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Low-Voltage Ride-Through Capability Improvement of DFIG-Based Wind Turbines

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***Abstract*:** *Since the usage of wind energy as a renewable energy source is increasing fast, there is a need to keep wind turbines connected to the grid during different grid faults. In this paper, a simple way for improving low voltage ride-through (LVRT) capability of variable speed wind turbines (WTs) equipped with a doubly fed induction generator (DFIG) is presented. To highlight the proposed technique, a doubly fed induction generator (DFIG) is considered as a wind turbine generator. The whole system is simulated in Simulink/ matlab software. The obtained results ensure that this way is effective in decreasing the fault currents and DC link voltage fluctuations. The voltage dip characteristics are discussed in accordance with international standards for wind turbines.*

Keywords: DC-link voltage, doubly fed induction generator (DFIG), low voltage ride through (LVRT), wind turbine.

I. INTRODUCTION

Doubly fed induction generators (DFIGs) are popular configurations for large variable-speed constant-frequency wind generator systems. Nowadays the installed capacity of existing wind power plant as well as the penetration level of new power plant is increasing. Among different renewable energy sources, wind energy has the major share due to their relative inferior cost. Using DFIG could achieve many advantages such as operation over a wide range of rotor speeds and decreasing the amount of power carried by the converter with substantial reduction in converter cost. The DFIG is currently the system of choice for multi-MW wind turbines. The aerodynamic system must be capable of operating over a wide wind speed range in order to achieve optimum aerodynamic efficiency by tracking the optimum tip-speed ratio [1]. Therefore, the generator's rotor must be able to operate at a variable rotational speed. The DFIG system therefore operates in both sub- and super-synchronous modes with a rotor speed range around the synchronous speed. The stator circuit is directly connected to the grid while the rotor winding is connected via slip-rings to a three-phase converter. For variable-speed systems where the speed range requirements are small, for example ±30% of synchronous speed, the DFIG offers adequate performance and is sufficient for the speed range required to exploit typical wind resources [2]. An AC-DC-AC converter is included in the induction generator rotor circuit. The power electronic converters need only be rated to handle a fraction of the total power – the rotor power – typically about 30% nominal generator power. Therefore, the losses in the power electronic converter can be reduced, compared to a system where the converter has to handle the entire power, and the system cost is lower due to the partially-rated power electronics. This chapter will introduce the basic features and normal operation of DFIG systems for wind power applications basing the description on the standard induction generator. Different aspects that will be described include their variable-speed feature, power converters and their associated control systems, and application issues. When a fault occurs into the grid, stator current increases and a voltage dip will appear at the generator terminals. In addition, excessive rotor current will flow due to the magnetic coupling between stator and rotor [1]. So, there is a need to improve the ability of wind turbines to remain connected to the grid during faults, which is termed as low-voltage ride-through (LVRT) capability [2]. Several studies have been done to improve LVRT capability of DFIG-based wind turbines. The most well-known method that is being used is the crowbar system [2]. Crowbar system comprises a set of resistors connected with the rotor side through power electronic devices in order to bypass the rotor side converter. By the crowbar system, rotor currents could be successfully reduced. However, when the rotor side converter is isolated by the crowbar, the DFIG behaves as a conventional induction generator [3]. Thus, it consumes reactive power from the grid leading to further decrease of grid voltage [4]. several control techniques and strategies have been proposed to fix these problems since now. However, most of these methods are too complicated for practical applications. This paper proposes a ride-through approach to fulfill the ride-through requirement in DFIG-based wind turbines. To ensure the validity of the proposed technique, the whole system is built using Matlab/Simulink software. Then, the effect of integrating proposed strategy on the stator and rotor currents during fault is studied. In addition, DC-link fluctuations is reduced through this strategy.

