (DFIG) have elicited the attention of many scholars. However, the short-circuit current (SCC) of power grid-contained DFIG under asymmetrical voltage drop cannot be accurately analyzed. The main difficulty is that the response and coupling of converters under partial voltage drop remain unclear. Thus, this paper presents an imperative study on SCC of DFIG, with particular attention to the transfer of negative-sequence voltage in the windings and rotor-side converter. The electromagnetic process and excitation control are simultaneously deduced in a uniform coordinate space by constructing positive- and negative-sequence vector models. The generating mechanism and analytical expressions of stator SCC are proposed. The positive- and negative-sequence equivalent models of DFIG during fault initial stage and steady-state process are constructed for practical short-circuit calculation. Simulation and physical testing are implemented to verify the theoretical analysis.

1. Introduction

Wind power has been exploited and utilized throughout the world in recent years [1]. The doubly fed wind turbine is the main equipment of wind generators and accounts for more than 50% of installed wind capacity [2]. The doubly fed induction generator (DFIG) is the core equipment that determines the output characteristics of the wind turbine. DFIG is a wound rotor induction generator with AC excitation. Excitation is implemented through the feedback of grid-side voltage by a series of converters [3]. The operating characteristics of the grid change with the large-scale application of DFIG because the converter has the capability to rapidly respond to disturbance [4].

A large, transient electromotive force (EMF) can be induced in a DFIG's rotor winding by stator DC current under grid fault. Converters with partial installed capacity can only offset EMF within a narrow range. Transient EMF causes rotor overcurrent and over DC voltages under the condition of deep voltage drop [5,6]. In this case, a rotor protection called Crowbar is often utilized to short circuit the rotor winding to prevent damage on the converters [7]. Therefore, the transient process of DFIG presents two different states: operation with Crowbar and under excitation control. The short-circuit current (SCC) contributed by DFIG under these two states could affect the protection and control of the power system, which have been a concern of engineers and researchers. However, existing studies focused on DFIG operated with a Crowbar and generally employed a simulation method [8–11]. Even the maximum current can occur when the excitation control is lost under deep voltage drop, the short-circuit currents contributed by DFIG are needed for protection settings. The transient process of DFIG operated with a Crowbar cannot cover the integrated characteristics under minor or remote fault. Moreover, the physical mechanism and numerical value of a component of electrical quantities cannot be obtained by simulation [12].

When excitation control is retained during a fault, the voltage drop changes the rotor current through the electromagnetic coupling of the stator and rotor. Meanwhile, the converter responds to the voltage drop and rotor current variation to regulate the rotor voltage [13,14]. The transient process of DFIG under

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excitation control becomes high-order closed-loop dynamics. Several researchers have deduced the SCC expressions of DFIG under partial voltage drop. However, the effects of excitation control are usually excluded by assuming that the rotor voltage is constant [15]. More importantly, the SCC expression cannot be utilized to calculate the fault electric variables at any location because of the massive scale and complex structure of the power system. Calculating the fundamental-frequency fault component under partial voltage drop is difficult because of the lack of an equivalent model of DFIG.

Asymmetrical short circuit is one of the most universal faults in power systems. The transient process becomes rather complex with the action of negative-sequence electrical variables under asymmetrical voltage. However, the transient process of DFIG under asymmetrical fault has not received sufficient attention. The SCC of DFIG under symmetrical voltage drop has been studied [16]. However, the proposed calculation method cannot be utilized for asymmetrical fault. The terminal negative-sequence voltage of DFIG is produced under asymmetrical fault. The negative-sequence voltage could generate an air-gap field with negative direction by stator magnetizing current and introduce a negative-sequence rotor excitation voltage through the feedback of converter control. This phenomenon makes the transient characteristics of DFIG under asymmetrical fault different from those of traditional generators and DFIG under symmetrical fault.

An imperative analysis of the characteristics and calculation method of the SCC of DFIG under partial and asymmetrical voltage drop is conducted in this study. The research focuses on the transient response of the converter and its effects on the output of DFIG. This paper mainly consists of five parts. The first part presents the construction of the positive- and negative-sequence vector models of DFIG in a reference frame of converter control. The second and third parts present the deduction of the SCC expressions of DFIG operated with and without excitation control. The response time of the rotor winding to excitation control is analyzed in the fourth part, and the positive- and negative-sequence equivalence models are obtained. Finally, the analyses are verified through simulation and short-circuit test in the fifth part.

2. Vector model of DFIG

2.1. General descriptions

The converters in DFIG are usually called rotor-side converters (RSCs) and grid-side converters (GSCs) depending on their AC connection. Vector control is utilized in converters to achieve the variable-speed operation of DFIG. The d-axis is oriented to the stator flux, or the q-axis is oriented to the stator voltage; these are the main methods of RSC control [17]. DFIG has a similar transient process under these controls. The difference is that the pulsating electrical variables could be caused when the d-axis flux-oriented control is adopted because the rational speed of the reference frame is changed by the DC flux linkage.

