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Series Voltage Compensation Using UPQC For DFIG Wind Turbine Low-Voltage Ride-Through Solution

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Abstract:

This paper describes the problem of voltage sags and swells and its severe impact on sensitive loads and introduces a new solution for doubly fed induction generators to stay connected to the grid during voltage sags. The main idea is to increase the stator voltage to a level that creates the required flux to keep the rotor side converter current below its transient rating. To accomplish this goal, a series compensator (UPQC) is added to inject voltage in series to the stator side line. The series converter monitors the grid voltage and provides compensation accordingly to accomplish this aim. To keep the current at its minimum, a control strategy has been developed to keep the injected voltage and line voltage in phase during and after the fault. Comprehensive results are presented to assess the performance of each device as a potential custom power solution.

Index terms: **Doubly fed induction generator (DFIG), grid fault, low-voltage ride through, series voltage compensation, DVR, UPQC.**

1. Introduction

The DFIG is an induction machine with a wound rotor where the rotor and stator are both connected to electrical sources, hence the term 'doubly fed'. The rotor has three phase windings which are energised with three-phase currents. These rotor currents establish the rotor magnetic field. The rotor magnetic field interacts with the stator magnetic field to develop torque. The magnitude of the torque depends on the strength of the two fields (the stator field and the rotor field) and the angular displacement between the two fields.

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.

An easy way to protect the converter is to disconnect the generator during low-voltage conditions. But many regulations have been developed and are under development to support the grid during short circuits with reactive power and prevent disconnection to deliver power when the voltage is restored. Recently, many researchers have focused on different techniques to overcome the low-voltage ride-through (LVRT) issue.

There are many different methods to mitigate voltage sags and swells, but the use of a custom Power device is considered to be the most efficient method. Switching off a large inductive load or Energizing a large capacitor bank is a typical system event that causes swells [1].

When short circuit occurs on the grid side, the rotor currents rise and if the converter is not protected against these high currents, it will be damaged. The system has two modes of operation which are: the series voltage compensation using DVR. In this mode of operation, the voltage sags are mitigated but not completely. So in this proposed solution, the system using UPQC for series voltage compensation. In this method the voltage sags are completely mitigated. The use of the Clarke transform, the real (Ids) and imaginary (Iqs) currents can be identified. The Park transform can be used to realize the transformation of the Ids and the Iqs currents from the stationary to the moving reference frame and control the spatial relationship between the stator vector current and rotor flux vector.

2. conventional system configuration of upqc

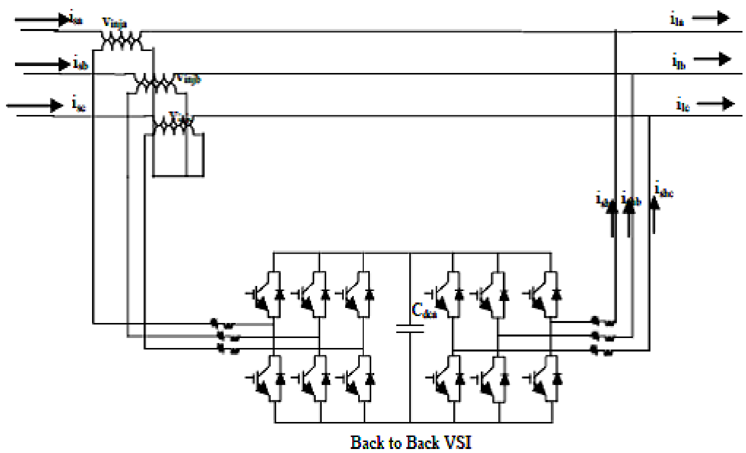

Fig.2.UPQC Block Diagram

The UPQC, realized by using two VSI is shown in Fig.2. One acting as a shunt APF, while the other as series APF. Both the APFs share a common dc link in between them. Each inverter is realized by using six IGBT (Insulated Gate Bipolar Transistor) switches. The voltage at the source side before UPQC, the load voltage at load, the voltage injected by series APF and the dc link voltage between two inverters are represented by v_s, v_L, v_{inj} and V_{dc} respectively. Whereas, the current on the source side, total current drawn by all the loads and the current injected by shunt APF are represented by i_s, i_l, and i_{sh} respectively.

DFIG during grid fault

Many references have discussed the modeling of DFIG wind turbines [8], [9]. Fig. 3 shows the block diagram of a DFIG wind turbine system. The generator has a three-phase wound rotor supplied, via slip rings, from a four-quadrant, pulse width modulation (PWM) converter with voltage of controllable amplitude and frequency [4].

