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Fault Ride Through in Grid-connected WECS Using FACTS

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Authors' contributions

This work was carried out in collaboration between all authors. Author MAS designed the study. Author MNE performed the mathematical analysis, wrote the protocol and wrote the first draft of the manuscript and managed literature searches. Author SMI shared in simulation. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

This paper discusses the effectiveness of installing two types of FACTS devices, namely STATCOM and DVR to enhance the fault ride through (FRT) capability of a doubly fed induction generator (DFIG) applied in wind energy conversion systems (WECS). The response of the DFIG to a 3-phase ground fault is investigated with each of these devices. Comparing the stator and rotor voltages, stator and rotor currents, active and reactive power, of the two investigated systems is presented. PI controllers are employed to allow the rotor speed to follow the turbine speed and to adjust the applied rotor voltage magnitude and phase angle according to the wind turbine speed for maximum power tracking. This is achieved by controlling the two PWM converters connected between the rotor circuit and the electrical grid. Results showed a better FRT when using the STATCOM device with the DFIG.

Keywords: Fault ride through; DFIG; dynamic voltage restorer; STATCOM.

1. INTRODUCTION

Among the wind turbine concepts, the doubly fed induction generator (DFIG) is a popular wind turbine system due to its high energy efficiency, reduced mechanical stress on the wind

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turbine, separately controllable active and reactive power, and relatively low power rating of the connected converter [1], but due to the direct connection of the stator to the grid, the DFIG suffers from a great vulnerability to grid faults [2].Quite a few studies have been carried out to improve the LVRT capability of DFIG WT. Among the available approaches, protection devices such as crowbars are mostly used to bypass the rotor side converter once overloads are detected [3–5]. However, once the crowbar is enabled, the machine controllability will be lost and DFIG becomes a regular induction machine. In this case, instead of providing reactive power support to the grid, the generator absorbs large amounts of reactive power from the grid, which is not conducive to the grid recovery. There are other proposed solutions for fault ride through of DFIG using additional hardware like a series dynamic resistance in the rotor [6] and the stator [7], or using a series line side converter (LSC) topology as proposed in [8]. The use of a dynamic voltage restorer and superconducting fault-current limiter-magnetic energy storage system to enhance the LVRT capability of DFIG during grid faults were also investigated recently in [9-15].

In this paper the response of a WECS employing DFIG during 3 phase ground fault when applying a DVR and a STATCOM is investigated and results are compared. The comparison covers the stator and rotor voltage and current transients due to 3 phase ground faults. The response time to regain system stability is considered. A sudden drop in the grid voltage causes a large current to flow in the rotor, so comparing the ability of each device to limit this current is investigated. The affected system power factor, active and reactive power, and rotor speed are also investigated. The system is simulated using MATLAB software, and the results compared to conclude the better device for FRT.

2. MODELING OF DFIG SYSTEM WITH DYNAMIC VOLTAGE RESTORER (DVR)

Fig. 1 shows the general configuration of the DFIG system, while Fig. 2 shows the single line diagram of DFIG with DVR. To eliminate the switching harmonics generated by the back-to-back converter, a high frequency ac filter is connected to the stator side. The application of the DVR to enhance the FRT capability of the DFIG is investigated in which the DVR is a voltage-source converter (VSC) connected in series between the grid and the wind turbine generator. The DVR output voltage is added to the grid voltage instantaneously to achieve constant stator voltage under grid fault condition including balanced and unbalanced voltage dips. This device is able to eliminate the transient in the generator current and power at grid fault condition, hence the grid disturbances have no direct effect on the generator operation.

2.1 Voltage Sag Compensation

The DVR, shown in Fig. 2, consists of an IGBT Voltage Source Inverter (VSI), an energy storage device, and low-pass passive filter connected in series with the distribution system via a transformer. PWM strategy is employed for triggering the IGBTs of VSI. Low-pass passive filters are used to convert the PWM inverted pulse waveform into a sinusoidal waveform by removing the higher order harmonic components generated from the DC to AC conversion in the VSI. The high voltage side of the injection transformer is connected in series with the distribution line, while the low voltage side is connected to the DVR power circuit. The basic function of the injection transformer is to adjust the voltage supplied by the filtered VSI output to the desired level while isolating the DVR circuit from the distribution network.

