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Dynamic behavior of the excitation circuit of a doubly-fed induction generator under a symmetrical voltage drop

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A B S T R A C T

The large-scale application of doubly-fed wind turbines has significantly changed the fault transient characteristics of power systems. However, the transient state of a doubly-fed induction generator (DFIG) under large disturbances is difficult to accurately evaluate. The main difficulty lies in the failure to acquire the transient process of the DFIG excitation circuit because of the high orders and the strong coupling of excitation control. This paper presents a detailed transient analysis of a DFIG, with focus on the dynamic behavior and effects of the excitation circuit. The dynamic models of the rotor-side converter and the grid-side converter, which include the excitation regulation and the electromagnetic process, were constructed. The effects of the implementation of controllers on the transient behavior of the DFIG are analyzed by deducing the transitive relation of transient processes. Simplified expressions of DFIG electrical variables are proposed with the excitation regulation considered.

1. Introduction

Wind power, which is regarded as a fossil fuel substitute, is the main source of renewable energy [1]. Currently, wind power is being developed from supplemental energy to a main power source [2]. A wind turbine equipped with a doubly-fed induction generator (DFIG) is used extensively in wind power. The doubly-fed wind turbine exhibits higher conversion efficiency than do constant speed wind turbines. Meanwhile, the doubly-fed wind turbine requires a smaller converter capacity than does the direct-drive wind turbine [3].

DFIG is essentially a wound rotor induction generator with alternating current (AC) rotor excitation. The direct current (DC) flux linkage is generated in the stator winding when the terminal voltage of the DFIG drops. The excitation circuit of the DFIG has limited capacity to counteract the rotor transient electromotive force (EMF). Thus, the surge rotor current and the DC-link overvoltage are produced in the DFIG during grid faults [4]. The previous practice was to disconnect the wind turbine from the grid to prevent damage to the DFIG [5]. However, new grid codes require wind turbines to remain connected to the grid during grid faults and facilitate voltage recovery after a fault [6].

The low voltage ride through of a wind turbine depends on the understanding of the DFIG transient process. Meanwhile, the DFIG transient behavior needs to be investigated to improve the protection scheme of the power system. With the accelerated exploitation of wind power, the transient analysis of DFIG has drawn significant interest [7,8]. Visible DFIG transient processes have been revealed through iterative simulation [9]. However, some characteristics of the transient behavior cannot be acquired by simulation. In some studies, the DFIG transient process was mathematically deduced without considering the exciting voltage [10–12]. The research object in these studies was essentially a conventional induction generator, which cannot completely cover the transient characteristics of the DFIG.

DFIG transient state includes the electromagnetic process of the generator and the regulation of the excitation circuit. Even when rotor protection operates after the fault, converter regulation can affect the DFIG transient behavior because the response time of the rotor winding to the converter is usually shorter than the operating time of protection. The auto-excitation equipment of the synchronous generator (SG) undergoes a slow and gradual process. Thus, the rotor excitation current in the SG is considered constant during the transient analysis. The excitation system of the DFIG varies from that of the SG. The DFIG excitation regulation can quickly respond to the voltage drop and change the operating state of the generator. More specifically, changes in state can affect the output of the

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Nomenclature

u	instantaneous voltage
i	instantaneous current
U	amplitude of the voltage
U_{dc}	DC-link voltage
R	phase resistance
L	phase inductance
C_{dc}	capacitance of DC-link
σ	leakage coefficient of the generator
P	slip of the induction generator
ω_0	electrical frequency of the power grid
ω_{di}	slip frequency of the induction generator
ω_b	rotational speed of the reference frame
P, Q	active and reactive power
k_{rp}, k_{ri}	parameters of the rotor current control
k_{gp}, k_{gi}	parameters of the grid-side current control
k_{dp}, k_{di}	parameters of the DC-link voltage control
Bold letters	complex vector

Superscripts

~	fault component
*	reference of the controller

Subscripts

s, r, g	stator, rotor and grid-side converter variables
d, q	variables on a rotating reference frame
n, f	electrical variables before and after fault

excitation circuit. Complex coupling occurs between the generator and the excitation circuit during grid faults [7].

A common method for simplifying the transient analysis of the DFIG is by disregarding the variation in exciting voltage [13]. However, this approach omits some critical transient information of the DFIG. A derivation has been conducted to investigate the effects of the DFIG exciting regulation. Reference [14] proves the influence of converter regulation on the operating state of the DFIG. However, the present fails to describe the dynamic characteristic under great disturbances because linear modal analysis is adopted. Reference [15] and [16] consider the excitation regulation in their analyses of the transient behavior; however, such consideration is limited to partial disturbances of the rotor-side converter (RSC). Systematic studies on the transient characteristics of the excitation circuit have rarely been reported.

