The Modeling and Analysis of Grid Connected DFIG with Low-Voltage Ride-Through Solution Using Series Compensator

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Abstract: This paper deals with a new solution to protect the DFIG wind turbine generator and allow staying connected to the grid during the faults on the grid side. During the faults the stator voltage is increased to a level that creates the required flux to keep the rotor side converter current below its transient rating. To maintain this, a series compensator is designed to inject voltage in series to the stator side line. The series converter monitors the grid voltage and provides compensation accordingly to keep DFIG to continue its operation. Since the turbine and converter stay connected, the synchronization of operation remains established during and after the fault and normal operation can be resumed immediately after the fault is cleared. 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. The energy efficiency of wind turbine systems equipped with doubly-fed induction generators are compared to other wind turbine generator systems.

Index Terms: Low Voltage ride through, Doubly-fed induction generator (DFIG), Point of Common Coupling, Series Grid Side Converter.

I. INTRODUCTION

The conventional energy sources are limited and have pollution to the environment. Hence more attention and interest have been paid to the utilization of renewable energy sources such as wind energy, fuel cell and solar energy etc. Wind energy is the fastest growing and most promising renewable energy source among them due to economically viable. The Doubly-Fed Induction Generator (DFIG) concept has become one of the most favorable options in modern wind power market due to its simple structure, low cost, durability and ability to adjust for reactive power. The main drawback of DFIG wind turbine is its vulnerability to grid side voltage sags and short circuits. Whenever 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. An easy way to protect the converter is to disconnect the generator during low-voltage conditions. But it is an unreliable one. Hence in this project we focused mainly to provide a best apt solution for DFIG to stay connected to the grid during faults also without being damaged. DFIG uses 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.

An easy way to protect the converter is to disconnect the generator during low-voltage conditions. But it is an unreliable one. This paper mainly focused on to provide a best optimal solution for DFIG to stay connected to the grid during faults also without being damaged. 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, any 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 as shown in Fig. 1.

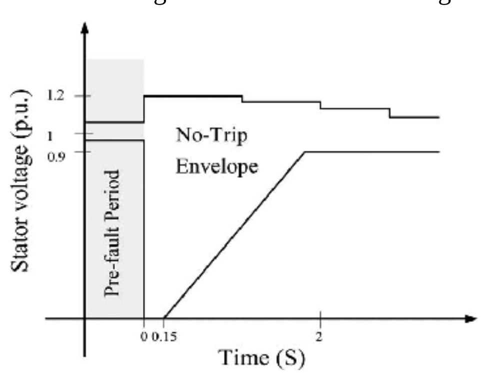

Fig.1: WECC voltage ride-through requirements for all generators.

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The wind turbine generator may disconnect from the line transiently outside without tripping and must reconnect within 2s to rebuild power output at 20% of rated power per second. This proposed advanced regulation has been a challenging requirement for the wind turbine manufacturers and utilities to meet. Newer types of wind turbine generators are more susceptible to short circuit fault due to presence of power electronics components.

Recently, many researchers have focused on different techniques to overcome the low-voltage ride-through (LVRT) issue. 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 circuits change the effective resistance across the rotor terminals using force commutation, PWM modulation, or actively changing the resistor clamp [2], [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