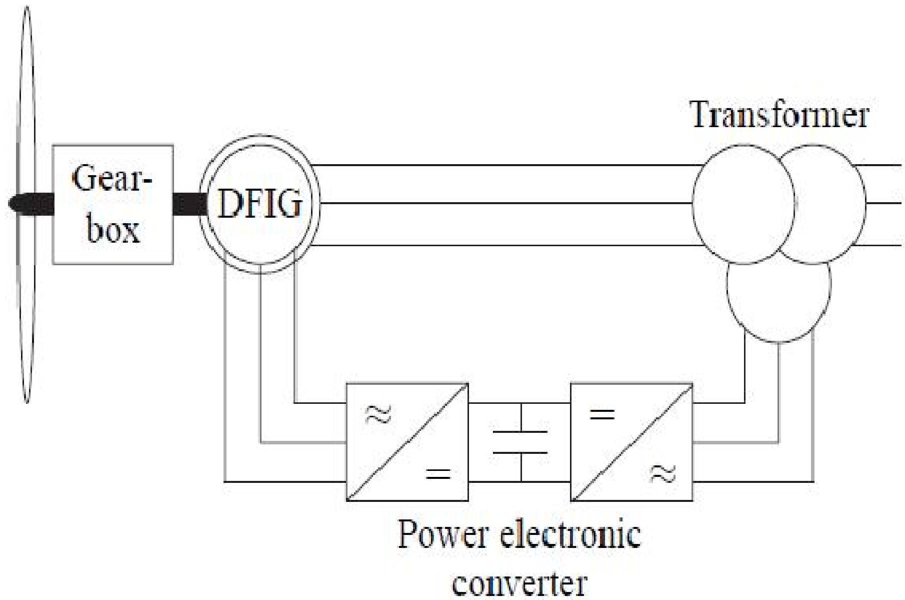

Fig. 1. DFIG general configuration

2.2 DVR Control Strategy

The aim of control technique of the DVR is to track the supply voltage and restore that to the pre-fault supply voltage during voltage sag or swell. Generally, voltage sags are associated with a phase angle jump in addition to the magnitude change. Thus, the control technique adopted should be capable of compensating for voltage magnitude, and phase shift. The adopted control scheme achieves the following functions:

i. Tracking the magnitude and phase angle of the supply voltage during normal operation to detect the occurrence of voltage sag or swell. This is achieved using software phase-locked loop (SPLL) technique.
ii. Computation of the correcting voltage.
iii. Generation of trigger pulses to the sinusoidal PWM based DC–AC inverter.
iv. Termination of the trigger pulses after voltage sag is fixed

The reference of the compensation voltage across the transformer to be injected by DVR can be expressed as follows:

$$\begin{bmatrix} v_{ca}^* \\ v_{cb}^* \\ v_{cc}^* \end{bmatrix} = \begin{bmatrix} v_{ga,\text{presag}} - v_{ga} \\ v_{gb,\text{presag}} - v_{gb} \\ v_{gc,\text{presag}} - v_{gc} \end{bmatrix} \tag{1}$$

where $V_{ga,\text{presag}}$ $V_{gb,\text{presag}}$, and $V_{gc,\text{presag}}$ are the voltages across the low-voltage side of the transformer before the voltage sag occurs, and V_{ga} , V_{gb} , and V_{gc} are those after the voltage sag occurs in the power system. This reference generation method is called a phase-invariant injection, and it is a very effective method for the DFIG since the DFIG is so sensitive to the phase jump of the grid voltage.

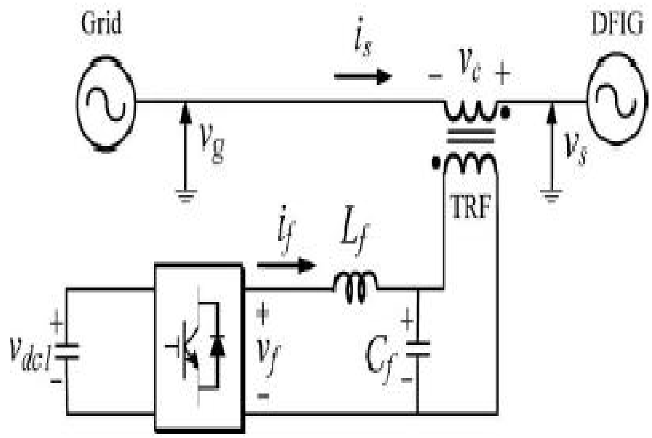

Fig. 2. Single line diagram of DVR

3. MODELING OF DFIG SYSTEM WITH STATCOM

STATCOM is a shunt-connected reactive power compensation device that is capable of generating or absorbing reactive power. 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-IGBT 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. 3 shows the STATCOM coupled with DFIG generation system.

