Variable Speed Wind Turbine Based DFIG Low Voltage Ride through Solution Using Series Voltage Compensation

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Abstract- Wind turbine technologies using doubly fed induction generators are sensible to grid voltage disturbances. Low Voltage Ride Through is an important feature for wind turbine systems to fulfill grid code requirements. Here a new solution is introduced for Doubly Fed Induction Generator (DFIG) to protect the rotor side converter to make it to stay connected to the grid during grid faults. The idea is to create required flux by increasing the stator voltage and limiting rotor current to a level to keep rotor side converter current below its transient rating. To achieve this goal, a series compensator is used in the stator side line to inject voltage. The series compensator monitors the grid voltage and provides compensation accordingly to achieve the required aim. The synchronism of operation is established during and after the fault and normal operation can be continued immediately after the fault has been cleared.

***Keywords*—doubly fed induction generator (DFIG), grid fault, low-voltage ride through, series compensator, dynamic voltage restorer**

NOMENCLATURE

$\bar{i}$	Current space vector
L_m	Magnetizing inductance
L_{ls}, L_{lr}	Stator and rotor leakage inductance
L_s, L_r	Stator and rotor self inductance
r	Superscript denoting rotor reference frame
R_s, R_r	Stator and rotor resistance
s, r	Superscript denoting stator and rotor
$\vec{v}$	Voltage space vector
$\vec{v}_{s-n}$	Nominal stator voltage vector
$\omega_s, \omega_r, \omega_{rn}$	Synchronous, slip and rotor angular frequency
$\vec{\varphi}$	Flux space vector
$\vec{\varphi}_{s-n}$	Stator flux at normal condition
τ_s	Stator time constant
σ	Leakage factor

I.INTRODUCTION

Renewable energy sources are highly concentrated nowadays. Among different renewable energy sources wind energy is well advanced and is expected to play a major role in the future renewable energy portfolio. Doubly fed induction generators (DFIGs) with variable speed wind turbine are the most common type of advanced wind turbine generators due to their durability, lower cost, simple structure, and ability to adjust reactive power. Other advantages of variable-speed wind turbines are that they reduce mechanical stresses, improve power quality, and they compensate for torque and power pulsations. The disadvantage of the variable-speed turbine is that it has a more complex electrical system, as a power-electronic converter is needed One of the main drawbacks of using DFIGs is their vulnerability to grid side voltage sags and short circuits. This type of generator utilizes a power converter on the rotor to adjust the rotor currents in order to regulate the active and reactive power on the stator side. This converter is typically rated up to 30% of the generator power. 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.

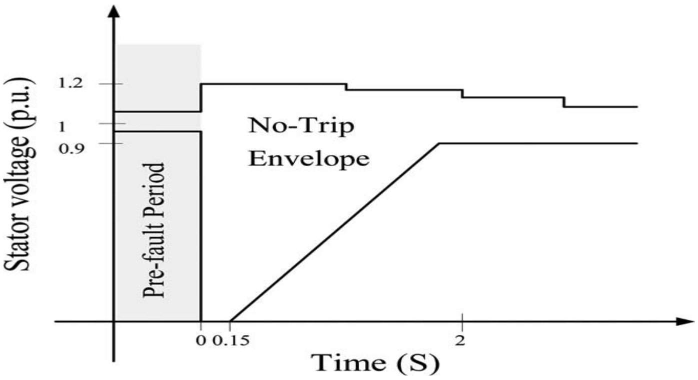

Fig. 1 Proposed WECC voltage ride-through requirements for all generators.

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. According to the Western Electricity Coordinating Council regulation, the machine has to remain online if a three-phase short circuit fault occurs at the terminal and lasts for 0.15 s followed by a ramp voltage rebuild to 90% of nominal voltage in 2.85 s shown in Fig. 1. The wind turbine generator may disconnect from the line transiently outside the no-trip envelope but must reconnect within 2 s and rebuild power output at 20% of rated power per second. This new proposed regulation has been a challenging requirement for the wind turbine manufacturers and utilities to meet. Recently, many researchers have focused on different techniques to overcome the low-voltage ride-through (LVRT) issue.

