



Application of STATCOM to improve the LVRT Capability of DFIG during VSC Fire-through

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ABSTRACT

Due to the convincing revolution in power electronic technology and the growing concern about greenhouse effect that is intensified due to the burning of fossil fuels, wind power generation is significantly increasing globally. Transmission line operators developed various grid codes that require wind turbines to remain connected to support power grids during intermittent disturbance events which motivated researchers to investigate the impact of various grid disturbances on the overall performance of the wind energy conversion system (WECS). No attention, however, has been given to investigate the impact of voltage source converter (VSC) faults on the low voltage ride through (LVRT) of the DFIG-based WECS. In this paper, the impact of a fire-through fault when it takes place within the RSC and the GSC on the LVRT capability of the DFIG are investigated. A STATCOM controller to mitigate the effects of these faults is proposed. The DFIG compliance with recently released LVRT grid codes under the studied faults with and without the STATCOM were examined and compared. Simulation results indicated that fire-through faults have a serious impact on the DFIG voltage profile, especially when they occur in the GSC. The proposed STATCOM controller is effective in improving the dynamic performance of the DFIG during the studied faults and hence the connection of wind turbine to the grid can be maintained.

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Introduction

The use of wind energy is growing rapidly and it is expected to provide ten percent of the global electricity generation by 2020 [1]. The implementation of the carbon tax in some countries is considered as a trigger to accelerate the utilization of renewable energy sources. In 2011 the global wind energy production market has increased by six percent than that in 2010 [2]. Among variable speed constant-frequency wind turbines, the doubly fed induction generator (DFIG) has been a popular candidate in the wind energy conversion systems (WECS) because of its advantages [3-6]. When compared to fixed-speed induction generators, the DFIG has the advantages of maximum power capture, less mechanical stresses, and less acoustical noise [4]. Compared with the full-converter variable-speed generators, the DFIG is a preferable choice in terms of size, cost, reduced losses and weight associated with the small converter [7]. The voltage source converters (VSCs) that interface the DFIG and the AC grid are rated at 30% of the generator power capacity for a rotor speed range of $\pm 30\%$ [8]. As the rotor side converter (RSC) operates at a low slip frequency range of $\pm 30\%$ of the line frequency, it can cause a high temperature variation and the power cycling capability of the IGBT bond wire can be reduced dramatically [9], and the whole IGBT-based system may easily fail [10]. Any problems caused to the IGBT or the controller circuit may result in rotor over-current. The common solution to protect the converter switches from DFIG rotor over-current is by connecting a crowbar circuit across the rotor terminals to isolate the converter from the rotor when rotor current exceeds the maximum safety margin.

The wind turbine breakdown is often attributed to defective / loose of mechanical components or to malfunction in the turbine control systems. Statistical surveys indicate that about 38% of power converter failures are due to converter switches while 53% of their failures are attributed to faults within converter control circuits [11, 12]. A recent industry-based survey concludes that the gate control circuits are the most susceptible components in converter faults [13]. Voltage source converters are subject to common faults such as fire-through [14-18]. These faults can be caused by various malfunctions in the control and firing equipment [15, 18]. Fire-through is the conduction of a switch before its programmed instant of conduction [15, 17, 19]. Although most internal converter faults are self-healed when the cause of these faults is of a transient nature [17], they can still have a detrimental impact on the overall performance of the DFIG-based WECS [20]. Researchers have given attention to the dynamic performance of the DFIG-based WECS during various grid disturbances such as load fluctuation, voltage sag and swell, and short circuit faults on the grid side [21-27]. There are some studies that have investigated the effect of internal converter faults on the performance of HVDC systems [28-30]. However, no attention has been given to investigating the impact of such fault on the performance of the DFIG-based WECS and its compliance with the recently developed grid codes.