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. The differential equations for Fig. 3 in three-phase form can be written as:

$$
\begin{aligned}
L\frac{di_a}{dt} &= -Ri_a + (v_a - v_{a1}) \\
L\frac{di_b}{dt} &= -Ri_b + (v_b - v_{b1}) \\
L\frac{di_c}{dt} &= -Ri_c + (v_c - v_{c1})
\end{aligned}
\tag{2}
$$

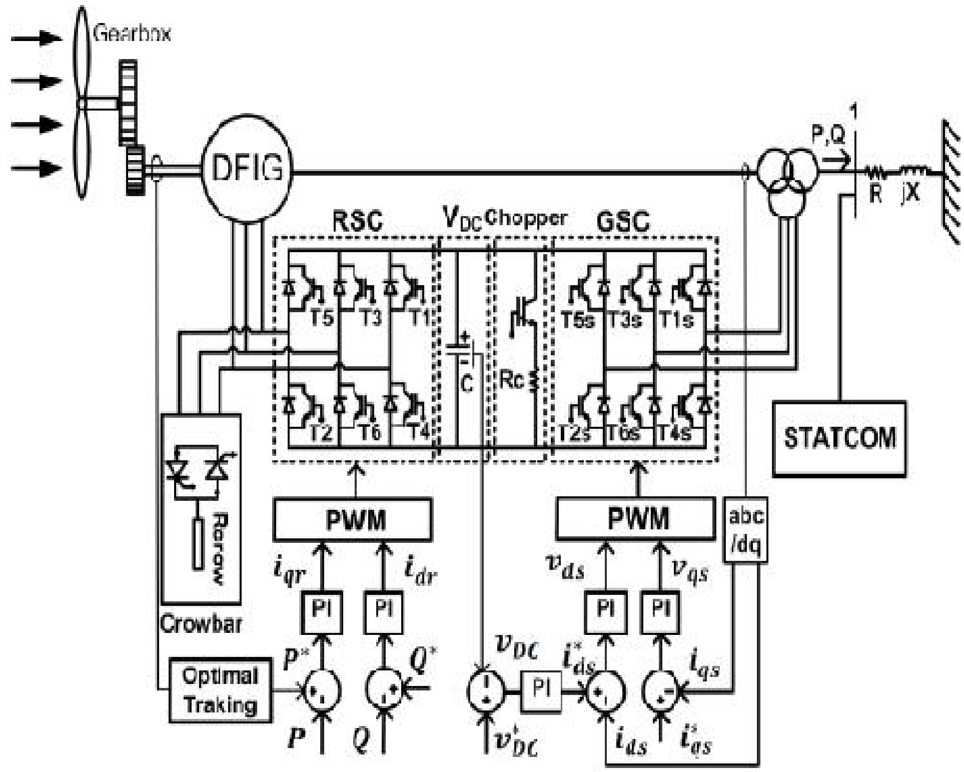

Fig. 3. Single line diagram of DFIG generation system with STATCOM

where i_a,i_b,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 frame. Equation (2) can be represented in the d-q frame as following:

$$L\frac{di_d}{dt} = -Ri_d + \omega L i_q + (v_d - v_{d1})$$
$$L\frac{di_q}{dt} = -Ri_q - \omega L i_d + \left(v_q - v_{q1}\right) \quad (3)$$

where ω is the synchronous angular speed of the fundamental system voltage. Neglecting the voltage harmonics produced by the inverter, and according to the PWM technique, the voltage at the inverter output terminals and the DC-side can be written as:

$$v_{d1} = Kmv_{dc}\sin\alpha$$
$$v_{q1} = Kmv_{dc}\cos\alpha$$

where K is the inverter constant, which can be determined by the inverter structure, m is the modulation index of the PWM, V_{dc} is the DC-voltage across the STATCOM capacitor, and α is the firing angle that controls the power flow between the STATCOM and the PCC. m and α are the PWM control variables which given by:

$$m = \frac{\sqrt{{v_{d1}}^2 + {v_{q1}}^2}}{Km}$$
$$\alpha = \tan^{-1}\frac{v_{q1}}{v_{d1}} \tag{5}$$