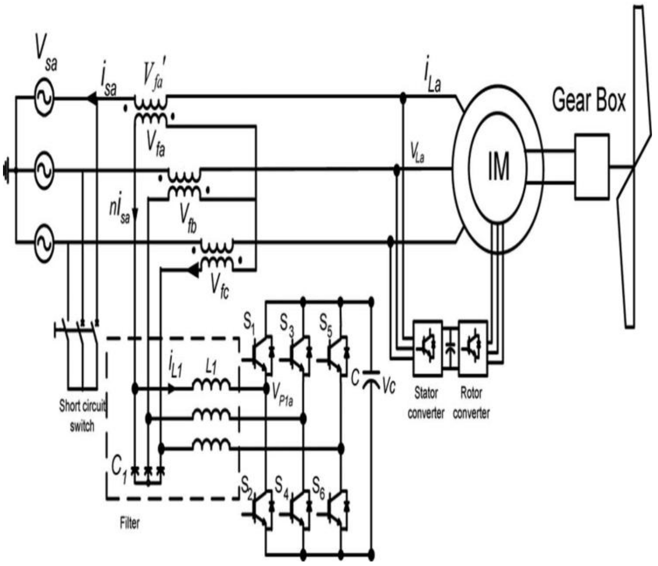

Fig. 2 Configuration of the series converter for the proposed LVRT solution

Majority of these solutions rely on a rotor clamp circuit that creates a short circuit on the rotor to divert the high rotor currents from the power electronics converters [2]. Some of the newer types place a definite resistance across the rotor terminal that helps in accelerating rotor current decay. These clamp circuit change the effective resistance across the rotor terminals using force commutation, PWM modulation, or actively changing the resistor clamp [1], [3]. In addition to the rotor clamp circuit, to meet the requirements, a commutated semiconductor switch on the stator may be used to control the phase of the voltage applied to the machine. The major drawback of these methods is that they are only aimed at protecting the rotor converter during fault. They convert the DFIG to a simple induction machine during fault since they create short circuit on the rotor [3]. The induction machine draws a lot of reactive power from the grid during fault and voltage build up. This exactly happens when the grid needs reactive power to resume normal operation. Therefore, using a rotor clamp circuit will further complicate the fault situation for the grid. In addition, when the wind turbine is working in super synchronous mode, the voltage on dc-link capacitor dramatically increases. The rotor clamp circuits do not offer any solution to protect this capacitor. An additional circuit is needed to lower the capacitor voltage [4].

Utilization of voltage compensation using series converters has been introduced and applied for many applications such as dynamic voltage restorer [6], static compensators [13], and harmonic compensations [14]. In this paper, we present a solution to use a series converter on the stator terminal of a DFIG to mitigate the effect of the short circuit on the wind turbine. This converter, as shown in Fig. 2, acts the same as a series active filter for voltage compensation. The converter consists of three insulated gate bipolar transistor switching legs with a capacitor (*C*) as energy storage. Each switching leg can be controlled independently. Therefore, effects of unbalanced short circuit faults on the turbine can also be mitigated. The converter delivers active power for a very short period. Therefore, a proper sizing of the capacitor is required. The converter continuously monitors the grid side voltage. When this voltage dips, the converter applies a voltage through series transformer to compensate for the voltage dip. Fig.3 shows the principle of operation of DVR. DVR can compensate voltage at both transmission and distribution sides.

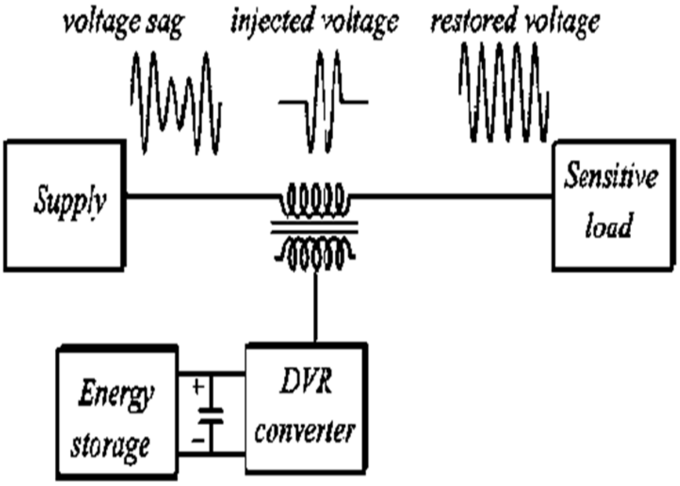

Fig.3 Principle operation of Dyanamic Voltage Restorer

The level of voltage compensation depends on the rating of the converter. Since the converter is considered to apply voltage for a very short period of time, the rating can be high for a compact size converter. The converter does not need to compensate for 100% of line voltage during short circuit. It only needs to compensate the voltage to a level that limits the short circuit fault current.