A Park model in the stationary stator-orientated reference frame, developed for DFIG in [10], is used to analyze the effect of grid fault on the generator. In this model, the rotor variables are referred to the stator side for simplicity. Using motor convention, the stator and rotor voltages in *abc* frame can be expressed as

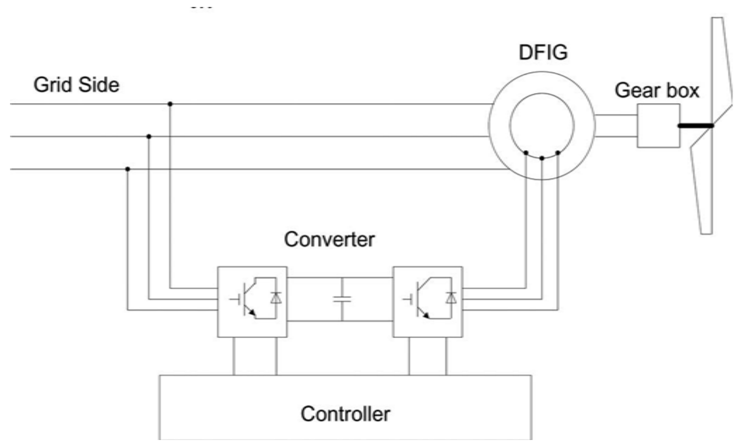

Fig. 3. Steady-state operation of the Doubly-Fed Induction Generator (DFIG)

$$\overrightarrow{Vs} = Rs\overrightarrow{is} + \frac{d}{dt}\overrightarrow{\Psi s} \quad (1)$$

$$\overrightarrow{Vr} = Rr\overrightarrow{ir} + \frac{d}{dt}.\overrightarrow{\Psi r} - j\omega m\overrightarrow{\Psi r} \quad (2)$$

The stator and rotor fluxes are given by

$$\overrightarrow{\Psi s} = Ls\overrightarrow{is} + Lm\overrightarrow{ir} \quad (3)$$

$$\overrightarrow{\Psi r} = Lr\overrightarrow{ir} + Lm\overrightarrow{is} \quad (4)$$

Where Ls=(Lls+ Lm) and Lr=(Llr+ Lm)

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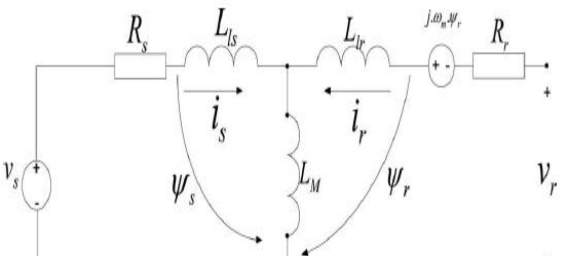


Fig.4. DFIG-equivalent circuit for short circuit analysis.

Fig. 4 shows the equivalent circuit corresponding to the aforementioned equations. For the purpose of the rotor over-current analysis during the short circuit, the rotor voltage from converter point of view is the most important variable in the analysis [10]. This voltage is induced by the variation of the stator flux, which can be calculated by deriving $\overrightarrow{is}$ from (3) and substituting into (4):

$$\overrightarrow{\Psi r} = \frac{Lm}{Ls}\overrightarrow{\Psi s} - \sigma Lr.\overrightarrow{ir}, \quad \sigma = 1 - \frac{Lm^2}{Ls.Lr} \qquad (6)$$

The rotor voltage given by (6) can be divided into two terms. The first term is the open circuit voltage (_*vr*0) and it depends on the stator flux. The second term is smaller and it is caused by the voltage drop on both the rotor resistance *Rr* and the rotor transient inductance σLr . From (6), when there is no current in the rotor circuit, the rotor voltage due to the stator flux is (_*vr*0):

$$\overrightarrow{Vro} = \frac{Lm}{Ls}\left(\frac{d}{dt} - j\omega m\right)\overrightarrow{\Psi s} \qquad (7)$$

A. Analysis under normal operation

Under the normal condition, rotor current control technique is utilized to adjust the active and reactive power at the generator terminal. The rotor current phase and magnitude are controlled to regulate the reactive power at zero and keep the generator running at unity power factor. Sensed wind speed is used to determine the reference active power of the turbine. Under normal operation, the rotor voltage can be described as

$$\overrightarrow{Vr} = \overrightarrow{Vs}\frac{Lm}{Ls}s + \left(Rr + \sigma Lr\left(\frac{d}{dt} - j\omega m\right)\right)\overrightarrow{ir} \qquad (8)$$

Where s is the slip (s= $\frac{\omega r}{\omega s}$, $\omega r = \omega s - \omega m$).

The rotor resistance and the transient reactance are typically small. In addition, since the generator slip is limited to +-30%, the rotor current frequency is $fr < 18$ Hz [10]. As a result, the magnitude of *Vri* in (8) is smaller than *Vr*0 . The rotor voltage due to the stator flux can be written as [10]

$$\overrightarrow{Vro} = j\omega r\frac{Lm}{Ls}\overrightarrow{\Psi s} = \frac{\omega r}{\omega s}\frac{Lm}{Ls}Vs e^{j\omega m t} \qquad (9)$$

The amplitude of the voltage _*vr*0 can be described as a function of the amplitude of the stator voltage as follows:

$$Vr0 = Vs\frac{Lm}{Ls}s \qquad (10)$$

During the normal operation, the rotor voltage $\overrightarrow{Vro}$ depends on the magnitude of the stator voltage and the slip.