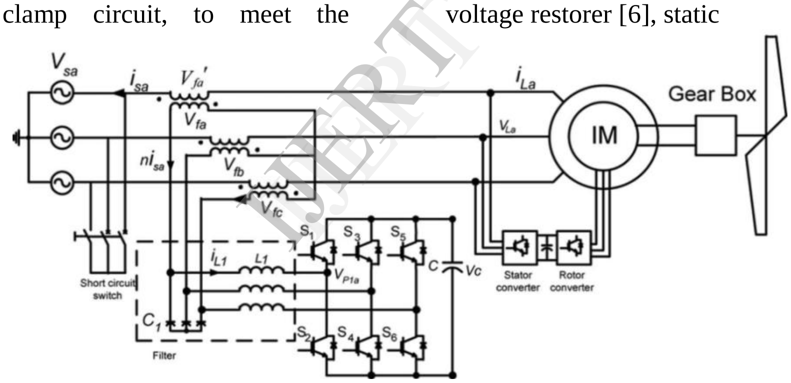

Fig. 2. Configuration for series converter for the proposed LVRT solution

Compensator [7] and harmonic compensations [8]. In this paper, we are presenting a new 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. 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. Typically, the converters on the rotor can tolerate up to 300% of its rated current in transient conditions. Therefore, the series converter can be designed at an apparent power rating well below the power rating of the turbine.

II. DFIG WIND TURBINE

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 DFIG system 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. 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.

A. DFIG Modeling Using Dynamic Vector Approach

A commonly used model for induction generator converting power from the wind to serve the electric grid is shown in Fig 3. The stator of the wound rotor induction machine is connected to the low voltage balanced three-phase grid and the rotor side is fed via the back-to-back PWM voltage-source inverters with a common DC link. Grid side converter controls the power flow between the DC bus and the AC side and allows the system to be operated in sub-synchronous and super synchronous speed. The proper rotor excitation is provided by the machine side power converter and also it provides active and reactive power control on stator and rotor sides respectively by employing vector control. DFIG can be operated as a generator as well as a motor in both sub-Synchronous and super synchronous speeds, thus giving four possible operating modes.

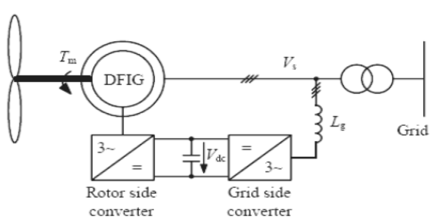

Fig.3. Configuration of a DFIG wind turbine system

Only the two generating modes at sub-synchronous and super synchronous speeds are of interest for wind power generation. To exploit the advantages of variable speed operation, the tracking of optimum torque-speed curve is essential. Speed can be adjusted to the desired value by controlling torque. So, an approach of using active power set point from the instantaneous value of rotor speed and controlling the rotor current *i*ry in stator flux-oriented reference frame to get the desired active power will result in obtaining the desired values of speed and torque according to the optimum torque speed curve. In the stator flux-oriented reference frame, reactive power can be controlled by controlling the *d*-axis rotor current. In stator flux-oriented control, both stator and rotor quantities are transformed to a special reference frame that rotates at an angular frequency identical to the stator flux linkage space phasor with the real axis (*x*-axis) of the reference frame aligned to the stator flux vector. At steady state, the reference frame speed equals the synchronous speed. This model is called dynamic vector model.

The main variables of the machine in rotating frame are flux linkages *φqs, φds φ'qr φ'dr* in state space form are derived.

Substituting the conditions ω = ωr and *V*q*r*=*Vdr*=0 in the flux linkage equation, we get:

$$\boldsymbol{\varphi}_{qs} = \boldsymbol{\omega_b}\int (\boldsymbol{V_{qs}} - \boldsymbol{\omega_r}/\boldsymbol{\omega_b}\boldsymbol{\varphi}_{ds} + r_s/x_{ls}(\boldsymbol{\varphi}_{mq} - \boldsymbol{\varphi}_{qs})) \quad (1)$$

$$\boldsymbol{\varphi}_{ds} = \boldsymbol{\omega_b}\int (\boldsymbol{V_{ds}} - \boldsymbol{\omega_r}/\boldsymbol{\omega_b}\boldsymbol{\varphi}_{qs} + r_s/x_{ls}(\boldsymbol{\varphi}_{md} - \boldsymbol{\varphi}_{ds})) \quad (2)$$

$$\boldsymbol{\varphi'}_{qr} = \boldsymbol{\omega_b}\int (\boldsymbol{r'r}/xl_r(\boldsymbol{\varphi}_{mq} - \boldsymbol{\varphi'}_{qr})) \quad (3)$$

$$\boldsymbol{\varphi'}_{dr} = \boldsymbol{\omega_b}\int (\boldsymbol{r'r}/xl_r(\boldsymbol{\varphi}_{md} - \boldsymbol{\varphi'}_{dr})) \quad (4)$$

