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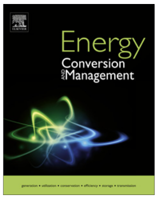

Efficient fault-ride-through control strategy of DFIG-based wind turbines during the grid faults

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ABSTRACT

As the penetration of wind power in electrical power system increases, it is necessary that wind turbines remain connected to the grid and contribute to the system stability during and after the grid faults. This paper proposes an efficient control strategy to improve the fault ride through (FRT) capability of doubly fed induction generator (DFIG) during the symmetrical and asymmetrical grid faults. The proposed scheme consists of active and passive FRT compensators. The active compensator is carried out by determining the rotor current references to reduce the rotor over voltages. The passive compensator is based on rotor current limiter (RCL) that considerably reduces the rotor inrush currents at the instants of occurring and clearing the grid faults with deep sags. By applying the proposed strategy, negative effects of the grid faults in the DFIG system including the rotor over currents, electromagnetic torque oscillations and DC-link over voltage are decreased. The system simulation results confirm the effectiveness of the proposed control strategy.

1. Introduction

In the past decades, world wind energy production has increased significantly due to cleanness and renewability. By increasing the penetration of wind power in electrical power systems, grid operators have modified the grid codes. According to this new grid codes, wind turbines must remain connected to the grid and supply reactive power to guarantee the grid voltage support during the grid faults [1]. This ability of wind turbines is termed as the fault ride through (FRT) capability and more generally low voltage ride through (LVRT) capability. Nowadays, DFIG is the most employed generator for wind turbines due to advantages of variable-speed-constant-frequency-based operation, decoupled control of active and reactive power and enjoy partial-scale converters. However, because the stator of the DFIG is directly connected to the grid, it is extremely vulnerable to the grid disturbances, especially grid faults. The voltage sag at the stator terminals due to the grid faults cause the rotor over currents, DC-link over voltage, and torque oscillations that could lead to destruction of the rotor side converter (RSC), DC-link capacitor and mechanical parts. So, without the proper control strategy and protective measures, the DFIG is not able to remain connected to the grid during the grid faults.

In the recent year, several approaches have been presented to improve the FRT capability of the DFIG. These approaches can be divided into two categories: hardware modification and modifying the DFIGs converters conventional control. The most common FRT solution is to install a crowbar circuit across the rotor terminals [2–4]. When the rotor overcurrent is detected, the crowbar circuit short circuits the rotor terminals and isolates the RSC from the rotor that provides conservative protection to the RSC. But, at the same time changes the DFIG to a squirrel cage induction generator, which absorbs reactive power from the grid when reactive power support is required. As result, static and dynamic VAR compensators or STATCOMs are sometimes installed at the DFIGs terminals to provide reactive power during the grid faults [5–7]. In [8,9] an additional series connected converter and in [10,11], a dynamic voltage restorer (DVR) is employed for improve the FRT capability of the DFIG. In these conditions, the stator voltage is equal to the grid voltage and the converter output voltage. So, during the grid faults, by compensating the stator voltage, the DFIG could be connected to the grid. The FRT scheme is proposed in [12], which is connected between the rotor circuit and DC-link capacitor in parallel with the RSC, consists of an uncontrolled rectifier, IGBT switches and an inductor. In this scheme, the input mechanical energy of the wind turbine during the grid fault is stored and utilized at the moment of fault clearance. Consequently, the rotor speed deviation and electromagnetic torque fluctuations are reduced. Another solution is connecting an additional battery energy storage system (BESS) or a brake chopper circuit across the DC-link of the converters [13,14]. The BESS and chopper can balance the extra power that goes through the RSC and prevent over voltage at the DC-link. However, these solutions require extra hardware

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Nomenclature

Vector and symbols

V, i, φ	voltage, current and flux vectors.
P, Q, T	active and reactive power and torque
R, L	resistance and inductance
t, ω, θ	time, angular speed and angle
f, s	frequency and rotor slip
p, ϕ	Sag depth and phase
σ, τ	leakage factor and time constant

Subscripts

d-q	synchronous stator-voltage frame
s, r, g	stator, rotor and grid
m, em, i	mutual, electromagnetic, initial
1, 2	positive and negative sequence components
ss, n	steady state and natural components

Superscripts

s, r	stator and rotor reference frames
$*$	reference value

that increases complexity and cost of the wind turbines system and decrease its reliability [2–14].

