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Research on short-circuit current of doubly fed induction generator under non-deep voltage drop

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ABSTRACT

The transient characteristics of power systems with large-scale doubly fed wind turbines undergo profound changes. Doubly fed induction generators (DFIG) under non-deep voltage drop generate short-circuit currents, which involves complicated electromagnetism and control coupling. This phenomenon has only been partially studied in the literature. Thus, this paper presents a detailed analysis of the short-circuit current of DFIG, with particular attention to the influence of converter adjustment. The dynamics of generator and converter control were simultaneously analyzed by vector analysis in uniform coordinate space. The generation mechanism, composition, and analytical expressions of short-circuit current were proposed. DFIG models were constructed to calculate the initial and steady-state short-circuit current. Simulation and experiment were performed to verify the efficacy of the proposed analyses.

1. Introduction

Wind generation is expanding rapidly as an integral part of the world energy-development strategy. Majority of variable-speed wind turbines adopt double-fed induction generators (DFIG) [1]. The DFIG has converters designed to provide excitation, thereby making DFIG a multivariable closed-loop system with strong coupling [2]. With the pervasive application of DFIG-based wind turbines, power systems are currently undergoing profound changes in terms of operating characteristics [3].

The DFIG generates DC in its stator winding to prevent sudden flux change caused by voltage drop when grid fault occurs. The resulting magnetomotive force produces overcurrent and peek voltage in the rotor winding. Rotor winding is usually shorted out by Crowbar to prevent damage to converters under deep voltage drop [4]. Converters suffer the minimal effect under non-deep voltage drop, therefore, the continuous operation of the converter is necessary for the DFIG [5]. In such case, converters can improve DFIG operation performance. However, the transient behavior of the DFIG becomes more complex under the influence of the exciting regulation of converters.

Transient analysis of the DFIG has gained much interest from the research community because new grid codes require that wind turbines remain connect to the grid during and after grid faults. Analyzing the transient process of DFIG to support the implementation of low voltage ride through is one of the main directions [6,7]. The transient behavior of DFIG cannot be fully reflected among those studies because the limiting conditions and the specific control mode are adopted. Many researchers have analyzed the transient characteristics of DFIG through simulation [8,9]. However, the mechanism of the transient process can be obtained due to the limitations of simulation method. The transient dynamic of DFIG needs to be analytically analyzed by mathematical derivation [10–12]. But there is still no method to properly account for the impact of converter regulation under uninterrupted excitation [13].

The calculation of short-circuit current (SCC) is the main work of transient state analysis of power system. Several researchers have derived expressions of SCC of DFIG [14,15]. However, these expressions are obtained under some suppositions. Complete expressions of SCC can be easily obtained under deep voltage drop because DFIG operates as a common induction generator (IG) after Crowbar action [16]. However, obtaining these expressions is difficult when partial voltage drop is present. Some studies have examined the condition in which the rotor exciting voltage remains unchanged during fault [17,18], but failed to consider the influence of converter adjustment. Other researchers proposed the calculation method of SCC for DFIG operated in steady state after fault, but they just analyzed the fault process since the end of converter regulation [19].

The expressions of SCC are used to compute SCC contributed by generators, but SCC calculation of power system requires the simplified equivalent circuits because of the complexity of the system [20]. Synchronous generator (SG) is excited by a revolving-armature type alternator whose voltage cannot abruptly change. Thus, SG is equivalent to a circuit with voltage source and reactance series to calculate initial and steady-state SCCs. The DFIG

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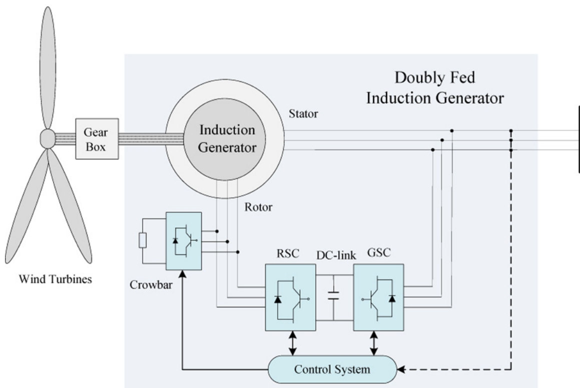

Fig. 1. Structure diagram of double fed induction generator.

has a rapidly varying excitation current when its converter rapidly responds to voltage drop. Several researchers have attempted to apply the model like SG in modeling the DFIG, but only for the DFIG operated with Crowbar [21].

This paper conducts an imperative study of the SCC of DFIG under non-deep symmetrical voltage drop. The electromagnetic dynamics of generator as well as the adjustment action of converters are simultaneously analyzed in theory and deduced in mathematics. This paper mainly consists of four parts. The first part presents a vector model of DFIG. The second part analyzes the electromagnetic transients of DFIG. The third part deduces the expressions of SCCs and obtains the equivalence models of the DFIG. Finally, the fourth part verifies the analyses by means of time domain simulation and experiment.

2. Complex-vector mathematical model of DFIG

DFIG is in fact a wound rotor IG exciting by the back-to-back converters, as shown in Fig. 1. The converters are often referred to as rotor-side converter (RSC) and grid-side converter. The DFIG is normally controlled in a synchronous rotating frame (SRF) via vector control technique [2]. The control is mainly divided into stator flux-oriented and voltage-oriented control, among which flux-oriented control is commonly used in RSC [5,22]. The d- and q-axes rotor currents are, respectively, applied to control the active and reactive power, and the d- and q-axes currents in grid-side converter are used for the DC-link voltage and reactive power control.