The instantaneous active and reactive power injected or absorbed at the PCC can be written as:

$$P = \frac{3}{2}\left(v_d i_d + v_q i_q\right)$$
$$Q = \frac{3}{2}\left(v_d i_q - v_q i_d\right) \tag{6}$$

while the instantaneous active power at the DC-side can be expressed as:

$$P = v_{dc} c \frac{dv_{dc}}{dt} \tag{7}$$

The system model given by the above equations, is used along with the PI controller to regulate the PCC and the DC-capacitor voltages.

4. SIMULATION RESULTS AND DISCUSSION

The performance of the two systems; that with DVR and that with STATCOM, during 3-phase fault occurring from t=0.2 till t= 0.3 are investigated, and results compared. Fig. 4a and 4b show the stator active and reactive power for the system employing the DVR and the system employing the STATCOM respectively. The smoother power profile for STATCOM is obvious, which proves the better system performance and lower transients. It is noticed that the series inductance of the DVR transformer prevents the power from reaching zero during the ground fault.

Fig. 5a and 5b show the stator current for the system employing the DVR and the system employing the STATCOM respectively. The current peaks are higher for DVR system within the whole fault presence time. This proves that the STATCOM helps in mitigating the transients which protects the generator from overheating.

Fig. 6a and 6b show the rotor current for the system employing the DVR and the system employing the STATCOM respectively. The current peaks are higher for DVR system as the fault starts and after it terminates. This proves that the STATCOM helps in mitigating the transients which protects the rotor converters from overheating.