Flexible AC transmission systems (FACTS) based power electronic converters such as static synchronous compensator (STATCOM) are currently being used extensively in power system applications because of their ability to provide flexible power flow control [31, 32]. STATCOM provides better reactive

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power support at low AC voltages when compared to static VAR compensator because the reactive power from a STATCOM decreases linearly with the level of AC voltage. STATCOM has the ability to provide reactive power during voltage collapse with rapid response as it has no delay associated with the thyristor firing [33].

This paper investigates the impact of the fire-through faults on the LVRT capability of the DFIG when it takes place either within the RSC or GSC. Compliance of the DFIG performance under fire-through faults with the LVRT codes of various recent grid codes is also investigated. A STATCOM controller is proposed to mitigate the impact of these faults and to maintain the PCC voltage constant through the fault duration.

System Under Study

The system shown in Fig. 1 is simulated to investigate proposed VSC faults in this paper. Fig. 1 shows the stator of DFIG is connected to the grid through a short transmission line and a coupling transformer, while the rotor windings are fed through back-to-back IGBT-based voltage source converters with a common DC-link capacitor and chopper to limit the over-voltage of the capacitor. The DFIG grid side converter (GSC) and rotor side converter (RSC) are controlled by a four quadrant vector control as detailed in [34, 35] and is briefly elaborated below.

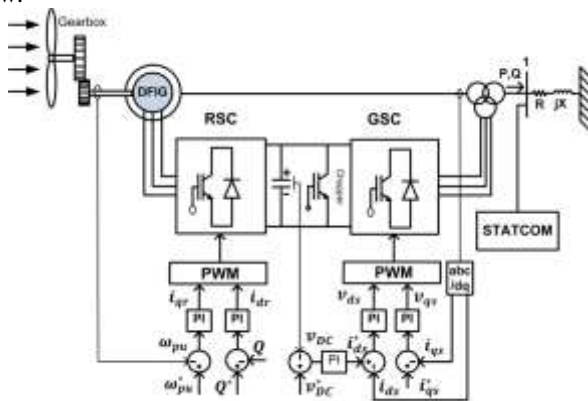


Fig. 1 Single line diagram of the system under study

GSC PWM Vector Control

The main task for GSC is to control the power exchange between AC grid and the DC-link to maintain the DC-voltage across the capacitor within permissible levels. In this context, a proper reference level for the d-axis stator current i_{ds}^* is created using the voltage error signal across the DC-link capacitor as an input to a proportional-integral (PI) controller while the q-axis reference current i_{qs}^* is assumed to be zero. Clarke-Park transformation [4] is used to convert the stator terminal currents from the a-b-c reference frame to the d-q reference frame (i_{ds} and i_{qs}) as shown in Fig. 1. The error signals of the stator d- and q- axes currents are used along with PI controllers to create appropriate d-q reference signals for stator voltages (v_{ds}^* and v_{qs}^*) that are used as inputs to the GSC pulse width modulation (PWM) circuit to create appropriate firing pulses to the GSC switches.

RSC PWM Vector Control

The RSC controls the generated active power according to the wind speed and the wind turbine characteristics while the reactive power command is set according to the utility requirements. A reference speed ω_{pu}^* is selected based on the wind turbine characteristics to track the maximum power, and it is compared with the measured rotor speed to create an error

signal that is fed to a PI controller to generate the q-axis rotor current i_{qr} . To achieve unity power factor operation, the reactive power reference is set to zero and is compared with the measured value to create an error signal that is fed to another PI controller to generate the rotor d-axis current i_{dr} . Currents i_{qr} and i_{dr} are used as inputs to the RSC PWM circuit to create appropriate firing pulses to the RSC switches.

