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Dynamic Performance of DFIG Wind Turbine Subjected to Symmetrical Grid Faults

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ABSTRACT

The doubly fed induction generator (DFIG) is the one of the most commonly used wind turbine generator. The advantage of this type of generator is the use of partial rated converters at its rotor. The commonly implemented converter is the back to back converter. The main disadvantage of this type of wind turbine is that it is easily prone to grid voltage faults since its stator is directly connected to the grid. The balanced and unbalanced grid voltage faults lead to detrimental effects like torque and stator power oscillations, over-current in the rotor converter and over-voltage in the DC link capacitor. The wind turbine gets disconnected from the grid on the occurrence of the grid faults. This makes the grid more unstable. This paper proposes the novel compensation controller to withstand the above said fault conditions. The design of compensation controller provides good fault ride-through capability to the DFIG wind turbine. The laboratory model of 3 kW DFIG wind turbine is tested and the results are validated. The DFIG wind turbine provides good ride through capability both at super synchronous and sub synchronous rotor speed conditions.

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INTRODUCTION

Wind energy is one of the promising renewable energy in today's world. There are different types of wind turbine generator configurations in use. Each has its own merits and demerits. This paper focuses mainly on the DFIG based wind turbine (WT). In this type, the stator is directly connected to the grid and the rotor is connected to the grid by means of a power electronic converter. The converter can be either the back-to-back converter separated by a DC link capacitor or a matrix converter or an uncontrolled rectifier with a pulse width modulated (PWM) inverter separated by a DC link capacitor. There are many papers in the literature that investigates the performance of the DFIG and the rotor converters under normal conditions. Nevertheless, the WT connected to weak grid, always experience balanced and unbalanced grid voltage dips (Kearney, 2013). During this scenario, there are oscillations in torque and power of the DFIG, over-current in the rotor converter, and the oscillations in the DC link voltage. These effects mainly lead to tripping of the DFIG WT from the grid to protect the rotor converter and the DC link capacitor. However, the switching off the DFIG WT further weakens the grid. Hence, it is necessary for the WT to stay connected during the grid voltage dips. Therefore, in order to protect the DFIG WT and to damp the oscillations in power and torque, the protection circuit is necessary. This paper analyses the dynamic performance of the DFIG WT under the fault conditions. The paper proposes the design of the novel compensation controller to protect the DFIG WT subjected to symmetrical faults in grid voltage.

DFIG based Wind Energy Conversion System:

The DFIG WT is now the most commonly used types of wind generator. In this system, the stator is directly connected to the grid and the rotor is connected to the grid by a power electronic converter by means of slip rings and brushes, as shown in figure 1. The main advantages of this type are: decoupled control of active power and reactive power, maximum power point tracking, power factor control, use of partial rated converters, reduced size, reduced cost, and reduced losses (Bolik, 2002). The disadvantage of this type is that since the stator is directly connected to the grid, it is highly prone to grid voltage faults. This paper analyses the symmetrical grid voltage dip of the DFIG WT connected to back-to-converter. As seen from the figure 1, the

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rotor of the DFIG is connected to the grid by means of the back-to-back converter separated by a DC link capacitor. The space vector modulated (SVM) inverter I, connected between the DC link capacitor and the rotor windings, is called as the rotor side converter (RSC) (Petersson, 2005). The SVM inverter II connected between the DC link capacitor and the grid is called as the grid side converter (GSC). The main objective of the RSC is to maintain the required stator active power and reactive power. In addition, the main objective of the GSC is to maintain constant DC link voltage and unity power factor at the stator.