The currents can now be calculated

$$i_{qs} = (\boldsymbol{\varphi}_{qs} - \boldsymbol{\varphi}_{mq})/x_{ls} \quad (5)$$

$$i_{ds} = (\boldsymbol{\varphi}_{ds} - \boldsymbol{\varphi}_{md})/x_{ls} \quad (6)$$

$$i'_{qr} = (\boldsymbol{\varphi'}_{qr} - \boldsymbol{\varphi}_{mq})/x'_{ls} \quad (7)$$

$$i'_{dr} = (\boldsymbol{\varphi'}_{dr} - \boldsymbol{\varphi}_{md})/x'_{lr} \quad (8)$$

Solving equations (3-7) the $\boldsymbol{\varphi}_{mq}, \boldsymbol{\varphi}_{md}$ are obtained as

$$\boldsymbol{\varphi}_{mq} = x_m\,(\boldsymbol{\varphi}_{qs}/x_{ls} + \boldsymbol{\varphi}'_{qr}/x'_{lr} \quad (9)$$

$$\boldsymbol{\varphi}_{md} = x_m\,(\boldsymbol{\varphi}_{ds}/x_{ls} + \boldsymbol{\varphi}'_{dr}/x'_{lr} \quad (10)$$

Where $x_m = 1/(1/x_m + 1/x_{ls} + 1/x_{lr}$

For maintaining proper flow of variables and for convenience of simulating, the above equations are separated into the q-axis, the d-axis and the rotor circuits. In the q-axis circuit, the Equations (2), (4), (6), (8) and (10) are used to calculate, φqs , φ'_{qr}, i_{qs} and i'_{qr} respectively and φ_{qs}, i_{qs} arc used in the calculation of electromagnetic torque. The rotor circuit makes use of the φ_{qs}, i_{qs} obtained from the q-axis circuit and φ_{ds}, i_{qs} obtained from the d-axis circuit and calculates the electromagnetic torque using equation (12).The rotor circuit also takes the input mechanical torque values supplied to it.

Now that we know *φqs, iqs and φds, ids,* the electromagnetic torque can be calculated by;

$$T_{em} = \left(\frac{3p}{4\omega_b}\right)(\boldsymbol{\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}}) \quad (11)$$

The equation that governs the motion of rotor is obtained by equating the inertia torque to the accelerating torque:

$$J(d\omega_m/dt) = T_{em} + T_{mec\,h} - T_{damp} \quad (12)$$

Expressed in per unit values, equation (9) becomes:

$$2Hd(\omega_r/\omega_b)/dt = T_{em} + T_{mec\,h} - T_{damp} \quad (13)$$

In equations (11) & (12), the flux linkages are 2-phase d-q axes rotating reference frame.

III. ANALYSIS OF DFIG DURING GRID FAULT

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

$$\vec{v}_s = R_s \vec{\imath}_s + \frac{d}{dt}\vec{\psi}_s \quad (14)$$

$$\vec{v}_r = R_r \vec{\imath}_r + \frac{d}{dt}\vec{\psi}_r - j\omega_m \vec{\psi}_r \quad (15)$$

The stator and rotor fluxes are given by

$$\vec{\psi}_s = L_s \vec{\imath}_s + L_m \vec{\imath}_r \quad (16)$$

$$\vec{\psi}_r = L_r \vec{\imath}_r + L_m \vec{\imath}_s \quad (17)$$

Where $L_s = (L_{ls}+L_m)$ and $L_r = (L_{lr}+L_m)$

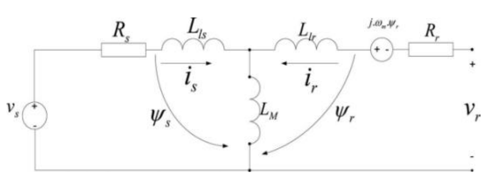

Fig.4. DFIG- equivalent circuit for short circuit analysis.