Statcom Modeling

The STATCOM is a shunt-connected FACTS which works mainly as a regulating device that can bi-directionally exchange reactive power with the AC grid based on the grid requirement. The STATCOM has three main components: voltage source converter (VSC), coupling transformer and the control circuit. The VSC is modeled as a six-pulse PWM GTO converter with a DC-link capacitor. The interaction between the AC system voltage and the voltage at the STATCOM terminals controls the reactive power flow. If the system voltage is less than the voltage at the STATCOM terminals, the STATCOM acts as a capacitor and reactive power is injected from the STATCOM to the system. On the other hand, if the system voltage is higher than the voltage at the STATCOM terminal, the STATCOM behaves as an inductor and the reactive power transfers from the system to the STATCOM. Under normal operating conditions, both voltages are equal and there is no power exchange between the STATCOM and the AC system.

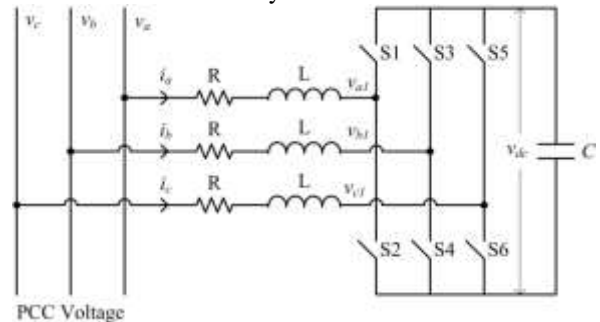


Fig. 2 The equivalent circuit of the STATCOM

The active and the reactive power exchange between the STATCOM and the AC system is controlled via the VSC firing angle α and the modulation index m to maintain the voltage at the point of connection and the DC-voltage within permissible limits.

A PI controller with the non-linear model of The STATCOM is used as detailed below:

Fig. 2 shows the STATCOM connected to the PCC in three-phase form, the differential equations for Fig. 2 in three-phase form can be written as

$$\begin{aligned}
 L \frac{di_a}{dt} &= -Ri_a + (v_a - v_{a1}) \\
 L \frac{di_b}{dt} &= -Ri_b + (v_b - v_{b1}) \\
 L \frac{di_c}{dt} &= -Ri_c + (v_c - v_{c1})
 \end{aligned}
 \tag{1}$$

where i_a , i_b , and i_c are the AC line currents of the STATCOM; v_a , v_b , and v_c are the PCC voltages; v_{a1} , v_{b1} , and v_{c1} are the inverter terminal voltages; R and L represent the equivalent conduction losses and the inductance for the transformer and the filter.

By considering the system parameters and the system voltages as a three-phase balanced system, the three-phase voltages and currents can be converted into a synchronously rotating d-q

reduced (Fig. 4). Fig. 7 shows that the DFIG terminal voltage experiences a voltage sag level of 20% of the nominal value during the fault and the generator voltage cannot be recovered after fault clearance. However, with the connection of the STATCOM and due to reactive power compensation, the voltage sag is reduced to only 3% during the fault and the voltage is recovered to its nominal steady state level after fault clearance.

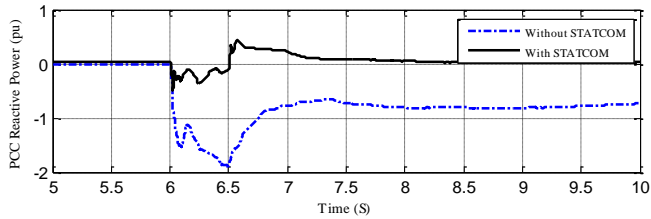


Fig. 4. PCC reactive power.

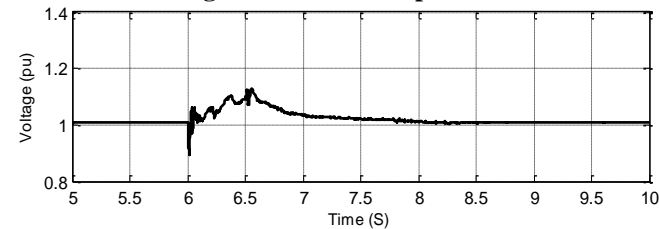


Fig. 5 The STATCOM converter terminal voltage.