II. DFIG DURING GRID FAULT AND MODELLING WITH DVR

There are many references that have discussed the modeling of DFIG wind turbines [9], [10]. Fig. 4 shows the block diagram of a DFIG wind turbine system with DVR. 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 [5]

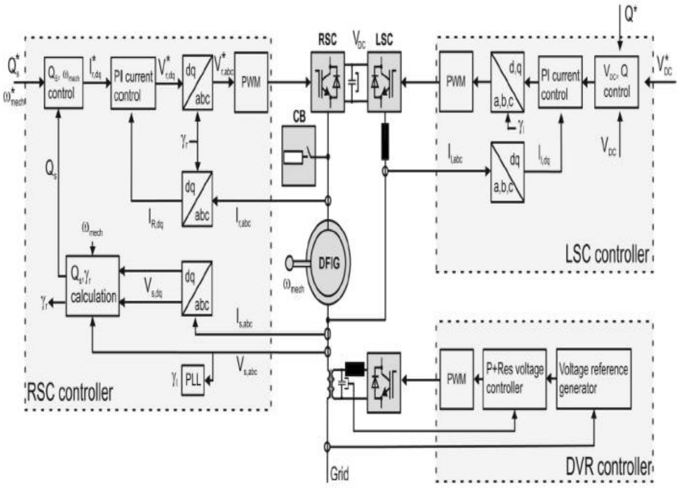

Fig. 4 Configuration of a DFIG turbine system With DVR.

A Park model in the stationary stator-orientated reference frame, developed for DFIG in [1], 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.

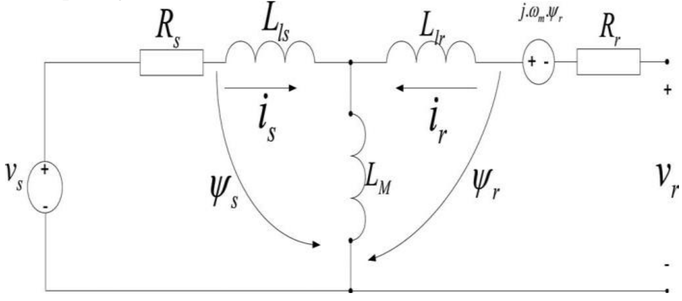

Fig. 5 DFIG-equivalent circuit for short circuit analysis.

Fig. 5 shows the equivalent circuit corresponding to the aforementioned equations. Using motor convention, the stator and rotor voltages in *abc* frame can be expressed as

$$\vec{v_s} = R_s\vec{i_s} + \frac{d}{dt}\vec{\varphi_s} \tag{1}$$

$$\vec{v_r} = R_r\vec{i_r} + \frac{d}{dt}\vec{\varphi_r} - j\omega_m\vec{\varphi_r} \tag{2}$$

The stator and rotor fluxes are given by

$$\vec{\varphi_s} = L_s\vec{i_s} + L_m\vec{i_r} \tag{3}$$

$$\vec{\varphi_r} = L_r\vec{i_r} + L_m\vec{i_s} \tag{4}$$

where $L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$.

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 [11]. This voltage is induced by the variation of the stator flux, which can be calculated by deriving $\vec{i_s}$ from (3) and substituting into (4):

$$\vec{\varphi_r} = \frac{L_m}{L_s}\vec{\varphi_s} - \sigma L_r\vec{i_r}, \ \sigma = 1 - \frac{L_m^2}{L_s L_r} \tag{5}$$

Thus, the rotor voltage can be found by combining (2) and (5)

$$\vec{v_r} = \frac{L_m}{L_s}\left(\frac{d}{dt} - j\omega_m\right)\vec{\varphi_s} + \left(R_r + \sigma L_r\left(\frac{d}{dt} - j\omega_m\right)\right) i_r \tag{6}$$

The rotor voltage given by (6) can be divided into two terms. The first term is the open circuit voltage ($\vec{v}_{ro}$) 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 R_r and the rotor transient inductance σL_r. From (6), when there is no current in the rotor circuit, the rotor voltage due to the stator flux is ($\vec{v}_{ro}$):

$$\vec{v}_{ro} = \frac{L_m}{L_s}\left(\frac{d}{dt} - j\omega_m\right)\vec{\psi}_s \tag{7}$$

Under the normal condition, rotor current control technique is utilized to adjust the active and reactive power at generator terminal. In normal operation, the rotor voltage can be described as

$$\vec{v_r} = \vec{v_s}\frac{L_m}{L_s}s + \left(R_r + \sigma L_r\left(\frac{d}{dt} - j\omega_m\right)\right)\vec{i_r} \tag{8}$$

III. CONTROL TECHNIQUE

In this section, the control technique for the series converter is described. The measured grid voltages (V_{sa}, V_{sb} , and V_{sc}) are converted into the stationary reference frame voltage quantities ($V_{s\alpha}$ and $V_{s\beta}$) using the following transformation [6]:

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{9}$$

Then, the stationary reference frame voltage quantities are converted into the synchronous rotating reference frame voltage quantities (V_{sd} and V_{sq}) rotating by the grid voltage angle of θ. A phase lock loop (PLL) is used to generate the grid voltage angle

$$\begin{matrix} V_{sd} \\ V_{sq} \end{matrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V_{s\alpha} \\ V_{\beta} \end{bmatrix} \qquad (10)$$

The synchronous rotating reference frame voltage components (V_{sd} and V_{sq}) are compared with the desired voltage to produce the reference voltage for voltage regulator as shown in Fig. 7. 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.