II. INVESTIGATED SYSTEM

A. System Description

A 9 MW wind farm consisting of six 1.5 MW wind turbines connected to a 25 kV distribution system exports

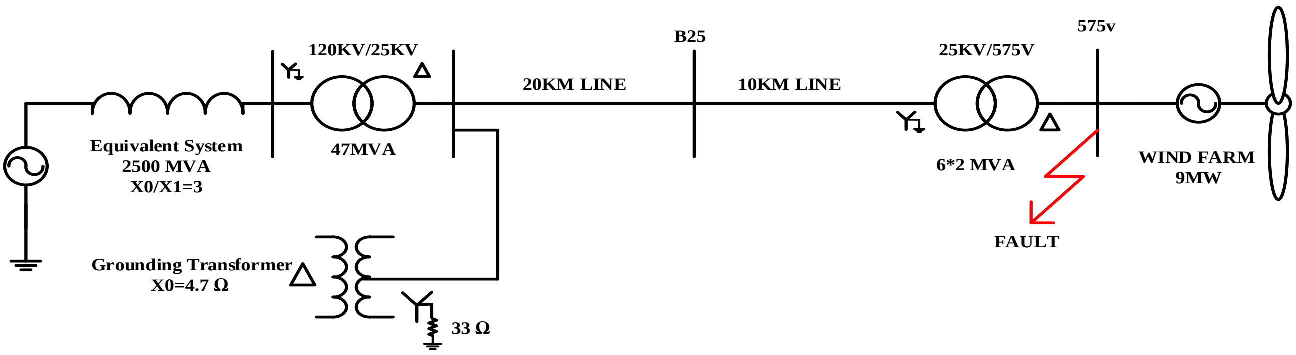


Fig. 1. Schematic diagram for the DFIG system under study

power to a 120 kV grid through a 30 km transmission line. Each wind turbine uses a doubly-fed induction generator (DFIG) consists of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter which is shown in Fig. 1. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. In this system, the wind speed is maintained constant at 10 m/s. The control system uses a torque controller in order to maintain the speed at 1.2 pu. The reactive power produced by the wind turbine is regulated at 0 Mvar [5].

B. DFIG-Based Wind Turbine Model

Detailed modeling of DFIG-based wind turbine is explained in the literatures. Here, only the important relations will be highlighted [2], [6]. The mechanical power extracted from the wind turbine is given by the following equation [6-8]:

$$P_{\omega} = 0.5 C_p A \rho V^3 \tag{1}$$

where C_p is the power coefficient, A is the swept area of rotor, ρ is the air density and V is the wind speed. The voltage equations of the stator and rotor circuits of the generator are expressed in the $d-q$ reference frame as follows [9]:

$$V_{ds} = R_s I_{ds} - \omega_s \lambda_{qs} + \frac{d\lambda_{ds}}{dt} \tag{2}$$

$$V_{qs} = R_s I_{qs} + \omega_s \lambda_{ds} + \frac{d\lambda_{qs}}{dt} \tag{3}$$

$$V_{dr} = R_r I_{dr} - (\omega_s - \omega_r)\lambda_{qr} + \frac{d\lambda_{dr}}{dt} \tag{4}$$

$$V_{qr} = R_r I_{qr} + (\omega_s - \omega_r)\lambda_{dr} + \frac{d\lambda_{qr}}{dt} \tag{5}$$

where λ is the flux linkage, ω is the angular frequency and R is the resistance per phase. The subscripts d and q denote the direct and quadrature axes, respectively, while the subscripts s and r denote the stator and rotor quantities, respectively [2]. In an induction machine the slip is defined as:

$$S = \frac{n_s - n_r}{n_s} \tag{6}$$

where ns and nr are the synchronous speed and the mechanical speed of the rotor respectively. The synchronous speed is given by [10]:

$$n_s = \frac{60 f_e}{p} \quad (rpm) \tag{7}$$

where p = number of pole pairs and fe is the electrical frequency of the applied stator voltage. The mechanical torque generated by the machine is found by calculating the power absorbed (or generated) by the rotor resistance component $Rr(1–s)/s$. This is shown to be [10-12]:

$$P_{mech} = 3\left|i_r{}^2\right|\left(\frac{1-s}{s}\right)R_r \tag{8}$$

In an ideal induction machine, we can ignore the rotor and stator phase winding resistance and leakage inductance. So the per-phase equivalent circuit becomes simple. By using this simplified circuit diagram, the mechanical torque production is [11]:

$$T_{mech} = 3\left|i_r'^2\right|\left(\frac{1-s}{s}\right)\frac{R_r'}{\omega_m} \tag{9}$$

III. PROPOSED STRATEGY

In this section, an improved strategy is proposed to satisfy grid codes for LVRT requirements. The layout of the proposed strategy is shown in Fig. 2. The proposed system consists of a switched series RC circuit and a conventional pitch angle controller.