B. Analysis During Short Circuit

At the moment of the short circuit ($t0 = 0$), the open circuit rotor voltage due to the stator flux is given by

$$\overrightarrow{Vro} = -\frac{Lm}{Ls}\left(\frac{1}{Ts} + j\omega m\right).\overrightarrow{\Psi o}.e^{-t/Ts}, \overrightarrow{\Psi o} = \frac{Vs}{j\omega s}e^{j\omega s to} \qquad (11)$$

where Ψ0 is the stator flux just before the short circuit.

$$\overrightarrow{Vro} = -\frac{Lm}{Ls}\left(\frac{1}{Ts} + j\omega m\right).\overrightarrow{\Psi o}.e^{-t/Ts}\,e^{-j\omega st} \qquad (12)$$

Using (12) and neglecting the term $1/\tau s$ due to its small value ($\tau S \approx 1s - 3s$) for a 1-MW machine and larger [7], [11], we have

$$Vro = \frac{Lm}{Ls}\frac{\omega r}{\omega s}Vs = \frac{Lm}{Ls}(1-s)Vs \qquad (13)$$

According to (13), *Vr*0 is proportional to 1 – *s*.

3. proposed method

In this paper, we present a solution to use a UPQC on the stator terminal of a DFIG to mitigate the effect of the short circuit on the wind turbine. This UPQC as shown in Fig. 2, acts the same as a series active filter for voltage compensation. The UPQC internally consists of DVR and DSTATCOM which are used to mitigate the effects of unbalanced short circuit faults on the turbine. The UPQC delivers active power for a very short period. The UPQC continuously monitors the grid side voltage. When this voltage dips, the UPQC applies a voltage through series transformer to compensate for the voltage dip. The level of voltage compensation depends on the rating of the UPQC. Since the UPQC is considered to apply voltage for a very short period of time. The UPQC need to compensate for 100% of line voltage during short circuit.

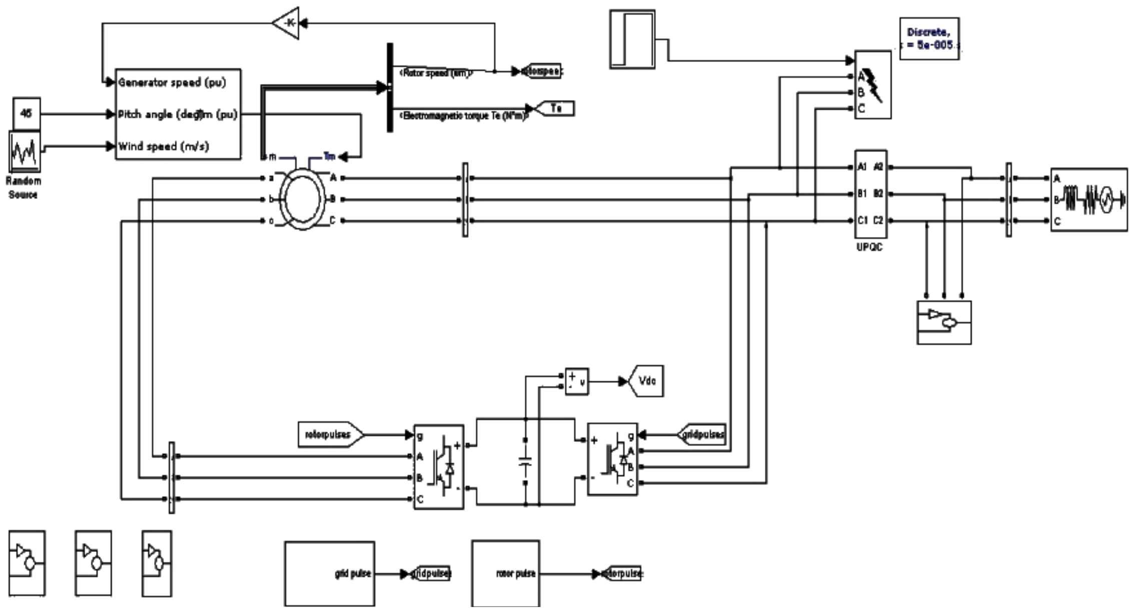


Fig1 : Simulink diagram of the series converter for the proposed LVRT solution

The main function of a UPQC is the protection of sensitive loads from voltage sags/swells coming from the network. Therefore as shown in Figure 1, the UPQC is located on approach of sensitive loads. If a fault occurs on other lines, UPQC inserts series voltage and compensates load voltage to pre fault value. The momentary amplitudes of the three injected phase voltages are controlled such as to eliminate any detrimental effects of a bus fault to the load voltage *VL*. This means that any differential voltages caused by transient disturbances in the ac feeder will be compensated by an equivalent voltage generated by the converter and injected on the medium voltage level through the booster transformer.

The UPQC works independently of the type of fault or any event that happens in the system, provided that the whole system remains connected to the supply grid, i.e. the line breaker does not trip. For most practical cases, a more economical design can be achieved by only compensating the positive and negative sequence components of the voltage disturbance seen at the input of the UPQC.