Fig. 4 shows the equivalent circuit corresponding to the a 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 i_s from (16) and substituting into (17).

$$\vec{\psi}_r = \frac{L_m}{L_s}\vec{\psi}_s - \sigma L_r.\vec{\imath}_r\ ,\ \sigma = 1 - \frac{L_m^2}{L_s.L_r} \quad (18)$$

Thus the rotor voltage can be found by combining (15) & (18)

$$\vec{v}_r = \underbrace{\frac{L_m}{L_s}\left(\frac{d}{dt} - j\omega_m\right)\vec{\psi}_s}_{v_{ro}} + \left(R_r + \sigma L_r\left(\frac{d}{dt} - j\omega_m\right)\right)\vec{\imath}_r. \quad (19)$$

The first term is the open circuit voltage $\vec{v}_r$ 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 $\vec{v}_{r0}$:

$$\vec{v}_{r0} = \frac{L_m}{L_s}\left(\frac{d}{dt} - j\omega_m\right)\vec{\psi}_s \quad (20)$$

A. *Analysis Under Normal Operation*

Under the normal condition, rotor current control technique is used 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

$$\vec{v}_r = \underbrace{\vec{v}_s \frac{L_m}{L_s} s}_{v_{ro}} + \underbrace{(R_r + \sigma L_r\left(\frac{d}{dt} - j\omega_m\right))\vec{\imath}_r}_{v_{ri}} \quad (21)$$

where *s* is the slip ($s = \omega_r/\omega_s$, $\omega_r = \omega_s - \omega_m$).

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 f_r < 18 Hz [10]. As a result, the magnitude of V_{ri} in (21) is smaller than V_{r0} . The rotor voltage due to the stator flux can be written as [10].

$$\vec{v}_{r0} = j\omega_r \frac{L_m}{L_s}\overrightarrow{\psi_s} = \frac{\omega_r}{\omega_s}\frac{L_m}{L_s}V_s e^{j\omega_s t} \quad (22)$$

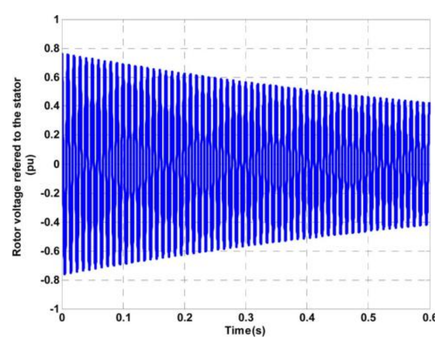

Fig.5. Rotor voltage with-0.2 slip and 1s stator time constant.

The amplitude of the voltage $\vec{v}_{r0}$ can be described as a function of the amplitude of the stator voltage as follows:

$$V_{r0} = V_s \frac{L_m}{L_s} s \qquad (23)$$

During the normal operating condition, the rotor voltage $\vec{v}_{r0}$ depends on the magnitude of the stator voltage and the slip.

B. Analysis During Short Circuit

At the moment of the short circuit ($t_0 = 0$), the open circuit rotor voltage due to the stator flux is given by

$$\vec{v}_{r0} = -\frac{L_m}{L_s}\left(\frac{1}{\tau_s} + j\omega_m\right).\vec{\psi}_0.e^{-t/\tau_s}, \ \ \vec{\psi}_0 = \frac{V_s}{j\omega_s}e^{j\omega_s t_0} \quad (24)$$

where ψ_0 is the stator flux just before the short circuit. The voltage is a space vector fixed to the stator and its amplitude decreases exponentially to zero. With respect to the rotor, this voltage rotates reversely with rotor angular frequency of ω_m.