The voltage and flux linkage equations of the DFIG are identical to those of the wound-rotor IG [23]. The electromotor convention is adopted for stator and rotor, and magnetic saturation is neglected. By transforming scalar electrical quantities into pace vectors in flux-oriented SRF [24], we can obtain

$$\begin{cases} \boldsymbol{u}_s = R_s\boldsymbol{i}_s + j\omega_s\boldsymbol{\psi}_s + \dfrac{d\boldsymbol{\psi}_s}{dt} \\ \boldsymbol{u}_r = R_r\boldsymbol{i}_r + j\omega_r\boldsymbol{\psi}_r + \dfrac{d\boldsymbol{\psi}_r}{dt} \end{cases} \tag{1}$$

$$\begin{cases} \boldsymbol{\psi}_s = L_s\boldsymbol{i}_s + L_m\boldsymbol{i}_r \\ \boldsymbol{\psi}_r = L_r\boldsymbol{i}_r + L_m\boldsymbol{i}_s \end{cases} \tag{2}$$

where $\boldsymbol{u}$, $\boldsymbol{i}$, and $\boldsymbol{\psi}$ are the voltage, current, and flux linkage vectors; R and L are the resistance and inductance, ω_s and ω are the synchronous and slip frequency, and the subscript s and r represent stator and rotor windings, respectively.

The response time of the RSC is ignored because of its faster response speed than that of an electrical machine. Assuming that the rotor voltage can always track the references by space vector pulse width modulation, the rotor voltage vector is obtained by

$$\boldsymbol{u}_r = k_p(\boldsymbol{i}_{r*} - \boldsymbol{i}_r) + k_i\int(\boldsymbol{i}_{r*} - \boldsymbol{i}_r)\ dt + j\omega\sigma L_r\boldsymbol{i}_r \tag{3}$$

where k_p and k_i are, respectively, the proportional and integral constants of the inner controller, and $\boldsymbol{i}_{r*}^c$ is the rotor current reference; σ is the leakage factor.

Because the dynamic of the outer-loop control has low impact, the rotor current reference is expressed according the relation between the out power and rotor current as follows:

$$\boldsymbol{i}_{r*} = \frac{\boldsymbol{\psi}_{s*}}{L_m} + \frac{L_s\boldsymbol{S}}{L_m\boldsymbol{u}_{s*}} \tag{4}$$

where $\boldsymbol{S}_* = P_{s^*} - jQ_{s^*}$, and P_{s^*} and Q_{s^*} are references of active and reactive power obtained by direct setting or maximum wind-power tracking and terminal voltage control.

3. Theoretical analysis of short-circuit current

The terminal voltage of DFIG drops instantaneously when grid fault occurs. However, the stator-induced electromotive force (EMF) remains constant at the fault instant because of the conservation principles of flux linkages. The power-frequency SCC i_{sf} is generated by the voltage difference. Meanwhile, A DC i_{sz} is also generated in stator winding to prevent the sudden change of stator flux, and counteracting the rotor flux variation that caused by armature reaction requires induction of the rotor DC i_{rz}. Given that the resistance of the converter connected to the rotor winding is nearly zero [13], the transient time constant of these DCs are essentially the same with that of the induction machine [23].

The DCs generate a static magnetic field and a magnetic field that rotates with the rotor body. The short-circuit currents (hereinafter referred to as speed-frequency SCC), which have angular frequency equal to the electrical rotor speed, are induced in respective winding. The decaying time constant of the stator speed-frequency SCC $i_{s\omega}$ and the rotor speed-frequency SCC $i_{r\omega}$ are equal to the rotor and stator time constant inversely.

The rotor current of DFIG is controlled to track references according to the operation condition of a grid [2]. The input errors of controller appear after voltage drop, thus causing changes in references. The rotor power-frequency SCC, which is relative to the stator-side, could increase from the normal current $i_{r|0|}$ into $i_{r|0|} + i_{r\upsilon}$ to maintain a certain power output by means of the converter control. This current variation can generate a current increment $i_{s\upsilon}$ in stator winding. Additionally, the converter control can suppress the rotor speed-frequency SCC because current references are foundational frequencies. This phenomenon is similar to that when a demagnetized rotor reaction is produced to reduce stator DC.

The rotor winding of the DFIG is equivalent to a circuit with two voltage sources connected to a series of rotor resistance and reactance during grid fault [25]. These voltage sources respectively equal to AC-side voltage of RSC and the counter EMF. The equivalent circuit is a first-order circuit without converter adjustment. The order of the rotor circuit increases when an integral controller is used to regulate the rotor exciting voltage. The stator speed-frequency SCC then changes when the rotor free current changes from DC into the current i_{rn} with the frequency decided by the implementation of controller.

The multiple induced currents are negligible and should be ignored. Table 1 shows the main components of the SCC. The stator forced current $i_{sn\omega}$ is generated by rotor free current i_{rn}, and the currents $i_{sz\upsilon}$ and $i_{r\omega\upsilon}$ represent the variation of the stator DC and rotor speed-frequency SCC. Both the composition and size of the SCC undergo changes under converter control.