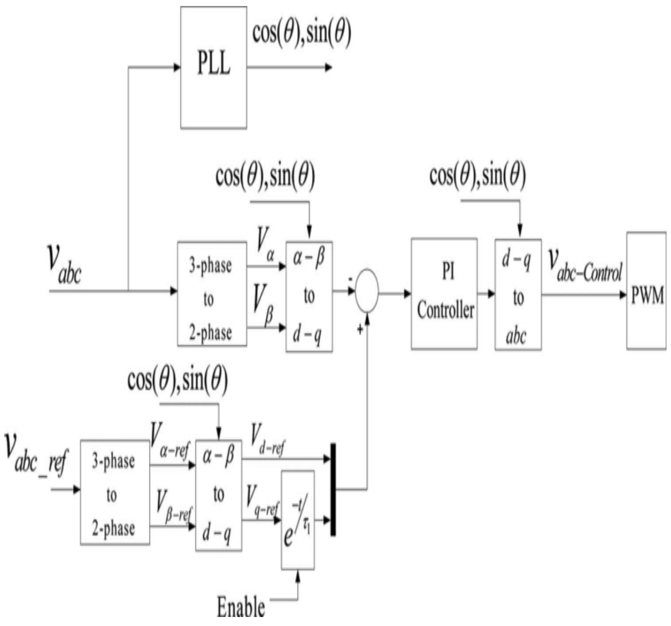

Fig. 6 Block diagram of the converter control technique

IV. ENERGY CALCULATION FOR DC CAPACITOR

During short circuit on the stator, the wind turbine cannot export any power to the grid. However, when the compensation is applied, the series converter absorbs all the turbine energy and charges the capacitor. If a decaying time constant is applied to the compensation voltage, the absorbed power and capacitor size can be greatly reduced.

When no time constant (τ_1) is introduced for the voltage compensation and the series converter provides 100% compensation during short circuit. We will have

$$E = \int_0^{0.2} \sqrt{3}\, IV_c \qquad (11)$$

where E is the energy delivered from 0 to 0.2 s. V_C is the capacitor voltage and I is the generator current. 0.2 s is the maximum three-phase short circuit duration that the turbine must withstand. The capacitor size for this case the can be calculated as

$$C = 2\frac{\int_0^{0.2} \sqrt{3}}{\Delta V^2} IV_c \qquad (12)$$

where ΔV is the maximum allowable voltage variation of the capacitor. In fact, the wind turbine delivers the same power before, during, and after the short circuit since the generator does not see the short circuit in this case. Therefore, a large capacitor bank is required to absorb the energy.

V. PROPOSED SOLUTION

To start analyzing the proposed solution, it is assumed that the generator is operating under normal condition when at time t_0 a three-phase short circuit occurs:

$$\vec{v}_s = \begin{cases} V_s\, e^{jt\omega_s}, & for\ t<0 \\ 0, & for\ t\geq 0 \end{cases} \qquad (13)$$

As soon as the short circuit is detected, we apply a voltage vector of $\vec{v}_c$ via the series converter on the stator, where $|\vec{v}_c| = |\vec{v}_s|$ at $t = 0$, and τ_1 is the time constant to be quantified later from energy equations of the system. Vector $\vec{v}_c$ is rotating with the speed of ω_s and its magnitude is declining with the time constant of τ_1 :

$$\vec{v}_c = \begin{cases} 0, & for\ t<t_0 \\ V_c e^{jt\omega_s}, & for\ t\geq t_0 \end{cases} \qquad (14)$$

Under this condition, the expression for the stator flux can be obtained from (1) and (3) as follows:

$$\frac{d\vec{\varphi}_s}{dt} = \vec{v}_s - \frac{R_s}{L_s}\vec{\varphi}_s \qquad (15)$$

Substituting $\vec{v}_s = \vec{v}_c$, the solution to this nonhomogeneous first order differential equation can be found. Assuming zero delay for the compensation, the homogeneous part of (15) can be eliminated. This part corresponds to the transient flux. Solving (15) for the stator flux, we get

$$\vec{\varphi}_s = \{{}^{V_c}/_{j\omega_s} - \left(\frac{1}{\tau_1}\right) + \left(\frac{1}{\tau_s}\right)\} e^{jt\omega_s} e^{\frac{-t}{\tau_1}} \qquad (16)$$

Substituting (16) into (7), the rotor voltage induced from the stator flux is obtained as follows:

$$\vec{v}_{r0} = \frac{Lm}{Ls}\left(\frac{d}{dt} - j\omega_m\right)\left\{{}^{V_c}/_{j\omega_s} - \left(\frac{1}{\tau_1}\right) + \left(\frac{1}{\tau_s}\right)\right\} e^{jt\omega_s} e^{\frac{-t}{\tau_1}} \quad (17)$$

$$\vec{v}_{r0} = \left(\frac{Lm}{Ls} V_c \frac{(j\omega_s - j\omega_m) - \left(\frac{1}{\tau_1}\right)}{j\omega_s - \left(\frac{1}{\tau_1}\right) + \left(\frac{1}{\tau_s}\right)}\right) e^{jt\omega_s} e^{\frac{-t}{\tau_1}} \quad (18)$$