$$\vec{v}_{r0}^{r} = -\frac{L_m}{L_s}\left(\frac{1}{\tau_s} + j\omega_m\right).\vec{\psi}_0.e^{-t/\tau_s}, \ \ e^{j\omega_m t} \quad (25)$$

Fig. 5 shows the rotor voltage behavior during three-phase short circuit with a slip of –20%. It can be seen that, the magnitude of the rotor voltage v_{r0} reaches its maximum value at the moment of the short circuit. Using (25) and neglecting the term $1/\tau_s$ due to its small value ($\tau_S \approx 1s - 3s$) for a 1-MW machine and larger [11], [12], we have

$$V_{r0} = \frac{L_m}{L_s}\frac{\omega_m}{\omega_s} V_s = \frac{L_m}{L_s}(1-s)V_s \qquad (26)$$

According to (26), V_{r0} is proportional to $1 - s$. On the contrary, the steady-state voltage is proportional to the slip, as given in (23). Since the slip is in the range of –0.3 to 0.3 [10], it can be concluded that the amplitude of the voltage induced on the rotor winding during short circuit is closer to stator voltage.

The ratio of rotor open-circuit voltage to rotor voltage caused by rotor impedance is larger in this case compared with steady state situation. It can even be higher if the machine operates at lower slips or at supersynchronous speed.

C. Analysis Under Partial Voltage Sag

For the analysis of DFIG during partial sag, we assume that the generator is running at the nominal stator voltage, when at $t = 0$ the stator voltage dips from $\vec{v}_{s-n}$ to $\vec{v}_s$, where $\vec{v}_{s-n}$ is the nominal stator voltage:

$$\vec{v}_s = \begin{cases} \vec{v}_{s-n}, \text{ for } t < 0 \\ \vec{v}_s, \text{ for } t \geq 0 \end{cases} \qquad (27)$$

$$\vec{v}_s = r_s\vec{i}_s + \frac{d\vec{\psi}_s}{dt} \qquad (28)$$

Solving for $\vec{i}_s$ from (16) and substituting into (28) yields

$$\frac{d\vec{\psi}_s}{dt} = \vec{v}_s - \frac{r_s}{L_s}\vec{\psi}_s \qquad (29)$$

Neglecting the stator resistant, the stator flux can be written as

$$\vec{\psi}_{s-n}\ (t < 0) = \frac{\vec{v}_{s-n}}{j\omega_s} \qquad (30)$$

Replacing phasor of $\vec{v}_{s-n}$ with $V_{s-n}\ e^{j\omega_s t}$, we achieve

$$\vec{\psi}_{s-n}\ (t < 0) = \frac{\vec{v}_{s-n}}{j\omega_s}\ e^{j\omega_s t} \qquad (31)$$

A Balanced voltage sag at the stator terminal is assumed to be a step change of the stator voltage. We define h as the ratio of the stator voltage before and after the sage as follows:

$$h = \frac{|\vec{v}_s|}{|\vec{v}_{s-n}|} \qquad (32)$$

Neglecting the stator resistant, stator flux response to a voltage sag occurring at $t = 0$ is explained as follows:

$$\vec{\psi}_s\ (t) = \frac{v_s}{j\omega_s}e^{j\omega_s t} + \left(\frac{v_{s-n} - v_s}{j\omega_s}\right)e^{-(t/\tau_s)}. \qquad (33)$$

Combining (32) and (33), the stator flux can be described as

$$\vec{\psi}_s\ (t) = \vec{\psi}_{s-n}\left(\text{h} + (1-\text{h})e^{-\left(j\omega_s + (1/\tau_s)\right)t}\right). \qquad (34)$$

The second component of (34), which describes stator flux,"freezes" according to Faraday's law (apart from the slow exponential decay). This "frozen" part appears to produce a transient oscillatory stator flux that decays with the stator time constant.