This paper investigates the transient characteristics of the DFIG excitation circuit under the common voltage-oriented control. The transient coupling among the generator, RSC, and grid-side converter (GSC) are analyzed emphatically by constructing dynamic models of the converters. The effects of the implementation method of the controller on the transient behavior of the DFIG are analyzed. Linearized expressions of the fault electrical variables are deduced using the transitive relation of the disturbance input.

This paper is organized as follows: Section 2 presents the dynamic model of the excitation circuit and the parameter design of the proportional–integral (PI) controller. Section 3 deduces the electromagnetic transient of the DFIG by using a complex model. Section 4 part analyzes the transient characteristics of the RSC regulation and obtains the disturbance input for the GSC. Section 5 analyzes the transient process of the GSC control and presents the expressions of the DC-link voltage and the GSC current. Finally, Section 6 explores and verifies the analyses by time domain simulation.

2. Modeling and control of DFIG

The composition of the DFIG is shown in Fig. 1. The excitation circuit of the DFIG typically consists of two four-quadrant converters, which feed the terminal voltage back to supply AC excitation to the induction generator. The two converters are often known as RSC and GSC, based on their AC-side connection. A capacitance is connected between two converters to restrain the fluctuation of the DC-link voltage [17].

2.1. Modeling of the RSC

The DFIG exhibits voltage and flux linkage equations similar to those of the conventional induction generator attributed to structural consistency. The stator–voltage orientation is adopted to control the rotor current of the DFIG [18]. The q-axis of the reference frame is aligned with the stator voltage, and the d-axis lags behind the q-axis by 90°. The generator convention and the motor convention are adopted for stator winding and rotor winding, respectively. The dynamic model of the DFIG in p.u. variables in the voltage-oriented coordinates is described by

$$\begin{aligned}
0 &= \left(\frac{R_s}{\sigma L_s} + \frac{1}{\omega_b}\partial\right)\psi_{sd} - \frac{R_s L_m}{\sigma L_s L_r}\psi_{rd} \\
u_{sq} &= \omega_0\psi_{sd} - \frac{R_s L_m}{\sigma L_s L_r}\psi_{rq} \\
u_{rd} &= \left(R_r + \frac{\sigma L_r}{\omega_b}\partial\right)i_{rd} - \omega_{di}\sigma L_i i_{rq} + e_d \\
u_{rq} &= \left(R_r + \frac{\sigma L_r}{\omega_b}\partial\right)i_{rq} + \omega_{di}\sigma L_r i_{rd} + e_q
\end{aligned} \tag{1}$$

where the back EMFs are given by

$$e_d = \frac{L_m}{\omega_b L_s}\partial\psi_{sd}, \quad e_q = \frac{\omega_{di}L_m}{L_s}\psi_{sd} \tag{2}$$

The d- and the q-axis rotor voltages exert an effect on each other because of the coupling terms $\omega_{di}\sigma L_r i_{rq}$ and $\omega_{di}\sigma L_r i_{rd}$. The d- and the

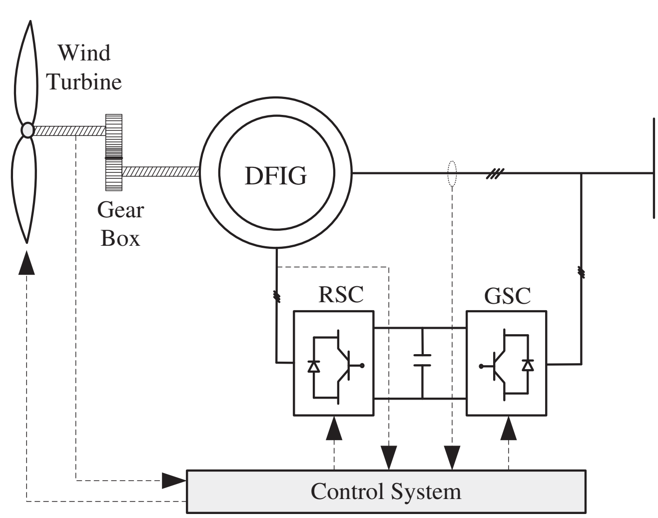

Fig. 1. Structure diagram of the DFIG.