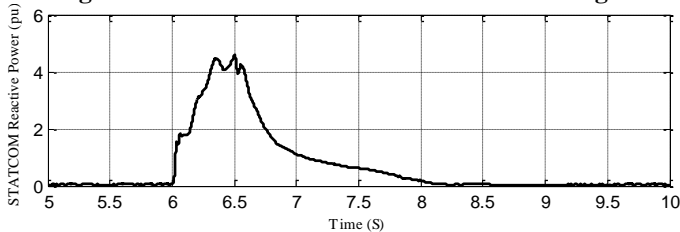


Fig. 6. The STATCOM reactive power.

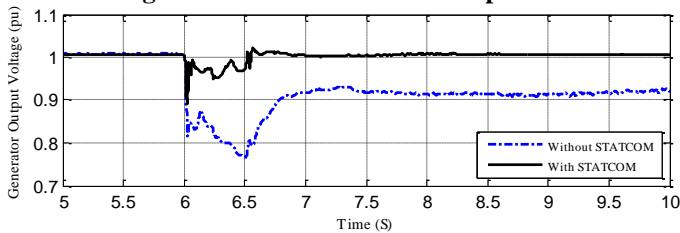


Fig. 7. Generator Terminal voltage.

The voltage at the PCC does not violate the LVRT of the all studied grid codes, however it will be on the margin of the lower level of the Denmark, Germany, US, and Ireland grid codes as shown in Fig. 8. The voltage recovery, due to the connection of the STATCOM, brings the voltage level to a safety level within all studied grid codes.

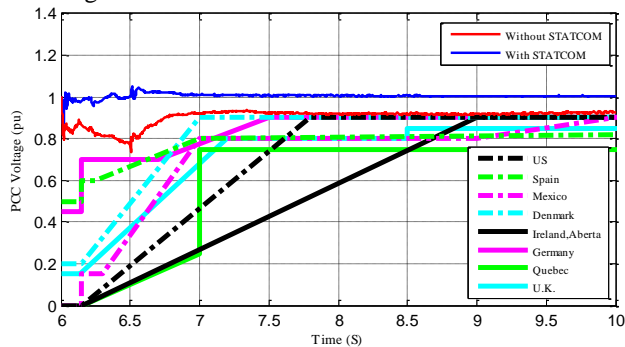


Fig. 8. PCC voltage compliance with various grid codes.

GSC fire-through fault

An intermittent fire-through was simulated on switch T3 of the GSC at $t = 6$ s as shown in Fig. 3. From Fig. 9 to 15 show the performance of the system under study during an intermittent fire-through within the GSC. Fig. 9 indicates during normal operating conditions, the DFIG output reactive power is maintained at zero level to achieve unity power factor operation as elaborated in section II. Upon fault occurrence at $t = 6$ s, the DFIG draws 2.65 pu reactive power from the grid for a few cycles, and it does not recover the steady-state zero level after the fault clearance. The proposed controller acts to increase the voltage at the converter terminals during the fault duration (Fig. 10). As a result, a reactive power support can be immediately provided by the STATCOM, and the reactive power (Fig. 12) at bus-1 of Fig. 1 can be regulated and maintained at zero level. Fig. 12 shows that the voltage at the generator terminal experiences voltage sag of 45% of its nominal value through the fault duration, and after fault clearing, the PCC voltage exhibits a steady-state error of 4% of its nominal value. This voltage sag is rectified and the voltage level can be maintained at its nominal value by regulating the reactive power using STATCOM.

Compared with the LVRT grid codes of the US, Spain, Mexico, Denmark, Germany, Quebec and the UK, the voltage at the PCC violates the LVRT level of Spain and Germany grid codes at the instant of fault clearance as seen in Fig. 13. This will call for the disconnection of the wind turbine from the grid to avoid any possible damages to the turbine. When the STATCOM is connected to the system and due to its reactive power compensation, the PCC voltage is brought to the nominal value, hence, the connection of the wind turbine can be maintained.