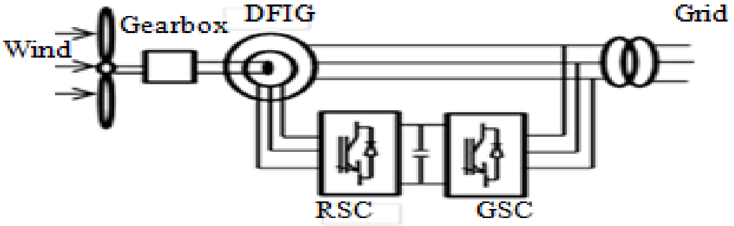


Fig. 1: Block Diagram of the DFIG Wind Turbine with the Back to Back Converter at the Rotor

The equations (1) and (2) gives the dynamic voltage and flux equations of the DFIG in the synchronous reference frame (Pena *et al.*, 2007).

$$\left.\begin{aligned}
v_{ds}{}^{e} &= r_s i_{ds}{}^{e} + \frac{d}{dt}\lambda_{ds}{}^{e} - \omega_s \lambda_{qs}{}^{e} \\
v_{qs}{}^{e} &= r_s i_{qs}{}^{e} + \frac{d}{dt}\lambda_{qs}{}^{e} + \omega_s \lambda_{ds}{}^{e} \\
v_{dr}{}^{e} &= r_r i_{dr}{}^{e} + \frac{d}{dt}\lambda_{dr}{}^{e} - (\omega_e - \omega_r)\lambda_{qr}{}^{e} \\
v_{qr}{}^{e} &= r_r i_{qr}{}^{e} + \frac{d}{dt}\lambda_{qr}{}^{e} + (\omega_e - \omega_r)\lambda_{dr}{}^{e}
\end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned}
\lambda_{ds}{}^{e} &= L_s i_{ds}{}^{e} + L_m i_{dr}{}^{e} \\
\lambda_{qs}{}^{e} &= L_s i_{qs}{}^{e} + L_m i_{qr}{}^{e} \\
\lambda_{dr}{}^{e} &= L_r i_{dr}{}^{e} + L_m i_{ds}{}^{e} \\
\lambda_{qr}{}^{e} &= L_r i_{qr}{}^{e} + L_m i_{qs}{}^{e}
\end{aligned}\right\} \quad (2)$$

$$\left.\begin{aligned}
P_s &= \frac{3}{2}(v_{ds}{}^{e} i_{ds}{}^{e} + v_{qs}{}^{e} i_{qs}{}^{e}) \\
Q_s &= \frac{3}{2}(v_{qs}{}^{e} i_{ds}{}^{e} - v_{ds}{}^{e} i_{qs}{}^{e})
\end{aligned}\right\} \quad (3)$$

The terms $v_{ds}{}^{e}$ and $v_{qs}{}^{e}$ represent the stator voltages in equation [1], $\lambda_{ds}{}^{e}$ and $\lambda_{qs}{}^{e}$ denote the stator flux linkages in equation [2], $v_{dr}{}^{e}$ and $v_{qr}{}^{e}$ represent the rotor voltages in the synchronous dq frame in equation [1], and $\lambda_{dr}{}^{e}$ and $\lambda_{qr}{}^{e}$ represent the flux linkages of the rotor in equation [2]. The terms ω_e and ω_r represents the angular velocities of the stator and rotor respectively. The superscript ’e’ denotes the synchronous reference frame. In this frame, all the alternating quantities (voltage, current and flux) in the three phase system appear as DC quantities, providing ease of control [Kanjiya *et al.*, 2013]. The equation [3] describes the stator active power and reactive power.

The DFIG WT generates power in both super-synchronous and sub-synchronous speeds either by absorbing or delivering power from/to the rotor (Lie Xu, 2008). During the super-synchronous speed, the stator and the rotor deliver active power to the grid. During the sub-synchronous speed, the stator delivers active power to the grid while the rotor absorbs the power from the grid via the GSC, the DC link capacitor and the RSC. In both ranges of the speed, the decoupled control of active power and reactive power is possible. It is also possible to maintain the stator at unity power factor. The maximum power is tracked between the cut-in and the rated wind speeds. The reference frame chosen for the vector control can either be the stator voltage oriented frame (SVO) or the stator flux oriented frame (SFO). In this paper, the SVO is chosen for active power and reactive power control. Similarly, the grid voltage oriented frame is chosen at the GSC controller to maintain DC link voltage constant (Song and Nam, 2007). By choosing the SVO in the RSC, the active power is controlled by regulating the d-axis rotor current, i_{dr}. The reactive power is controlled by regulating the q-axis rotor current, i_{qr}. The unity power factor is maintained by setting the reactive power reference, q_{ref} as zero.