By substituting (34) into (20), the rotor voltage caused by the stator flux, in stationary reference frame, is achieved as follows:

$$\vec{v}_{r0} = |\vec{v}_{s-n}|\frac{L_m}{L_s}\left(h.s.e^{j\omega_s t} - (1-h)(1-s)e^{-t/\tau_s}\right) \quad (35)$$

The two terms in (35) are different in nature. The first part is generated by the new grid voltage and its amplitude is small because it is proportional to the slip. The second voltage is the transient term and its amplitude is proportional to the depth of the voltage dip and to 1 – *s*. This voltage causes huge rise in the rotor current. Equation (35) is the rotor voltage when there is no rotor current. However, during the normal operation, the rotor converter controls the rotor current in order to achieve the active and reactive reference power. The voltage in the rotor terminals that has to be generated by the converter is provided by

$$\vec{v}_s = |\vec{v}_{s-normal}|\frac{L_m}{L_s}\left(\mathrm{h.s.}e^{j\omega_s t} - (1-\mathrm{h})(1-\mathrm{s})e^{-t/\tau_s}\right) + \left(R_r + \sigma L_r\left(\frac{d}{dt} - j\omega_m\right)\right)\vec{\iota_r} \quad (36)$$

For a short circuit at turbine terminal, the aforementioned analysis is applied by setting *h* to 0.

IV. PROPOSED **LVRT** SOLUTION WITH SERIES COMPENSATOR

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:

$$\vec{v}_s = \begin{cases} V_s e^{j\omega_s t}, & for\ t < 0 \\ 0, & for\ t \geq 0 \end{cases} \quad (37)$$

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:

$$\vec{v}_c = \begin{cases} 0, & for\ t < t_0 \\ V_c e^{j\omega_s t} e^{-t/\tau_1}, & for\ t \geq t_0 \end{cases} \quad (38)$$

Under this condition, the expression for the stator flux can be obtained from (14) and (16) as follows:

$$\frac{d\vec{\psi}_s}{dt} = \vec{v}_s - \frac{R_s}{L_s}\vec{\psi}_s \quad (39)$$

Substituting $\vec{v}_s = \vec{v}_c$, the solution to this non homogeneous first order differential equation can be found. Assuming zero delay for the compensation, the homogeneous part of (39) can be eliminated. This part corresponds to the transient flux. Solving (39) for the stator flux, we get

$$\vec{\psi}_s = \frac{V_c}{j\omega_s - (1/\tau_1) + (1/\tau_s)} e^{j\omega_s t} e^{-t/\tau_1}. \quad (40)$$

Substituting (40) into (20), the rotor voltage induced from the stator flux is obtained as follows:

$$\vec{v}_{r0} = \frac{L_m}{L_s}\left(\frac{d}{dt} - j\omega_m\right)\frac{V_c}{j\omega_s - (1/\tau_1) + (1/\tau_s)} e^{j\omega_s t} e^{-t/\tau_1} \quad (41)$$

$$\vec{v}_{r0} = \left(\frac{L_m}{L_s} V_c \frac{(j\omega_s - j\omega_m) - (1/\tau_1)}{j\omega_s - (1/\tau_1) + (1/\tau_s)}\right) e^{j\omega_s t} e^{-t/\tau_1}. \quad (42)$$

This voltage is a space vector that rotates at synchronous frequency. 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 $\tau_1 \ll \tau_s$, the rotor open circuit voltage can be written in terms of the slip as follows:

$$\vec{v}_{r0} = \left(\frac{L_m}{L_s} V_c s\right) e^{-t/\tau_1} e^{j(\omega_s - \omega_m)t}. \quad (43)$$

Substituting (43) into (21), the rotor voltage connected to the converter can be found

$$\vec{v}_r = \vec{v}_c e^{-t/\tau_1}\frac{L_m}{L_s} s + \left(R_r + \sigma L_r\left(\frac{d}{dt} - j\omega_m\right)\right)\vec{\iota}_r \quad (44)$$

The initial magnitude of the new rotor voltage at the moment of the short circuit ($t \geq t_0$) due to the stator flux equals to the magnitude of the stator voltage under normal condition and it exponentially decreases to zero with the stator time constant, as shown in Fig. 6. According to (43), 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 “frozen” component of the stator flux that causes the second term of (35) is removed. The rotor current will not rise due to a step change in stator voltage. As can be seen in (43) and (44), 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.