In the reference frame of RSC control, the d-axis stator voltage is basically zero. Stator active power is determined only by the q-axis components of voltage and rotor current. Reactive power depends on the q-axis voltage and d-axis rotor current. Even if coupling occurs between the d- and q-axis rotor voltages, the coupling terms can be compensated after calculating the d- or q-axis rotor voltages with a PI controller according to the d- or q-axis rotor currents because the coupling terms are relatively small. Therefore, the q-axis rotor current reference can be calculated according the electromagnetic torque obtained by maximum power point tracking. The q-axis rotor voltage reference is obtained by the rotor current reference to realize the control of active power. Similarly, the d-axis rotor voltage reference can be calculated by the reactive power reference to control the stator reactive power [18]. Therefore, the references of d- and q-axis rotor currents are expressed by

$$i_{rq*} = -\frac{T_{e*}}{3n_p\psi_{sd}}, \quad i_{rd*} = -\frac{L_sQ_{s*}}{3L_mu_{sq}} + \frac{\psi_{sd}}{L_m} \tag{1}$$

where u、i and ψ are voltage, current and flux linkage, respectively. L is inductance. L_m is magnetizing inductance. T_{e*} and Q_{s*} are references of electromagnetic torque and reactive power. n_p is number of pole-pairs. Subscript s and r denote the stator and rotor parameters. Subscript d and q indicate the d- and q-axis components.

The time delay and tracking error of PWM control are neglected. The rotor voltages are determined by rotor current references as follows:

$$\begin{cases} u_{rd} = k_{rp}\Delta i_{rd} + k_{ri}\int \Delta i_{rd}dt - \omega L_{\sigma r}i_{rq} + e_d \\ u_{rq} = k_{rp}\Delta i_{rq} + k_{ri}\int \Delta i_{rq}dt + \omega L_{\sigma r}i_{rd} + e_q \end{cases} \tag{2}$$

where $e_d = L_m d\psi_{sd}/(L_s dt)$, $e_q = L_m\psi_{sd}/L_s$; $L_{\sigma r} = \sigma L_r$ is rotor transient inductance; $\sigma = 1 - L_m^2/(L_sL_r)$ is leakage coefficient; ω is difference between the synchronous frequency ω_s and rotor speed ω_r; k_{rp} and k_{ri} are proportional and integral constants, respectively; Δi_{rd} and Δi_{rq} are respectively current differences between reference and real-time value.

2.2. DFIG modeling

A phasor of an asymmetrical variable can be decomposed into positive-, negative-, and zero-sequence phasors through the symmetrical component method. The asymmetrical variable is changed into the superposition of the instantaneous value of positive-, negative-, and zero-sequence components by extracting the real parts. The synthesis of a three-phase axis vector is defined as a space vector. The axis vector is the product of the three-phase asymmetrical variables multiplied by the unit vector of the phase axis. Therefore, the space vector of asymmetrical variables is converted to the superposition of the sequence vectors after introducing positive-, negative-, and zero-sequence components into three-phase variables as follows:

$$\boldsymbol{F}_{abc} = \dot{F}_{ap}e^{j\omega_s t} + \dot{F}_{an}e^{-j\omega_s t} \tag{3}$$

where $\dot{F}_{ap}$ and $\dot{F}_{an}$ are the positive- and negative-sequence phasors of the A-phase variable, respectively.

The above vector is based on static three-phase coordinates. Therefore, the vector in the coordinates with positive and reversed rotating direction can be obtained through coordinate transformation as follows:

$$\begin{cases} \boldsymbol{F}_{dq}^{+} = \boldsymbol{F}^{+}e^{j\theta_c} + \boldsymbol{F}^{-}e^{j\theta_c}e^{-j2\omega_s t} \\ \boldsymbol{F}_{dq}^{-} = \boldsymbol{F}^{+}e^{j\theta_c}e^{j2\omega_s t} + \boldsymbol{F}^{-}e^{j\theta_c} \end{cases} \tag{4}$$

where $\boldsymbol{F}^{+} = \dot{F}_{ap}e^{-j\theta_c}$, $\boldsymbol{F}^{-} = \dot{F}_{an}e^{-j\theta_c}$; θ_c is the initial angle by which the A-phase axis lags the d-axis.

The sequence components are independent of one another for the symmetric element. Therefore, the dynamics of DFIG can be described by two models in positive and reversed rotating direction according to (4). The model in the flux-oriented coordinate with positive synchronous rotation is provided by