. Its amplitude decreases exponentially with the time constant of τ_1. With respect to the rotor, this voltage rotates reversely at the slip frequency. Since the time constant for large machines is much greater than 200 ms, if we set $\tau_1 < \tau_s$, the rotor open circuit voltage can be written in terms of the slip as follows:

$$\vec{v}_{r0} = \left(\frac{L_m}{L_s} V_c s\right) e^{-t/\tau 1}\, ej^{(\omega_s - \omega_m)t} \quad (19)$$

Substituting (24) into (8), the rotor voltage connected to the converter can be found

$$\vec{v}_r = \vec{v}_c\, e^{-t/\tau 1} \frac{L_m}{L_s} s + \left(R_r + \sigma L_r \left(\frac{d}{dt} - j\omega_m\right)\right) \quad (20)$$

According to (19), the time constant of rotor voltage due to the stator flux no longer depends on the stator time constant or stator voltage. The time constant has changed to the new time constant of τ_1. The rotor current will not rise due to a step change in stator voltage. As can be seen in (19) and (20), this could have been performed without adding the time constant of τ_1. However, adding the time constant reduces the requirement for energy storage size for the series converter while keeping the rotor side inverter current within the acceptable limits. Fig. 7 shows the transient of stator flux trajectory due to three phase short circuit when compensation is applied during which magnitude decreases exponentially with time constant τ_1.

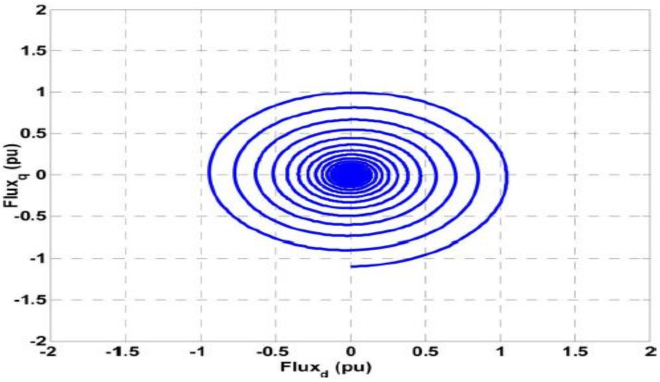

Fig. 7 Stator flux trajectory transients with compensation

Fig.8 shows the simulation diagram of three phase short circuit without DVR. Fig. 12 shows rotor current and speed for the system behavior during a symmetrical three-phase short circuit at $t = 0.5$ s. The rotor current rises to 0.4 p.u and during the short circuit, the electromagnetic torque shows the disturbance. Active power, reactive power in Fig. 14 and torque in Fig. 13 reduce to zero after a transient. These short circuit characteristics are what make the system very venerable to short circuit.

Fig. 9 shows the simulation diagram of three phase short circuit with DVR. Fig. 15 shows the stator voltage and rotor current with DVR. Fig. 17 shows the reactive and active power and Fig. 18 shows the torque with DVR. Thus the results of three phase short circuit with DVR clearly show that voltage distortions are reduced.

Extension can be done for this with help of DVR based MLI for which the simulation diagram is shown in Fig. 10. Fig. 20 shows the torque and Fig. 21 shows the reactive and active power with DVR based MLI.

Thus the series converter has advantage as it injects the required voltage at stator terminal and helps DFIG to connect to the grid even during the voltage sags and also helps it to maintain required grid codes.