Fig. 8 shows the simulation results for the system behavior during a symmetrical three-phase short circuit at $t = 0.3$ s. The rotor current rises to 5 p.u. and the dc-bus voltage rises approximately to 1.6 p.u. as well. During the short circuit, the electromagnetic torque spikes approximately to 2.5 p.u. Active power, reactive power, and torque reduce to zero after a transient. These short circuit characteristics are what make the system very venerable to short circuit.

Fig. 9 shows the system behavior with voltage compensation. The simulation result reveals the effectiveness of the DVR for keeping the rotor current under rated value at the moment of short circuit. The series converter does not need to compensate with a 100% magnitude decaying voltage. The initial converter voltage can be less than 100%. However, this will cause the rotor current to rise.

Fig. 10 shows the simulation results for a voltage compensation. The results show that the effectiveness of the UPQC for keeping the rotor current under rated value at the moment of short circuit. The series converter need to compensate with a 100% magnitude decaying voltage. The proposed solution of voltage compensation guarantees successful voltage ride though with a smaller energy storage requirements and smaller series converter rating.

4. Control technique

In this section, the control technique for the UPQC is described. The measured grid voltages (*Vsa* , *Vsb* , and *Vsc*) are converted into the stationary reference frame voltage quantities

(*Vsα* and *Vsβ*) using the following transformation [6]

$$\begin{bmatrix} Vs\alpha \\ Vs\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} Vsa \\ Vsb \\ vsc \end{bmatrix} \qquad (32)$$

Then, the stationary reference frame voltage quantities are converted into the synchronous rotating reference frame voltage quantities (*Vsd* and *Vsq*) rotating by the grid voltage angle of θ. A phase lock loop (PLL) is used to generate the grid voltage angle

$$\begin{bmatrix} Vsd \\ Vsq \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} Vs\alpha \\ Vs\beta \end{bmatrix} \qquad (33)$$

The synchronous rotating reference frame voltage components (*Vsd* and *Vsq*) are compared with the desired voltage to produce the reference voltage for voltage regulator as shown in Fig. 11. During normal operation, the compensator is not injecting any voltage. In this case, if the capacitor is charged at its predetermined voltage, the compensator operates at standby mode. Otherwise, it will charge the capacitor from the line.

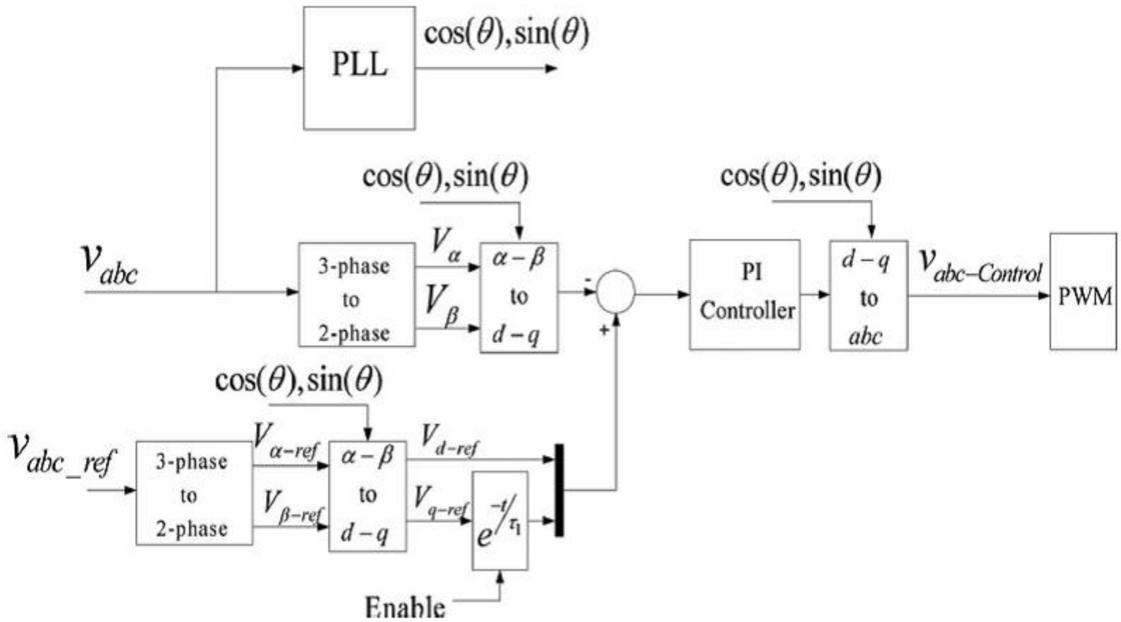
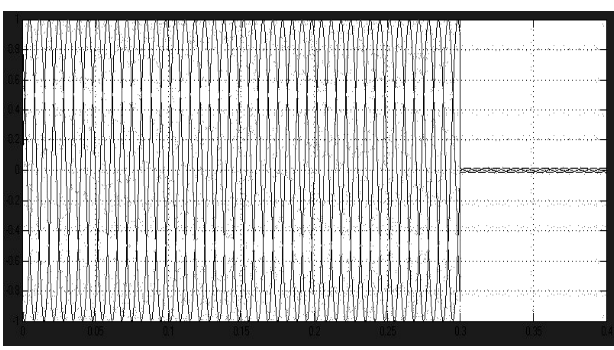