Effects of balanced Grid Voltage Dips on the DFIG WT:

As discussed earlier in this paper, the stator of the DFIG that is directly connected to the grid is more prone to the grid voltage faults (Brekken and Mohan, 2003). The types of grid voltage faults can be balanced or unbalanced voltage swell/sag. This paper discusses only the balanced voltage sag. The balanced/symmetrical fault leads to the reduction in magnitude of the three-phase voltages. This fault results in the transient over-current at the rotor converter. This transient over current raises the DC link current across the capacitor (Zhou *et al*., 2007), thus damaging the RSC and the DC link capacitor. The DFIG WT disconnects itself from the grid, to protect the RSC and the DC link capacitor. The disconnection of DFIG WT further worsens the grid voltage conditions. In order to avoid this, an additional hardware circuit, commonly called as a crowbar, is provided in the RSC. This circuit protects the RSC and the DC link capacitor from the over-current and the over-voltage. The effect of the symmetrical faults is studied in Matlab/Simulink platform for the laboratory model 3 kW DFIG. The figure 2 shows the laboratory prototype of 3 kW DFIG WT. The figures 3-9, show the response of the system parameters like electromagnetic torque, stator current, rotor current, stator power, rotor power, DC link voltage and current subjected to symmetrical faults.

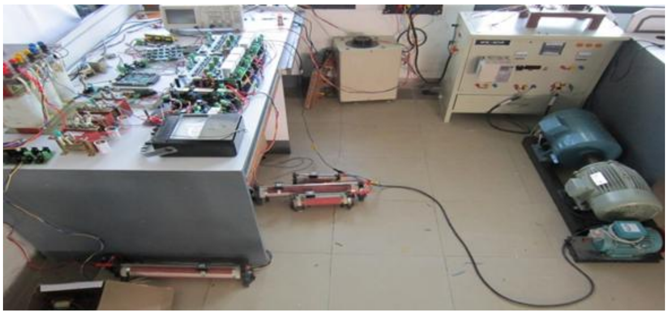


Fig. 2: Laboratory Prototype of DFIG Wind Turbine

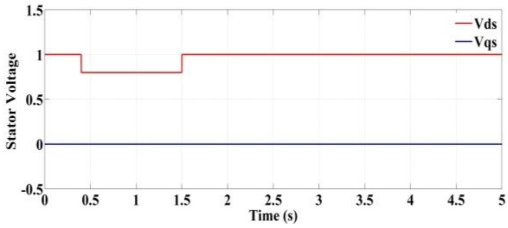


Fig. 3: Stator Voltage (V) vs. time (s)

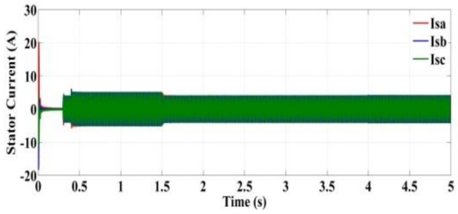


Fig. 4: Stator Current (A) vs. time (s)