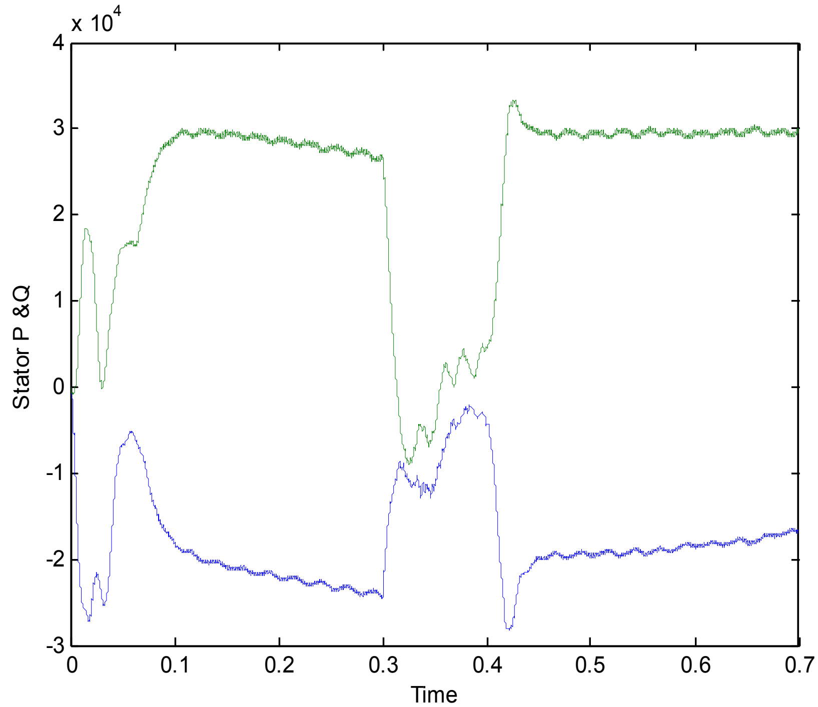

Fig. 4a. P and Q with DVR

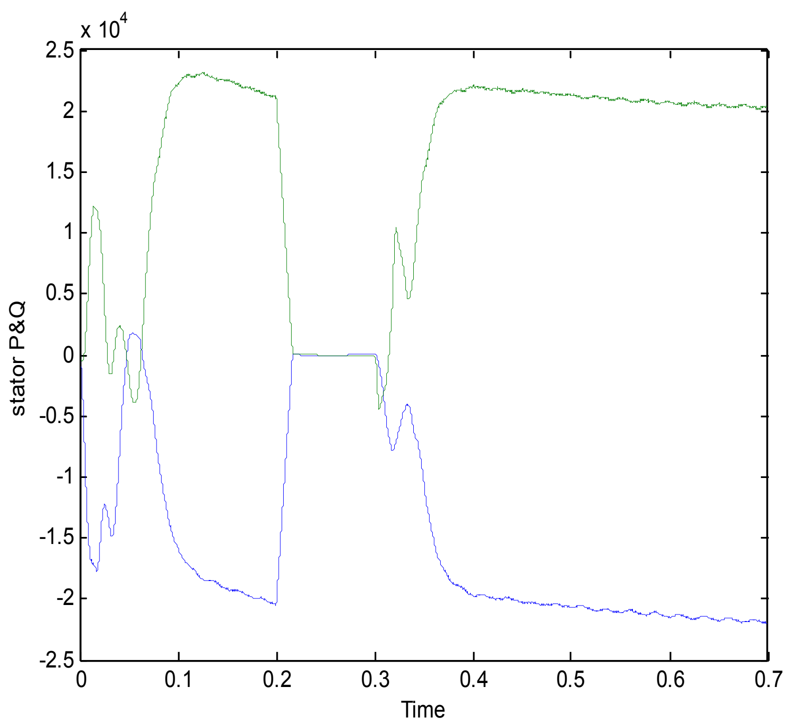

Fig. 4b. P and Q with STATCOM

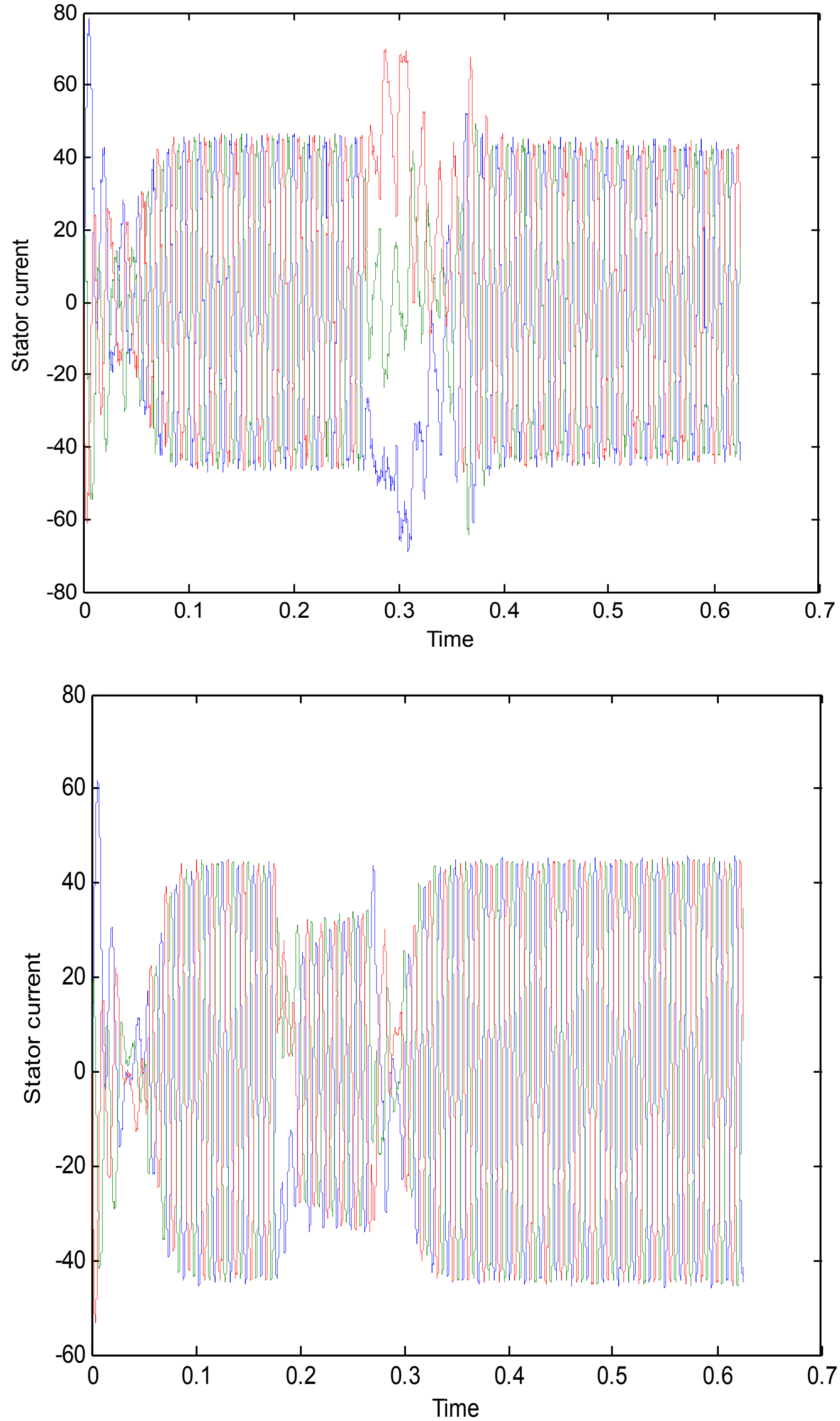

Fig. 5a and b. Stator Currents

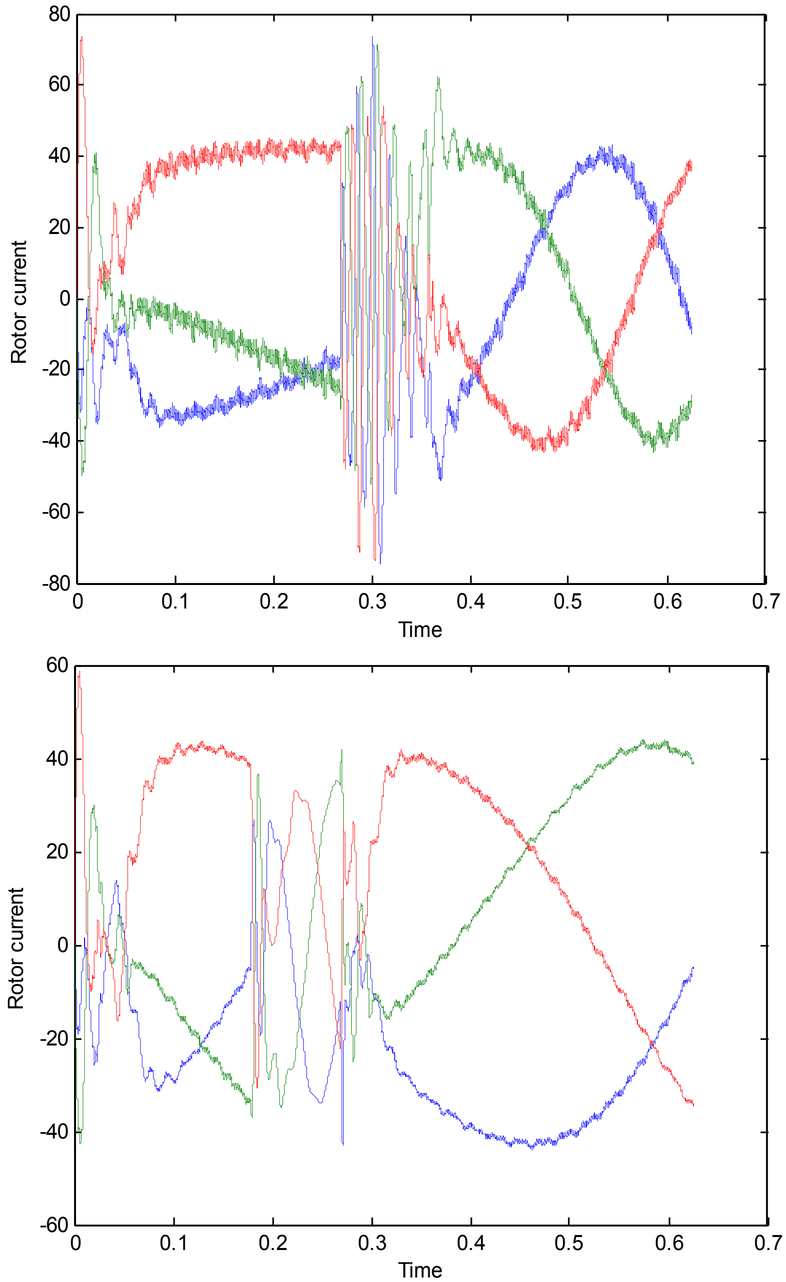

Fig. 6a and b. Rotor currents

Fig. 7a and 7b show the stator voltage for the system employing the DVR and the system employing the STATCOM respectively. The voltage reaches zero during the fault with the STATCOM device, while the series transformer inductance keeps an appreciable voltage magnitude during the fault with the DVR device. This result is in favor with DVR acting as protection for stator windings. However, this inductance increases the stator voltage to very high magnitudes which may damage the windings. This result is renders the STATCOM as better protection device.