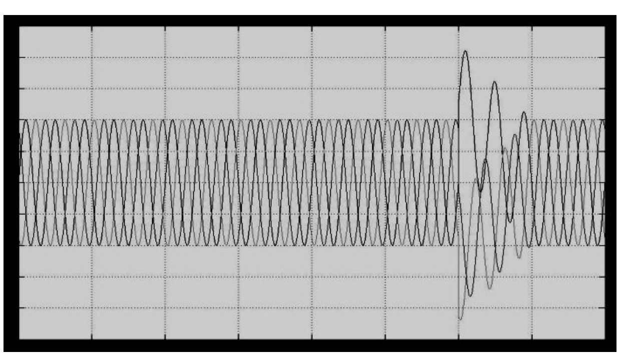
Fig. 11. Block diagram of the converter control technique.

5. simulation results:

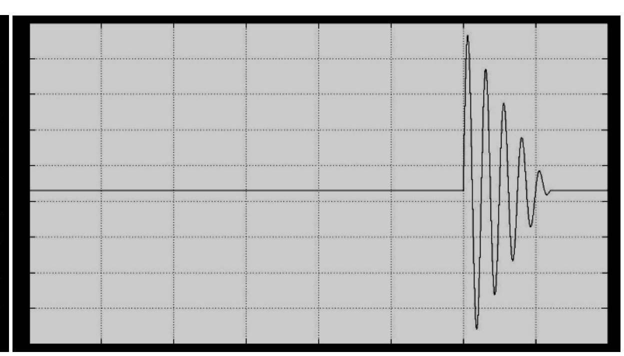


Stator voltage(pu)

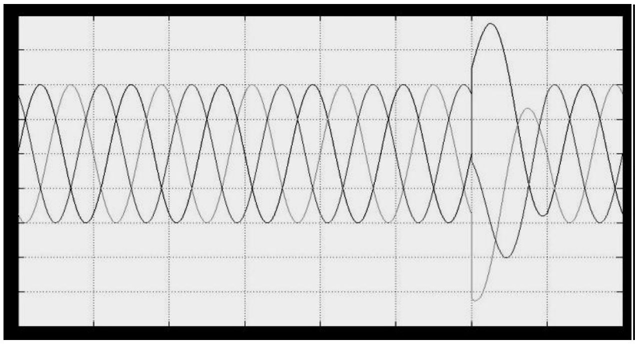
rotor speed(pu)



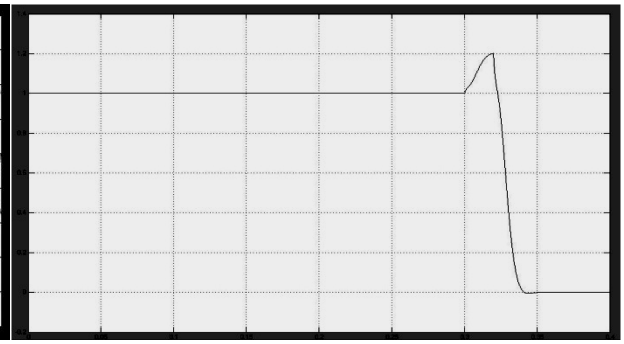
Injected voltage(pu)



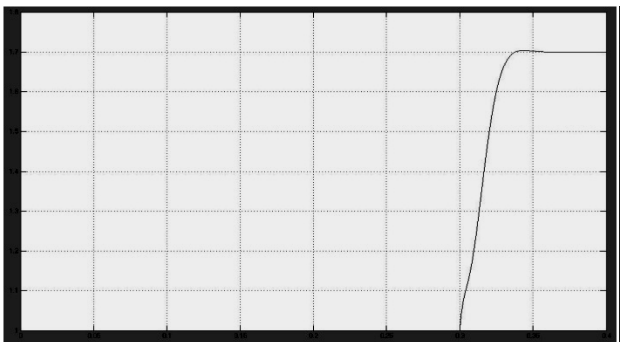
torque(pu)



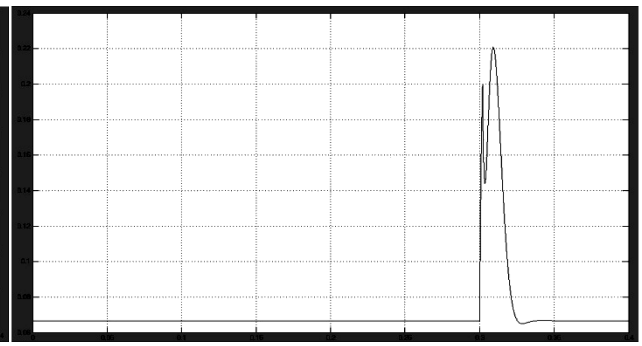
Rotor current



active power

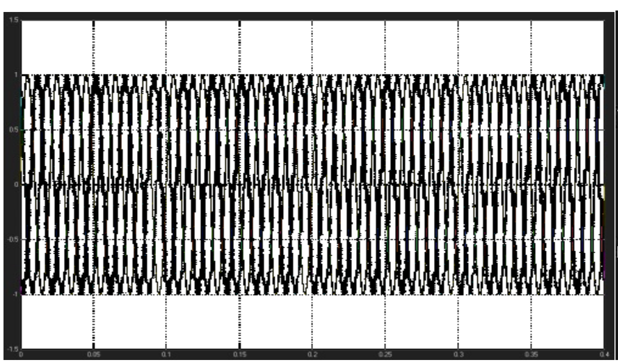


Dc voltage(pu)