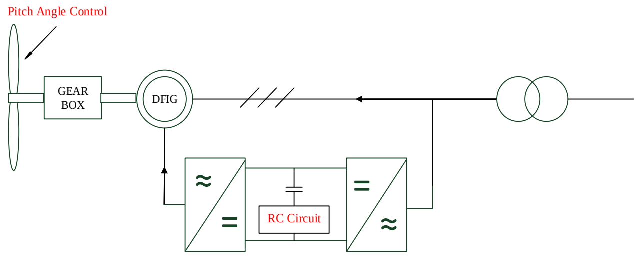


Fig. 2. The layout of the proposed strategy

A. Switched RC Circuit

In the back-to-back PWM converter of DFIG, the bidirectional power is transferred between the grid side and the generator rotor side. Under a constant dc-link voltage, the input power from the grid side should be equal to the input power of the generator rotor when ignoring the power losses of power electronic devices. When fault occures, the rotor-side converter runs at the energy feedback status, thus the grid-side converter can not feed more instantaneous power back to the grid so that the dc-link voltage will increase due to the overmuch instantaneous energy. So, the dc-link voltage may fluctuate because of the imbalanced power flow between the input and output instantaneous energy of the converter during the dynamic regulation of DFIG [7]. To reduce the DC link voltage fluctuations and dissipate the extra energy, a switched RC circuit series to the DC link capacitor is proposed. The RC circuit topology is shown in Fig. 3.

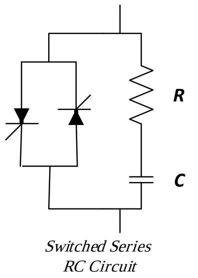


Fig. 3. Switched RC Circuit

B. Pitch Angle Control

The new control strategy will not cause excessive mechanical stress to the WT system. When the DFIG WT is operating at or close to the rated speed (12 m/s), the acceleration due to the proposed control scheme during the fault may accelerate the wind turbine speed above its rated value. This can increase the thrust and centrifugal forces, applied to the rotor construction that may endanger the wind turbine mechanical system. However, the over-speed of the WT can be effectively restrained by the pitch control, which will be activated immediately when the rotor speed becomes higher than the rated value. Due to the short duration and rare occurrence of grid faults, the duration of the over-speed is short. According to the thrust and centrifugal forces expressions, the negative impacts due to the proposed control strategy can be little to the safe operation of WTs [5]. This analysis will be verified by the simulation results in Section IV.

IV. SIMULATION AND RESULTS

The purpose of introducing the LVRT strategy is to ensure the DFIG can stay connected to the faulted grid by effectively limiting the stator and rotor circuit currents as well as the DC-link voltage. A symmetrical fault was considered at the integration point with the grid as shown in Fig. 1. The fault occures at 0.3 s and cleared after 120 ms which is shown in Fig. 4. During the fault, the terminal voltage drops to about 0.2 pu. For the results in this paper, the wind turbine operates at a wind speed of 10 m/s. The DFIG's reference reactive power is set to zero. For the switched RC circuit, a 6 Ω resistance and a 1μF capacitor were considered in this study. In normal operation, S1 is closed and the switched RC circuit is bypassed. When a grid fault is detected, the switch is turned off, and the RC circuit lies in series with the DC-link capacitor.