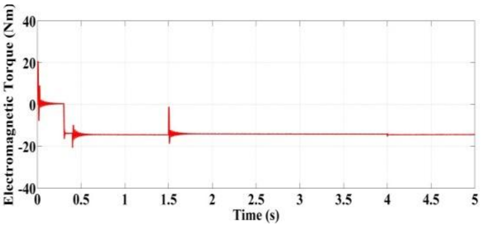


Fig. 5: Electromagnetic Torque (Nm) vs. time (s**)**

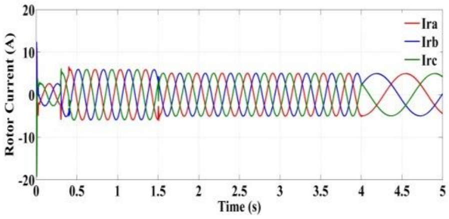
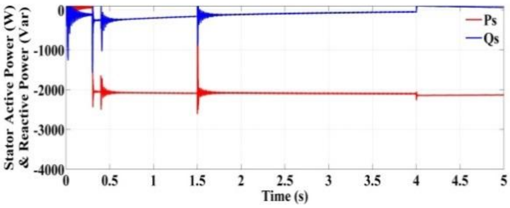


Fig. 6: Rotor Current (A) vs. time (s)



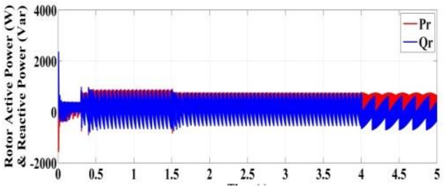


Fig. 7: Stator Active Power (W) and Reactive Power (VAr) **Fig. 8:** Rotor Active Power (W) and Reactive Power (VAr)

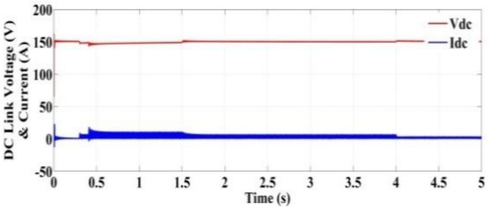


Fig. 9: DC link Voltage (V) and Current (A)

As seen in the figure 3, when the grid voltage dips to 0.8 p.u., the d-axis of the stator voltage experiences a reduction of 0.2 p.u. The effects of symmetrical faults are the rise of the stator current, rotor current, electromagnetic torque and is shown in figures 3, 4 and 5 respectively. The stator tries to absorb more reactive power from the grid during the fault time, t = 0.5 s to 1.5 s as seen in figure 6. During this period there is also a dip in the DC link voltage and the increase in DC link current, as seen in figure 8.

Design of Novel Compensation Controller for the DFIG WT subjected to Symmetrical faults:

As available in literature, the asymmetrical faults can be mitigated by the compensation controller. This does not require an external hardware circuitry. However, the mitigation of symmetrical faults requires the crowbar circuit in order to protect the DFIG WT. This paper introduces the design of novel compensation controller, which mitigates the symmetrical faults as shown in figure 10. This technique allows the elimination of the crowbar circuit. The proposed compensation controller forces the high rotor current to reduce. The Matlab/Simulink results in figures. 11-17, show the protection of the DFIG WT from symmetrical faults using the novel compensation controller.

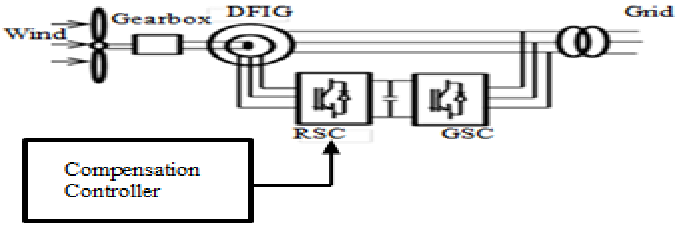


Fig. 10: Block Diagram of the DFIG Wind Turbine with the Compensation Controller at the Rotor Side Converter.