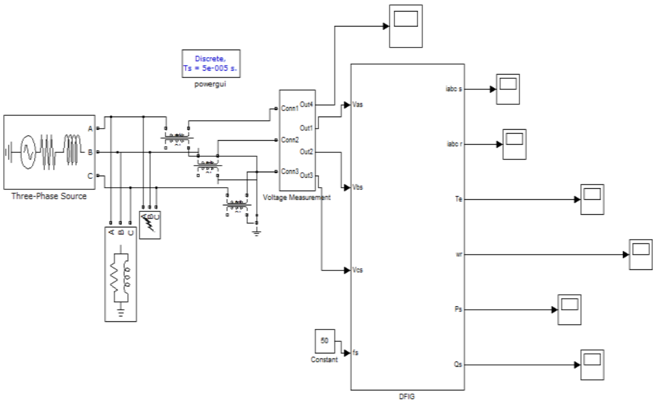

Fig. 8 Simulation model of three phase short circuit without DVR

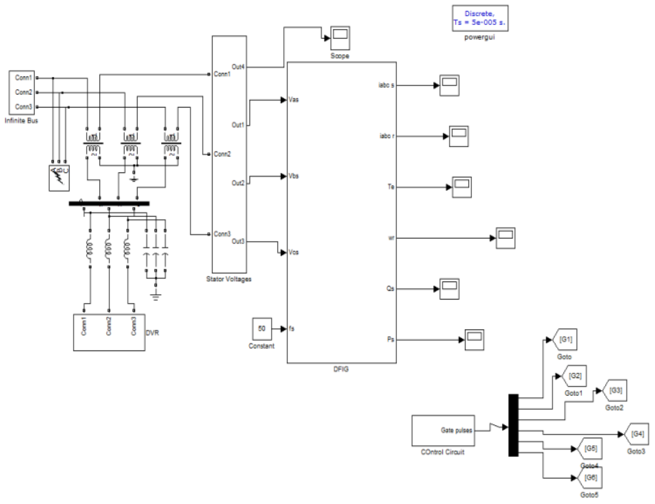

Fig. 9 Simulation model of three phase short circuit with DVR

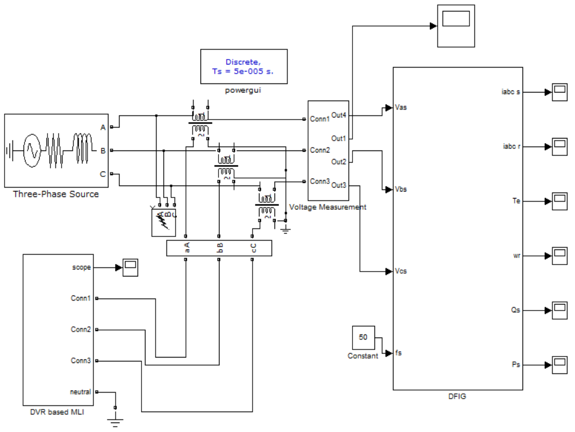

Fig. 10 Simulation model of three phase short circuit with DVR based MLI

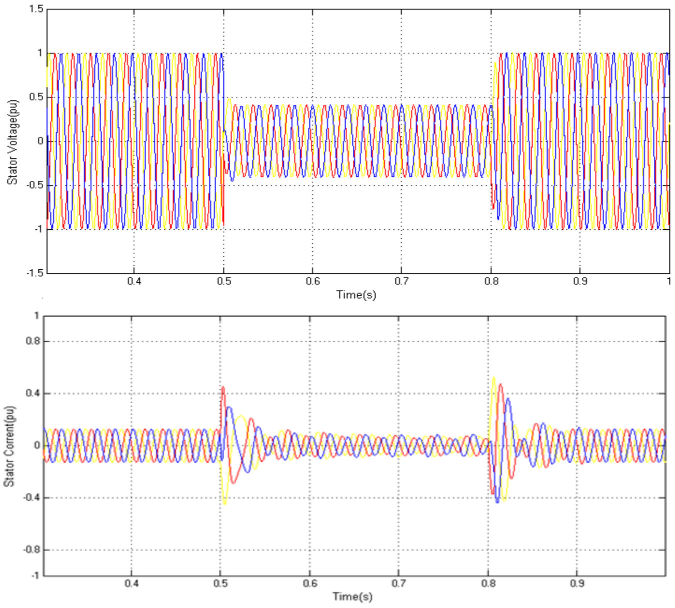

Fig. 11 Stator Voltage and Current without DVR

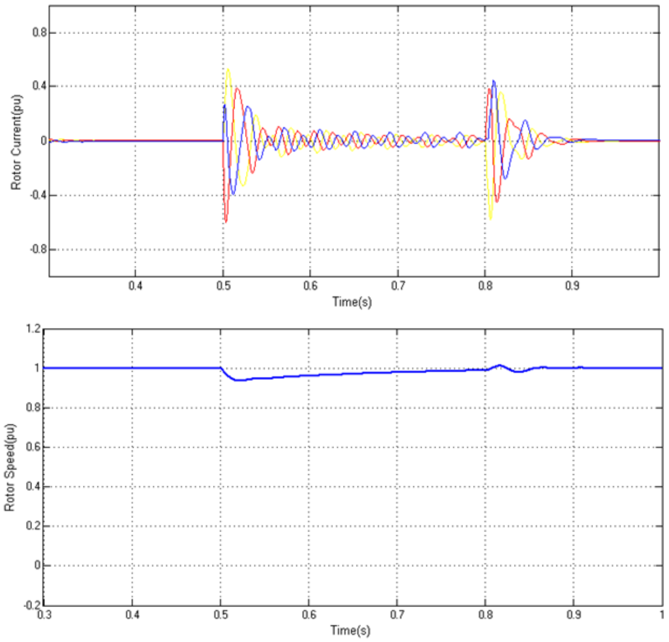

Fig. 12 Rotor Current and Speed without DVR

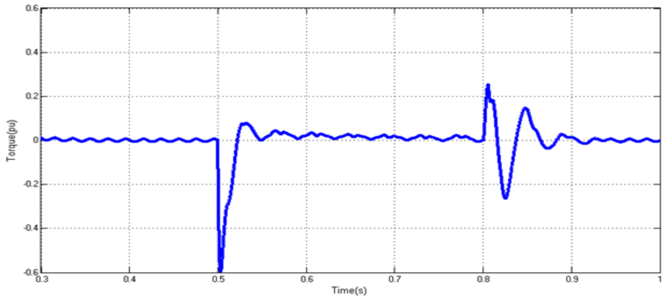

Fig. 13 Torque without DVR