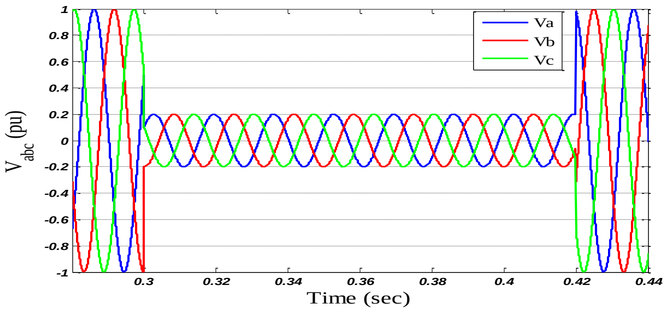
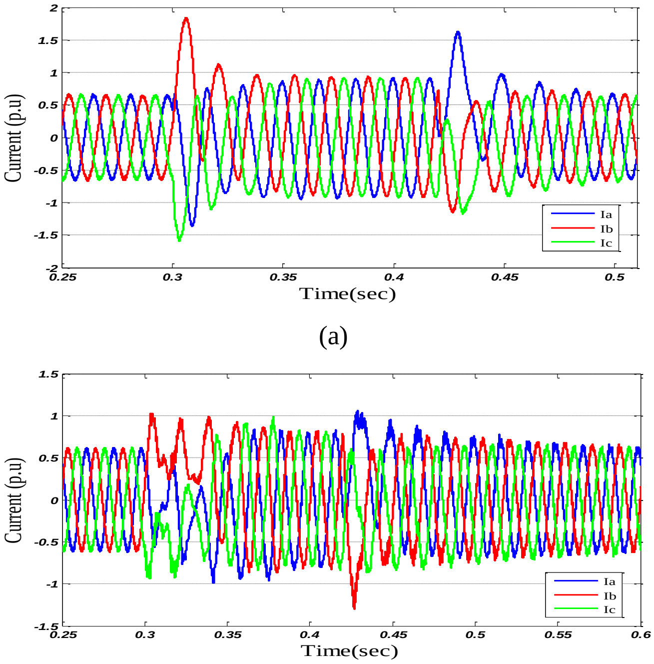


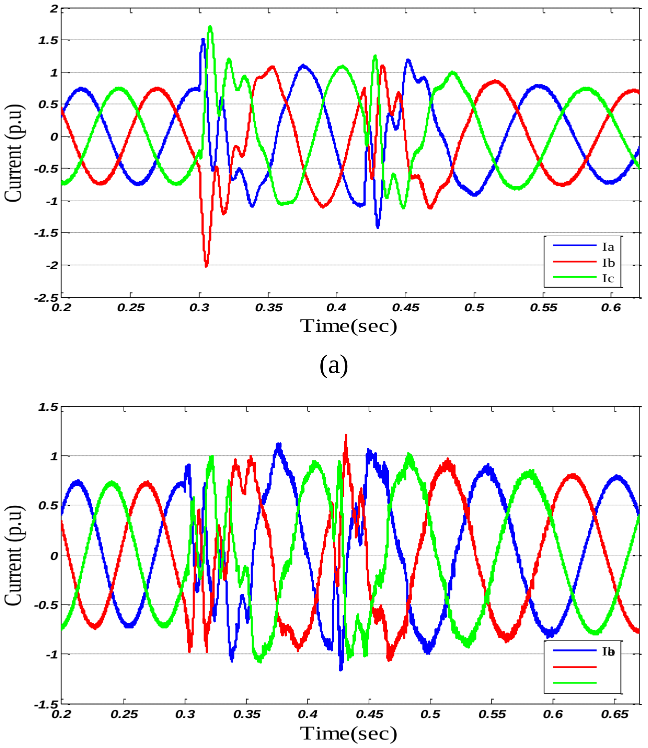
Fig. 4. Stator Vlotage



(a)

(b)

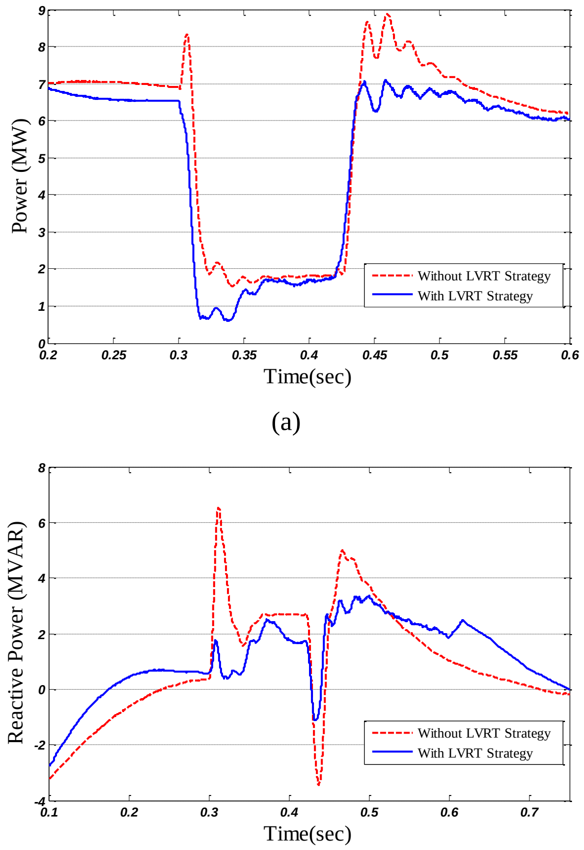
Fig. 5. Stator current behavior with and without LVRT Strategy. (a) Without LVRT Strategy. (b) With LVRT Strategy.