Finally, modified control approaches are presented as the most successful FRT strategy. In these schemes, the control structure is modified instead of using the extra hardware. Some authors by injecting the stator voltage feed-forward compensation terms into the outputs of the RSC current controller, increase the RSC outputs voltage and decrease the rotor over currents [15,16]. The rotor flux is controlled immediately to track the changing stator flux in order to decrease the rotor overcurrent [17]. The torque reference is set to zero and the input mechanical energy of the wind turbine during the grid faults is transformed into the rotor's inertia energy to decrease the rotor over current and DC-link over voltage [18]. A part of the captured wind energy during the grid faults is stored temporarily in the rotor's inertia energy and the DFIG's reactive power capacity on the stator and the grid side converter (GSC) is handled carefully to satisfy the new grid code requirements strictly [19]. Authors in [20], use the stator currents as the rotor current references during the grid faults that cause the stator and rotor over currents are decreased. In order to decrease the rotor over currents and increase the flux attenuation, the gains of the PI current controllers of the RSC are adjusted optimally [21]. The Controllers are designed simultaneously for both the RSC and GSC using a linear quadratic output feedback decentralized control strategy to limit the oscillations and peak value of the rotor current and the DC-link voltage [22]. The rotor current is controlled using adaptive internal model controller (AIMC) with variable gain adjustment mechanism to improve the LVRT capability of the DFIG [23]. The rotor virtual resistance is used to limit the rotor over currents, which increases the stator dynamic resistance and flux damping [24].

The FRT control scheme is proposed in [25] consists of a nonlinear control strategy applied to the RSC and a DC-link voltage control applied to the GSC. This scheme improves the damping of the DFIG transient response and minimizes oscillations of the rotor current, electromagnetic torque and DC-link voltage during the grid faults. A control strategy is proposed for the GSC based on the instantaneous rotor power feedback that limits the DC-link voltage fluctuation [26]. According to nonminimum phase behavior of the GSC dynamic and DC-link voltage, a nonlinear control scheme is applied to the GSC which stabilizes the internal dynamics and limits the DC-link voltage fluctuations [27]. A coordinated control strategy is proposed to supply reactive power to the grid and assist the grid voltage recovery, which uses the GSC as the main reactive power controller and the RSC as auxiliary [28]. However, most of the control modification approaches show results for the symmetrical grid faults [18–28], whereas majority of the grid faults in the power system are asymmetrical. Moreover, all these approaches can improve the FRT capability of the DFIG in moderate voltage sags and they cannot solely limit the rotor inrush currents during the deep voltage sags [15–28]. Lopez et al. [29] presented a solution combining the crowbar and use of demagnetizing currents to improve the FRT capability of the DFIG during deep sags. But, this solution has a drawback too, because the RSC control is temporarily lost during the crowbar activation and the DFIG absorbs reactive power from the grid. In Table 1, the strategies to improve the FRT capability of the DFIG with their advantages and disadvantages are shown together.

In order to overcome the aforementioned problems, this paper proposes an efficient control strategy to improve the FRT capability of the DFIG during the symmetrical and asymmetrical grid faults. The proposed scheme consists of active and passive FRT compensators. The active compensator is carried out by determining the rotor current references to reduce the rotor over voltages. The passive compensator is based on the RCL arrangement located in series with rotor windings. It considerably reduces the rotor over current at the instants of occurring and clearing the grid faults with deep sags. By applying the proposed strategy, the rotor over currents, torque oscillations and DC-link over voltage are decreased and the FRT capability of the DFIG is increased. This paper has been organized as follow: in Section 2, DFIG system is described and in Section 3, DFIG model and behavior under grid faults is analyzed. In Section 4, the proposed FRT control strategy is discussed and in Section 5, the system simulation results are shown. Finally, the conclusion is presented in Section 6.

2. The DFIG WT system description

The schematic diagram of the grid-connected DFIG WT system is shown in Fig. 1. The DFIG control includes the RSC and the GSC controllers. The RSC controls the stator active and reactive power and the GSC regulates the DC-link voltage and generates an independent reactive power that is injected into the grid [30]. The most employed control method used in the DFIG is a vector control (VC). In this method, the stator active and reactive powers are controlled through the rotor current vector control. The phase angle of the stator-flux space vector is usually used for synchronizing the controllers. However, according to slow dynamic of the stator flux and producing a DC component in it during the grid faults, the accurate estimation of the stator flux position can be a critical problem. Therefore, in this paper, the stator-voltage-oriented frame (SVOF) is used for Synchronizing Controllers. As result, the stator active and reactive powers are expressed as [31]:

$$P_s = \frac{-3L_m}{2L_s} V_{ds} i_{dr} \tag{1}$$