Fig. 8a and 8b show the rotor voltage for the system employing the DVR and the system employing the STATCOM respectively. The two systems' responses are nearly the same due to isolation of rotor circuit from the applied FACTS devices. However, harmonics are higher in the system with DVR. Lower harmonics in the system with STATCOM means better power quality.

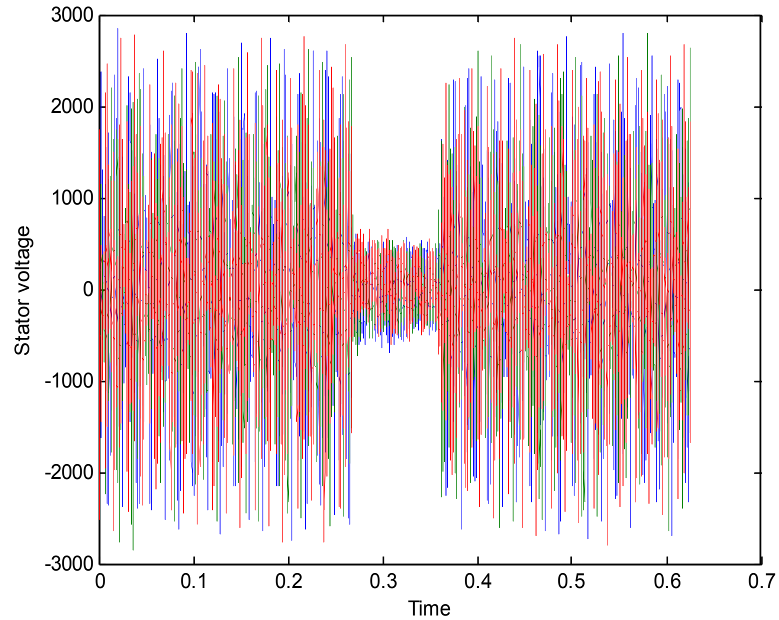

Fig. 7a. Stator voltage with DVR

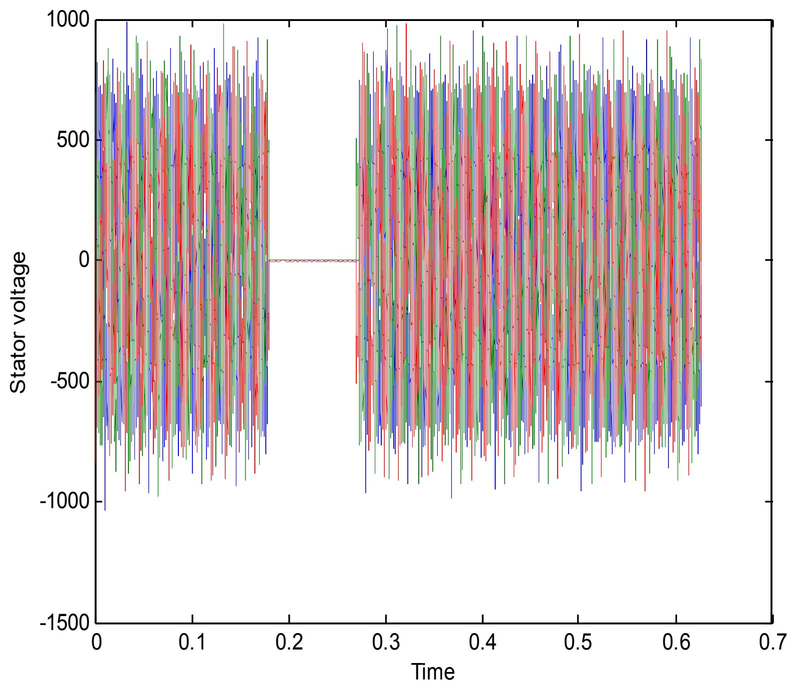

Fig. 7b. Stator voltage with STATCOM

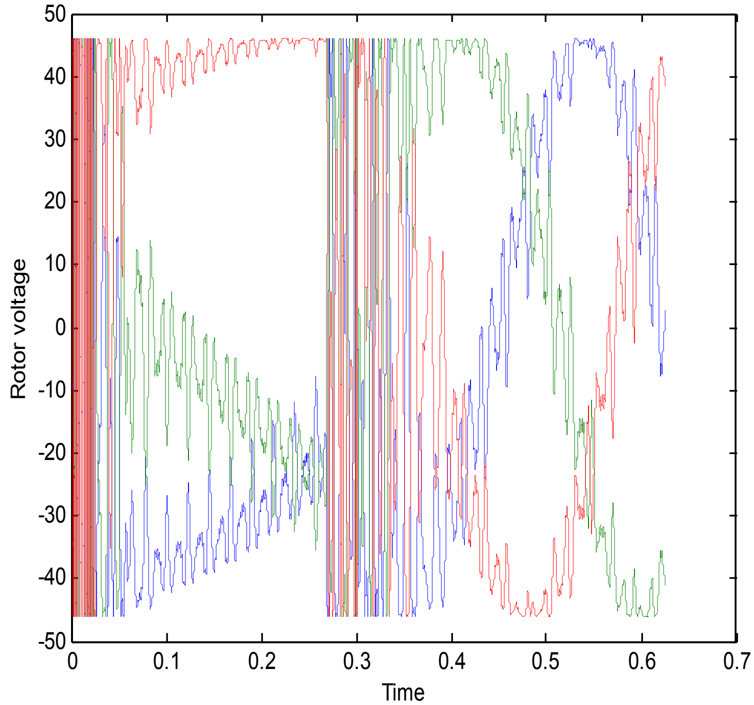

Fig. 8a. Rotor voltage with DVR

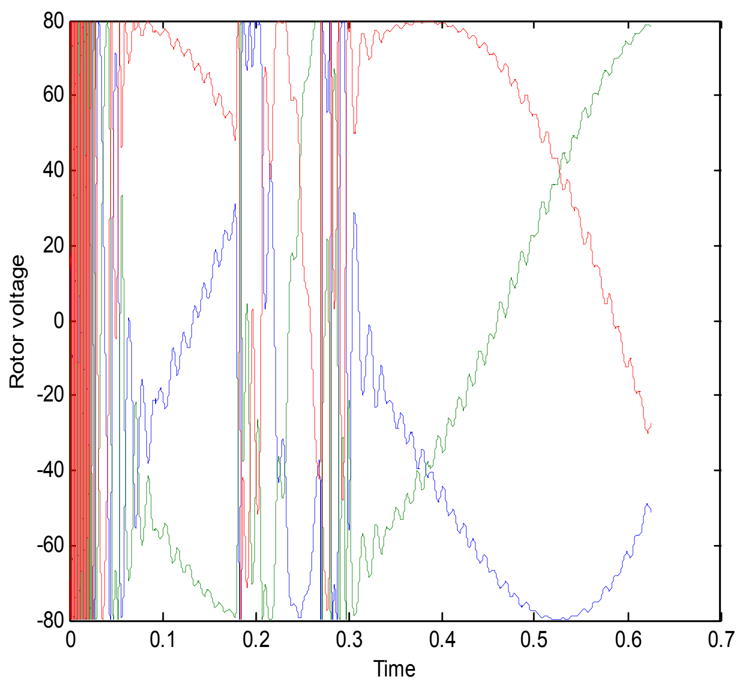

Fig. 8b. Rotor voltage with STATCOM

5. CONCLUSION

The fault ride through (FRT) capability of a doubly fed induction generator (DFIG) applied in wind energy conversion systems (WECS) is enhanced by applying DVR and STATCOM. PI controllers are tuned for MPPT and voltage adjustments. A comparison is done between the voltages, currents, active power, and reactive power for the generation system with DVR and that with STATCOM when a 3-phase ground fault occurs. The simulation results reveal the lower transients, lower system harmonics, and smoother power profiles for the system employing the STATCOM. The only merit for DVR application is the non-zero stator voltage, which provides protection for stator windings.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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