(a)

(b)

Fig. 6. Rotor current behavior with and without LVRT Strategy. (a) Without LVRT Strategy. (b) With LVRT Strategy.



(a)

(b)

Fig. 7. Active and reactive power responses: (a) Active power response. (b) Reactive power response.

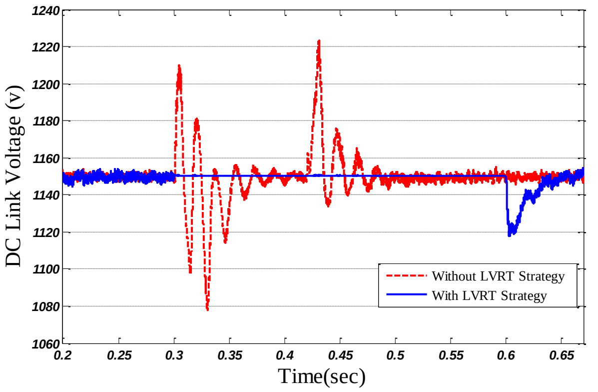


Fig. 8. DC Link Voltage

A. Stator Current Limitation Results

Fig. 5 shows the current limitation capability of the proposed strategy through illustrating the stator current behavior regarding the mentioned fault. As shown in Fig. 5(a), without connecting the RC circuit, the first peak of the stator current signal reaches about 1.4 p.u for phase a, 1.8 p.u for phase b and 1.55 p.u for phase c, where fault clearance normally results in transient components similar to its starting point of occuring fault but with less severity. After inserting the RC circuit as represented in Fig. 5(b), the fault peak current was limited effectively to about 1 p.u for each phase. The difference of peak of currents in corresponding behavior between phases is attributed to the different fault starting angles. It is important to note that the peak after fault clearance has also been decreased for all phases after connecting RC circuit. So, the overall dynamic performance of DFIG has been improved.

B. Rotor Current Behavior

Fig. 6 shows the change of rotor current under fault with and without RC circuit. After connecting RC circuit in the DC-link branch, the rotor current is limited to about 1.2 p.u by the effect of magnetic coupling between rotor and stator, while this current was about 1.8 to 2 p.u without RC. By adjusting the current limiting elements to a proper value, the rotor currents can be limited within their safety margins. This would prevent the rotor side converter from disconnection from the generator during faults and keep the wind turbine connected to the grid. Consequently, fault ride-through capability will be improved. Moreover, by using this strategy, the rotor current after fault clearance returns to its steady state value without any further oscillations.

C. Active and Reactive Power Behavior

Fig. 7 shows the active and reactive power responses with and without connecting the RC circuit. As shown in Fig. 7(a), without the proposed strategy the active power has a quick peak when fault occurs and clears; but with the added RC circuit, these quick oscillations are to a great degree reduced that causes a reduction in electromagnetic torque oscillations. In addition, the reactive power characteristics have been improved as shown in Fig. 7(b) after connecting RC circuit. The proposed strategy reduces the reactive power drawn from the grid.

D. DC Link Voltage Characteristics

Fig. 8 shows the DC-link voltage with and without the proposed strategy. This figure clearly shows the increase and decrease in the voltage when fault occurs and clears. The peak values reach about 1220 V and the voltage fluctuates during the fault; but with added RC circuit, these fluctuations are omitted.

V. CONCLUSION

The utilization of RC circuit to improve fault ride-through capability of DFIG has been proposed. The DFIG model integrated with RC has been built using Matlab/Simulink software. By using RC circuit, the rotor currents have been limited effectively and the minimum voltage level at the generator terminals has been increased leading to compliance with international grid codes. The reduction of rotor current has been reflected on the stator currents due to the magnetic coupling. In addition, the overall dynamics of DFIG, represented by active and reactive power have been improved. The obtained results pointed out the effectiveness of using RC circuit series with the DC-link capacitor in DFIG-based wind turbine.

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