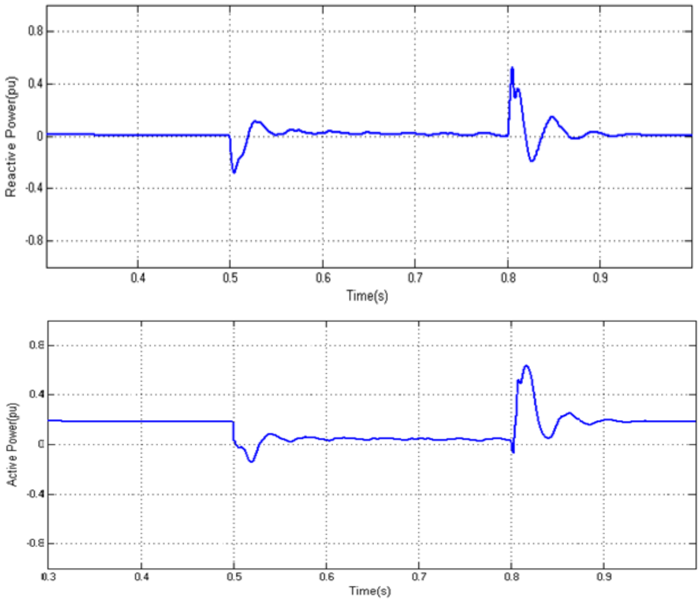

Fig. 14 Reactive and Active Power without DVR

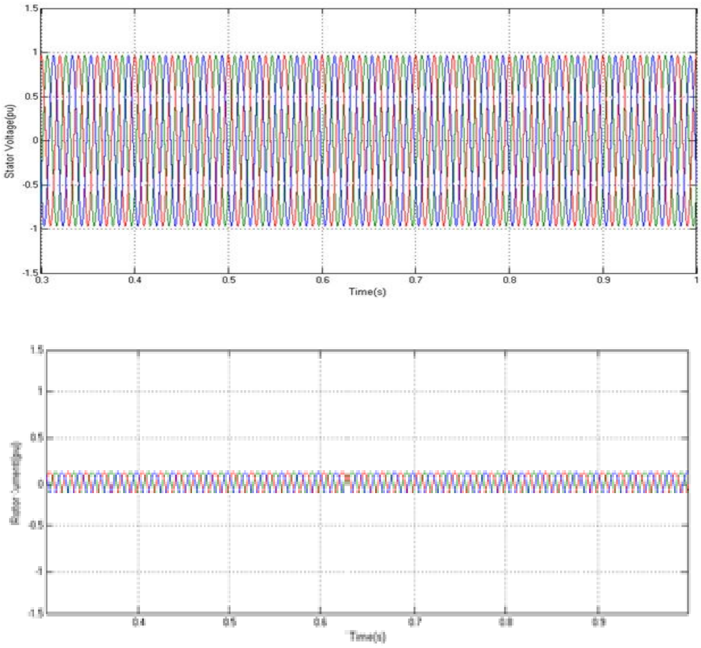

Fig. 15 Stator Voltage and Rotor Current with DVR

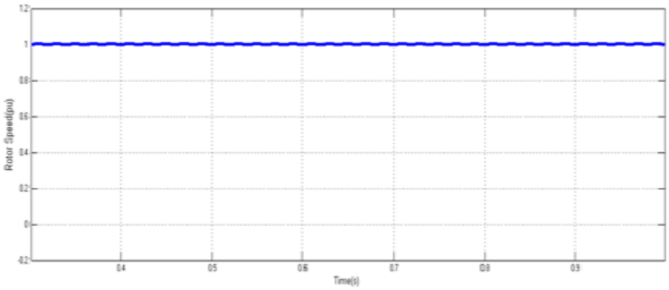

Fig. 16 Rotor Speed with DVR

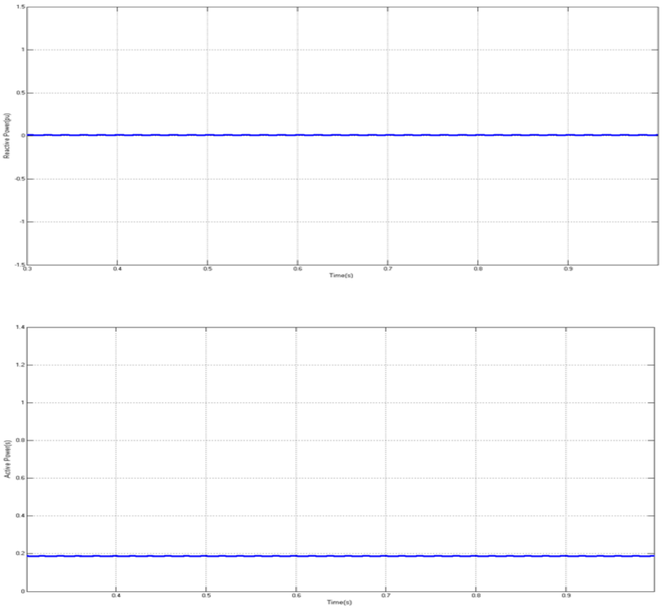

Fig. 17 Reactive and Active Power with DVR

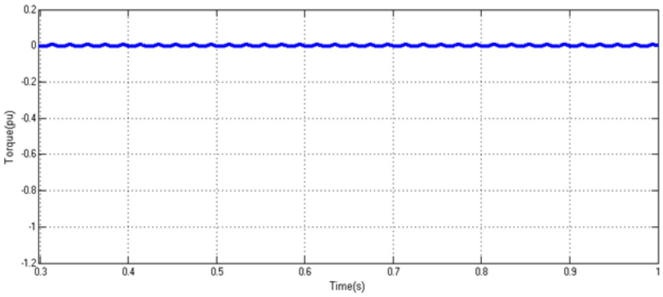

Fig. 18 Torque with DVR

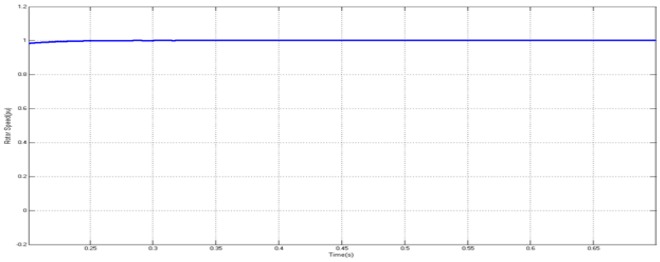

Fig. 19 Rotor Speed with DVR based MLI

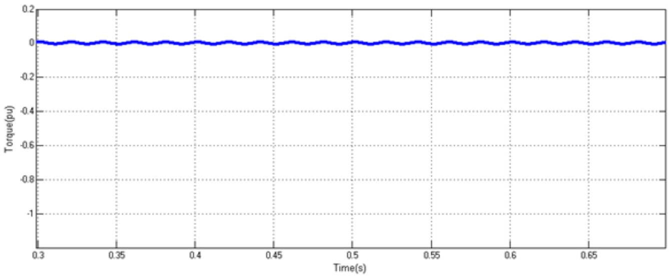

Fig. 20 Torque with DVR based MLI