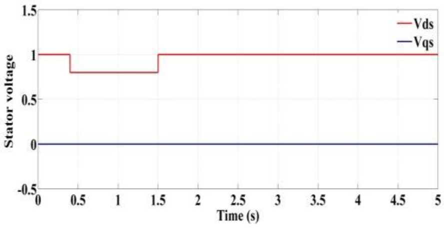


Fig. 11: Stator Voltage (V) vs. time (s)

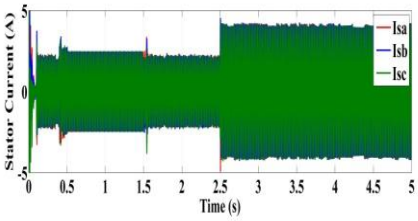


Fig. 12: Stator Current (A) vs. time (s)

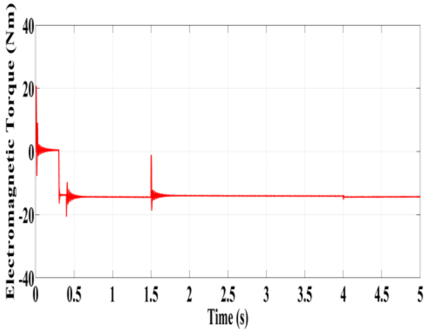


Fig. 13: Electromagnetic Torque (Nm) vs. time (s)

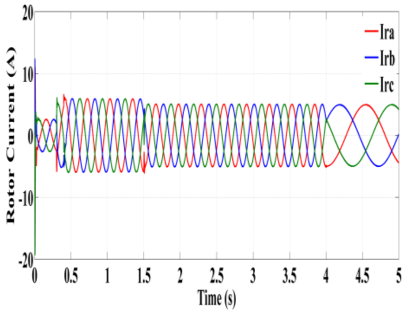


Fig. 14: Rotor Current (A) vs. time (s)

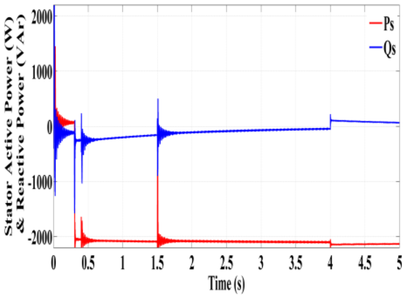


Fig. 15: Stator Active Power (W) and Reactive Power (VAr)

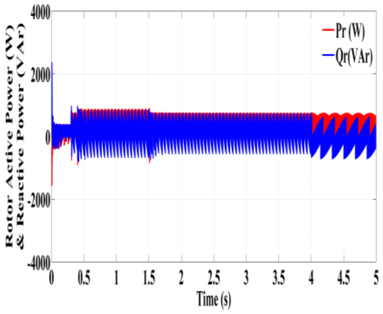


Fig. 16: Rotor Active Power (W) and Reactive Power (VAr)

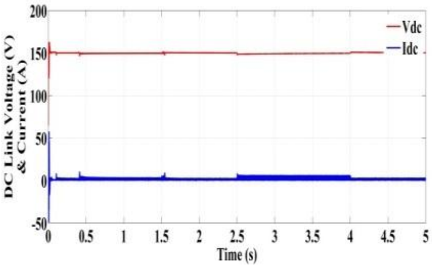


Fig. 17: DC link Voltage (V) and Current (A) vs. time (s)

RESULTS AND DISCUSSIONS

As seen from the figures 9 and 17, the rise in the rotor current and the DC link current is reduced by the compensation controller. The reduction in the rotor current and DC link current protects both the RSC and the DC link electrolytic capacitor. Thus, the proposed compensation controller replaces effectively the traditional hardware crowbar circuit and mitigates the symmetrical faults occurring in the DFIG WT. This allows the DFIG WT to stay connected to the grid under symmetrical fault conditions.

Conclusions:

As seen from the simulated results, the symmetrical faults impose severe effects on DFIG WT. The symmetrical fault is mitigated by crowbar resistance, which requires an additional hardware upgrade. The proposed compensation controller helps to eliminate the need of crowbar protection circuit and mitigates the symmetrical faults. Another advantage of the proposed controller is the oscillation in DC link current is reduced. By implementing this controller, the DFIG WT can ride through the symmetrical faults without any additional hardware. The power quality of DFIG WT is also increased by using this technique. Hence, this paper gives the complete understanding of the behavior of DFIG WT during the symmetrical voltage dip conditions and its mitigation measures.

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