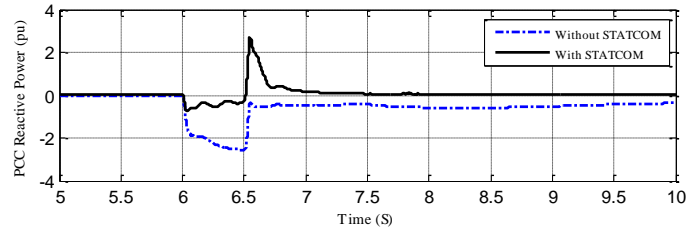


Fig. 9 PCC reactive power.

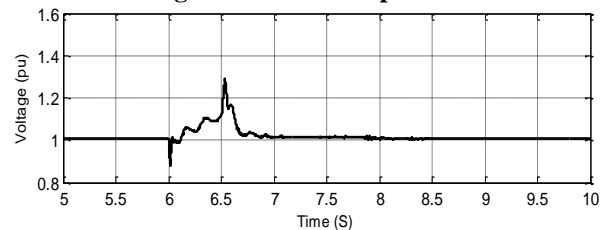


Fig. 10 STATCOM converter terminal voltage.

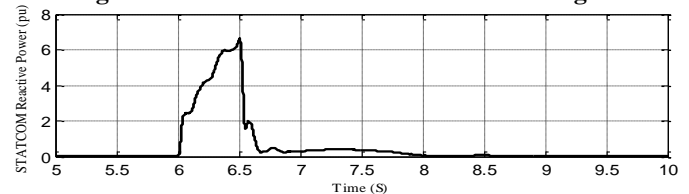


Fig. 11 The STATCOM reactive power.

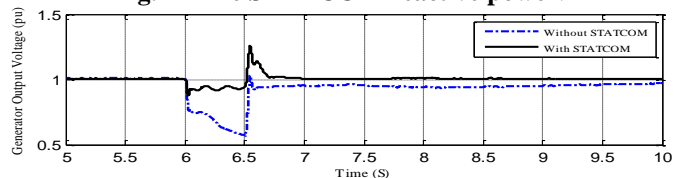


Fig. 12 Generator Terminal voltage.

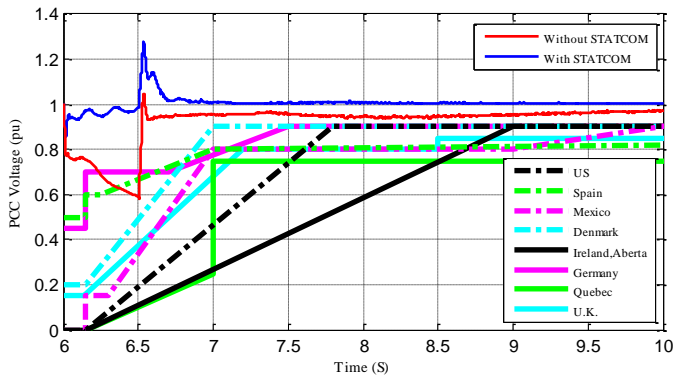


Fig. 13 PCC voltage compliance with various grid codes.

Conclusion

In this paper, a study has been performed to investigate the impact of RSC and GSC fire-through faults on the dynamic performance of a DFIG-based WECS. Compliance of the WECS under both faults with the LVRT of various grid codes has been also investigated. Results showed that RSC and GSC fire-through have significant impact on the overall performance of the WECS. The impact is worse when the fault occurs within the GSC which is directly connected to the grid.

A STATCOM controller is proposed to mitigate the impacts of the fire-through fault. Results show that the proposed controller is capable of bringing the voltage profile at the PCC to the nominal steady state level and maintaining the unity power factor operation of the DFIG through the faults duration.

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