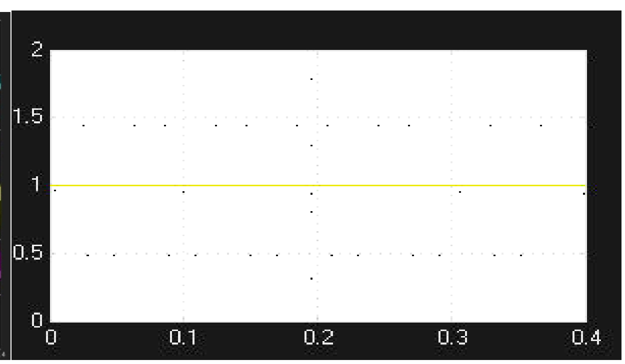


reactive power(pu)

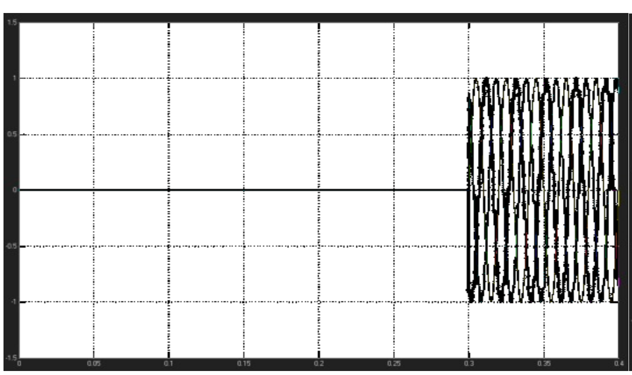
Fig.8: Simulation results for a three-phase short circuit on the terminal of a 1.5-MW DFIG wind turbine.



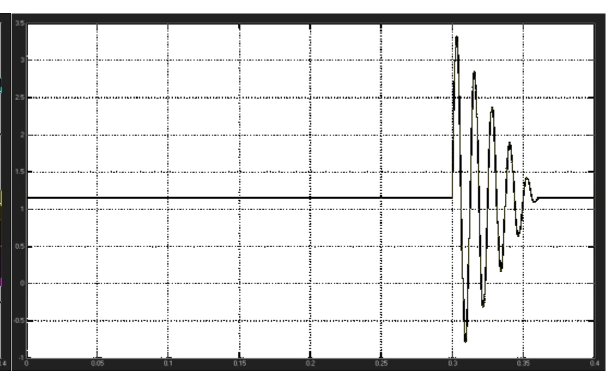
Stator voltage(pu)



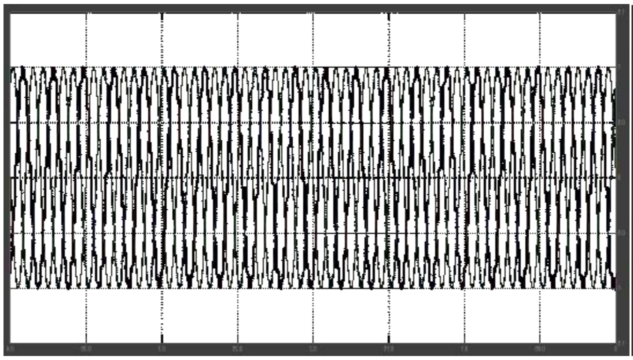
rotor speed(pu)



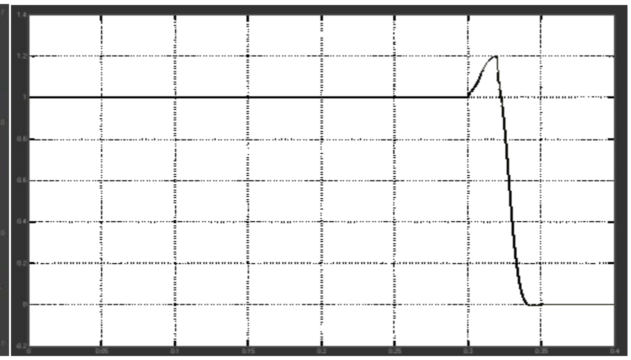
Injected voltage(pu)