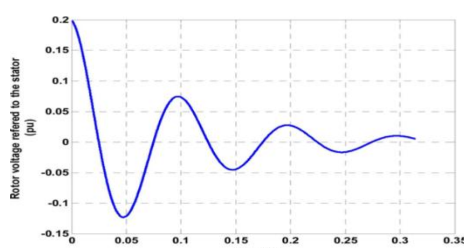

Fig. 6. Open circuit rotor voltage during short circuit with slip of –0.2 and τ_1 of 0.1 s at $t \geq t_0$.

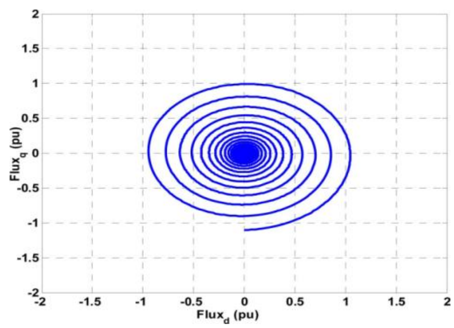

Fig. 7. Stator flux trajectory transients with compensation.

the stator circuit to keep the stator flux rotating at synchronous speed but its magnitude decreases exponentially with the time constant of τ_1 . Since the stator flux keeps rotating during the short circuit transient at stator frequency, the induced voltage in the rotor due the stator flux does not exceed its nominal value.

V. 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 ($Vs\alpha$ and $Vs\beta$) using the following transformation [7]:

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \qquad [45]$$

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

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V_{s\alpha} \\ V_{\beta} \end{bmatrix} \qquad [46]$$

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.8. 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.

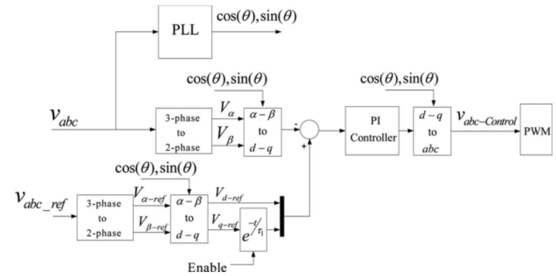

Fig. 8. Block diagram of the converter control technique.

A. Energy calculations 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.

a. Case 1

In this case, no time constant (τ 1) is introduced for the voltage compensation and the series converter provides 100% compensation during short circuit. We will have

$$E = \int_0^{0.2} \sqrt{3}\, V_c I \qquad [47]$$

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

$$C = \frac{2\int_0^{0.2} \sqrt{3} V_c\, I}{\Delta V^2} \qquad [48]$$

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.

b. Case 2

In this case, time constant τ_1 is introduced for the voltage
compensation. Substituting $V_c = V_c\, e^{-t/\tau 1}$ into (48), we get

$$C = \frac{2E}{V^2} = \frac{2\int_0^{0.2} \sqrt{3}.V_c e^{-t/\tau_1}.I}{V^2} \qquad [49]$$

From the aforementioned equation, it can be found that the energy delivered is a function of the time constant τ_1 and can be controlled by adjusting it. In addition, the capacitor size can also be significantly reduced. Fig. 9 shows the active and reactive power

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of the turbine during short circuit with compensation. Both power decline to zero after a fast transient.

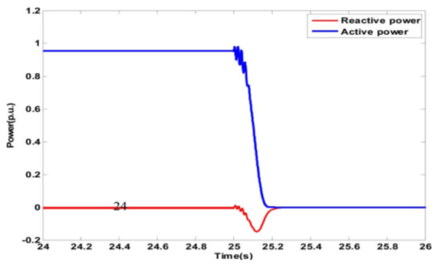

Fig. 9. Active and reactive power delivered with exponentially decaying voltage compensation ($V_c = V_c\, e^{-t/\tau 1}$).