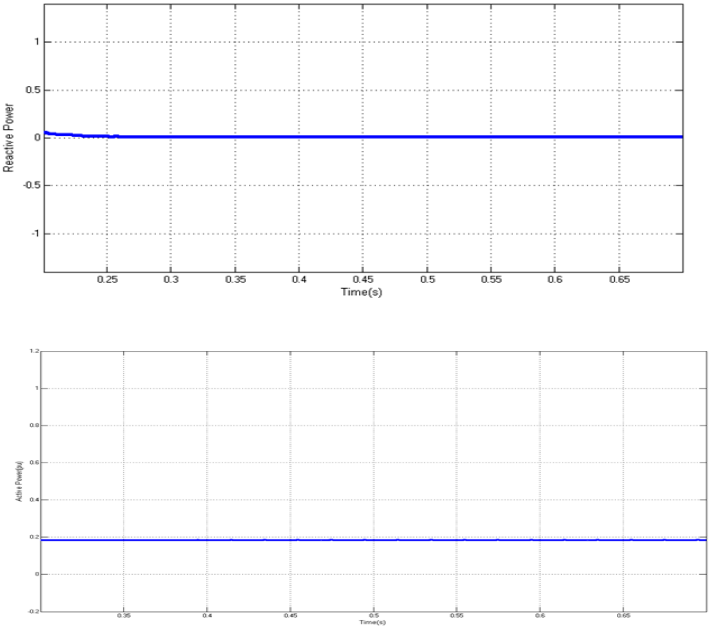

Fig. 21 Reactive and Active Power with DVR based MLI

VI. 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 such as DVR described in this paper is able to stay connected to the grid and limit the rotor currents within an acceptable range. 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 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. The extension is done with DVR based MLI and its results are are found to be more effective than DVR.

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