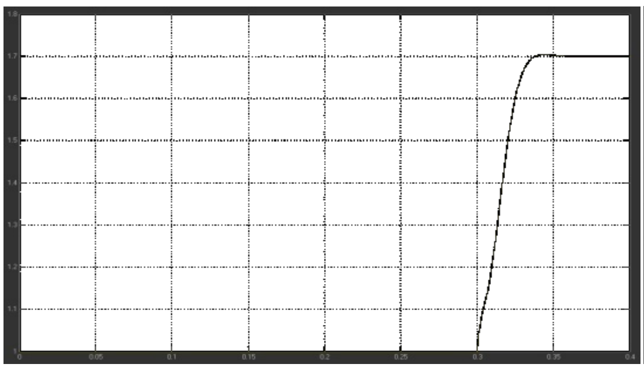
torque(pu)



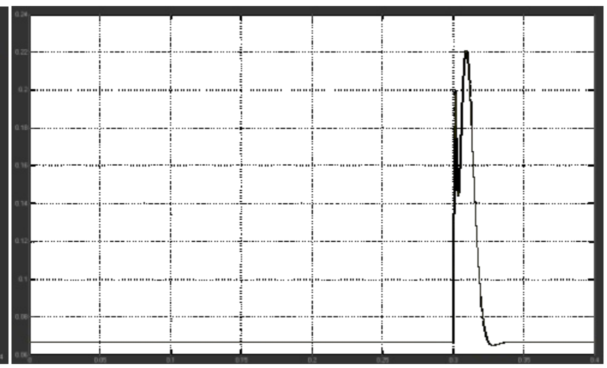
Rotor current



active power

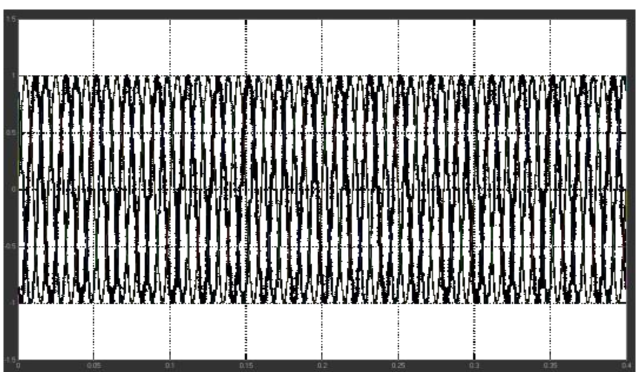


Dc voltage(pu)

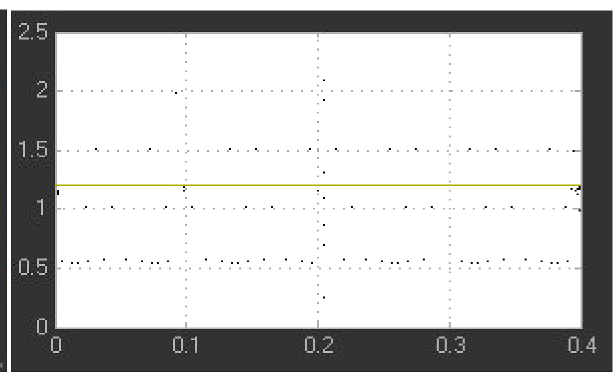


reactive power(pu)

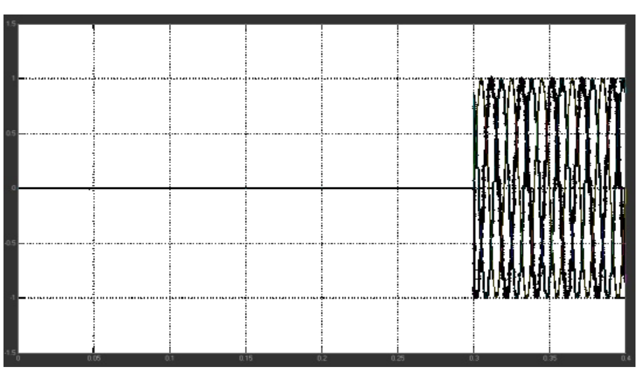
Fig.9: Simulation results for a three-phase short circuit on the terminal of a 1.5-MW DFIG wind turbine when a DVR is applied.



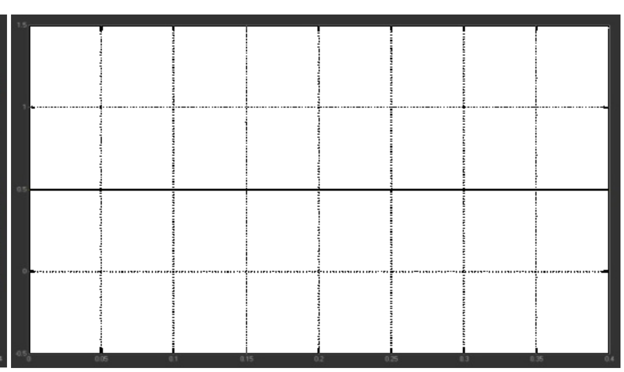
Injected voltage(pu)