VI.SIMULATION RTESULTS

Fig.10 shows the simulation results for the system behavior during a symmetrical three-phase short circuit at $t = 0.1$ s.The rotor current rises to 2 p.u. 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.

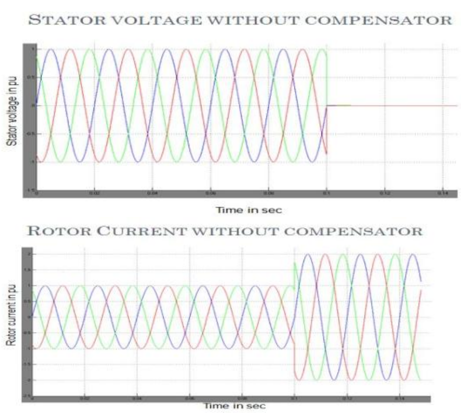

Fig. 10. Simulation results for a three-phase short circuit on the terminal of a 1.5-MW DFIG wind turbine.

Fig. 9 shows the system behavior with voltage compensation. The simulation result reveals the effectiveness of the proposed solution 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. The partial voltage compensation with an initial magnitude of 50%, the rotor current is approximately rises to 2.5 p.u. As the converter can tolerate transient currents of up to three times its rated current, the partial voltage compensation guarantees successful voltage ride though with a smaller energy storage requirements and smaller series converter rating.

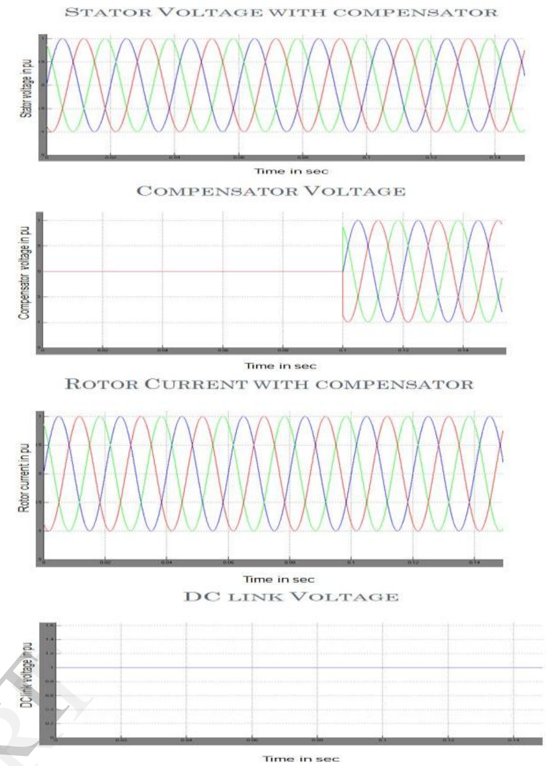

Fig. 9. Simulation results for a three-phase short circuit on the terminal of a 1.5-MW DFIG wind turbine when a full compensation is applied.

VII. CONCLUSION

During the grid side voltage sag DFIG is subject to intense stress. Additional measures must be taken to protect the turbine and provide LVRT even at zero grid voltage in accordance with utility requirements. DFIG Wind turbine equipped with series voltage compensator described in this paper is able to provide LVRT solution and the wind turbine stay connected to the grid and limits 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. In the new grid code requirements, the wind power generators must be capable of supporting to the network during the steady and abnormal conditions. In this paper, new Series Grid-Side Converter (SGSC) topology is explored. The dynamic performance with a proposed controller is investigated using voltage sag and step response to reactive power injection. It has been shown that dynamic performance of modified DFIG is well damped and far better than conventional DFIG. During the abnormal conditions, the modified DFIG out performs with the proposed controllers. It is shown that during steady state the series converter can be utilized to provide reactive power capability. 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.

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