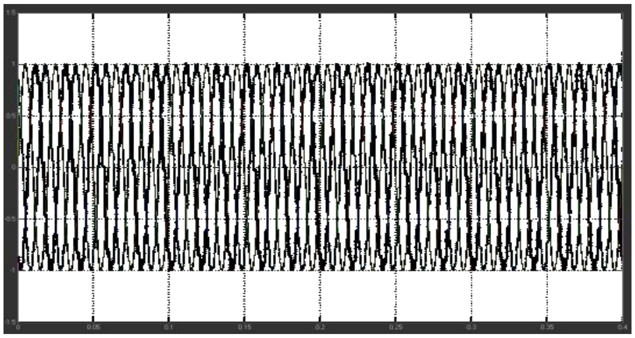
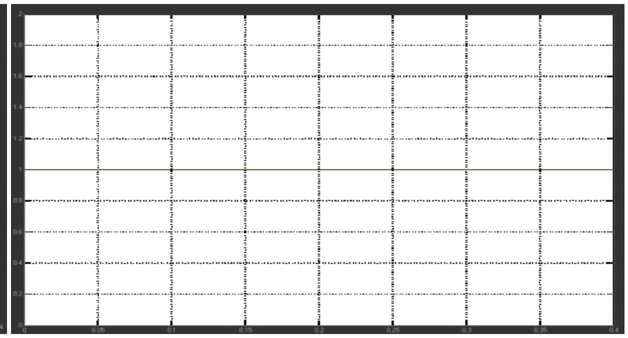
torque(pu)



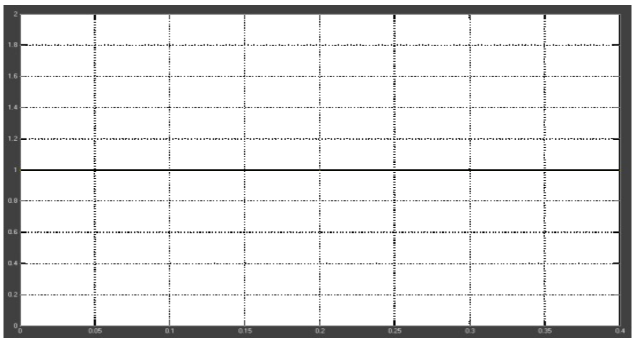
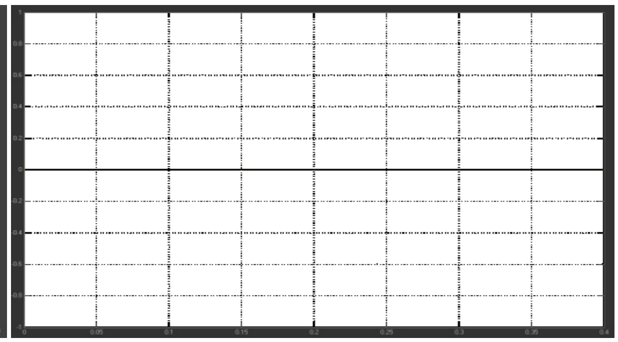
Injected voltage(pu)



torque(pu)

Rotor current(pu) **active power(pu)**

Dc voltage(pu) **reactive power(pu)**

Fig.10: Simulation results for a three-phase short circuit on the terminal of a 1.5-MW DFIG wind turbine when a full compensation is applied using UPQC.

6. conclusion:

DFIG is subject to intense stress during considerable grid voltage sag. Additional measures must be taken to protect the turbine and provide LVRT even at zero grid voltage in accordance with utility requirements. Wind turbine equipped with series voltage compensator described in this paper is able to stay connected to the grid and limit the rotor currents within an acceptable range. This LVRT solution for the DFIG also allows for reactive power support to the grid during grid fault. The aim of the proposed technique is to limit the rotor side converter high currents and to provide the stator circuit with the necessary voltage via a series transformer without disconnecting the converter from the rotor or from the grid. The wind turbine can resume normal operation within a few hundred milliseconds after the fault has been cleared. For longer voltage dips, the generator can even supply reactive power to the grid. Simulation and experimental results verify the effectiveness and viability of the proposed technique. According to analyses presented, the size of the energy storage capacitor does not need to be excessively large for the system to operate.

7. Appendix

The parameters of the machine and controller that have been used for modeling and simulations are given as follows.

Simulation Parameters	Experimental Setup Parameters
Ratings: S_n = 1.5 MW, f_n = 50 Hz, U_n = 690 V (line–line, rms), 6 pole, PF= 0.9 Stator resistance: R_S = 0.03 Ohms. Stator leakage inductance: L_{ls} = 59 mH. Rotor resistance (referred to the stator): R'_r = 0.022 Ohms. Rotor leakage inductance(referred to the stator): L_{lr}' = 59 mH. Magnetizing inductance: L_m = 0.035 mH. Series voltage controller parameters: K_p=20, K_i=5.	Ratings: 1hp, 230V, 4 poles , 50Hz, 5A. Stator resistance: R_s=2.715 Ohms. Rotor resistance: R_r=1.421 Ohms. Stator leakage inductance: L_{ls}=11.1mH. Rotor leakage inductance: L_{lr}=11.1mH. Magnetizing inductance: L_m=202.5mH. Moment of inertia is J = 0.004 Kg-m^2. $C_1 = 2.7\mu F.$ $L_1 = 0.5mH.$

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