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# Low-Voltage Ride-Through Solution for a grid connected DFIG Wind Turbine using Series Voltage Compensation

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**ABSTRACT**

*This paper presents a new solution for doubly fed induction generators to stay connected to the grid at the time of faults and sags. To create the required flux to keep the rotor side converter current below its transient rating the stator voltage is increased to certain level at the time of faults. In order to maintain that one we are injecting the required voltage in series to the stator side line by designing a series compensator. The series converter will examine the grid voltages 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.*

**KEY WORDS:** *low-voltage ride-through, DFIG, injected voltage*

## INTRODUCTION

With the increase in penetration of wind in power generation, the dynamic behavior of the power system will change because of various technologies used for wind and conventional generators. The DFIG is the most widely used device for wind power generation. DFIG is a popular WT system due to advantages like it can operate in generator and motor mode for both sub and super-synchronous speed mode, also speed variation of ±30% around synchronous speed can be obtained, and the size of the converter is related to the selected speed range. Recently, the number of small size wind farm based on DFIG located within the distribution system is increasing at a very fast rate. As the penetration of wind power continually increases, more wind turbines are required to stay, grid connected during a grid fault to maintain the reliability during and after a short-term fault [1]. The capability of WT to stay connected to the grid during voltage dips is called as the low-voltage ride-through (LVRT) capability. In order to fulfill the LVRT conditions for DFIG based WTs, there are two important conditions to be considered during a fault condition. The first is the over-current that can occur in rotor and stator circuits, while the second is over voltage in the DC-link, both leads to the unbalanced energy that cannot be transmitted into the grid. For reducing the inrush currents in the rotor and the DC-link over-voltage during the faults, an advanced control strategies for the rotor and grid side converters is used.

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.

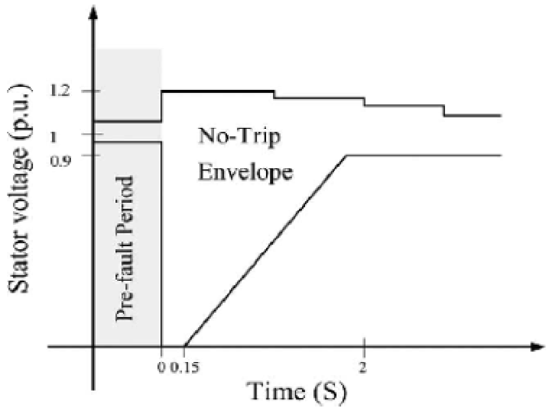



**Fig.1:** WECC voltage ride-through requirements for all generators. 494

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 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

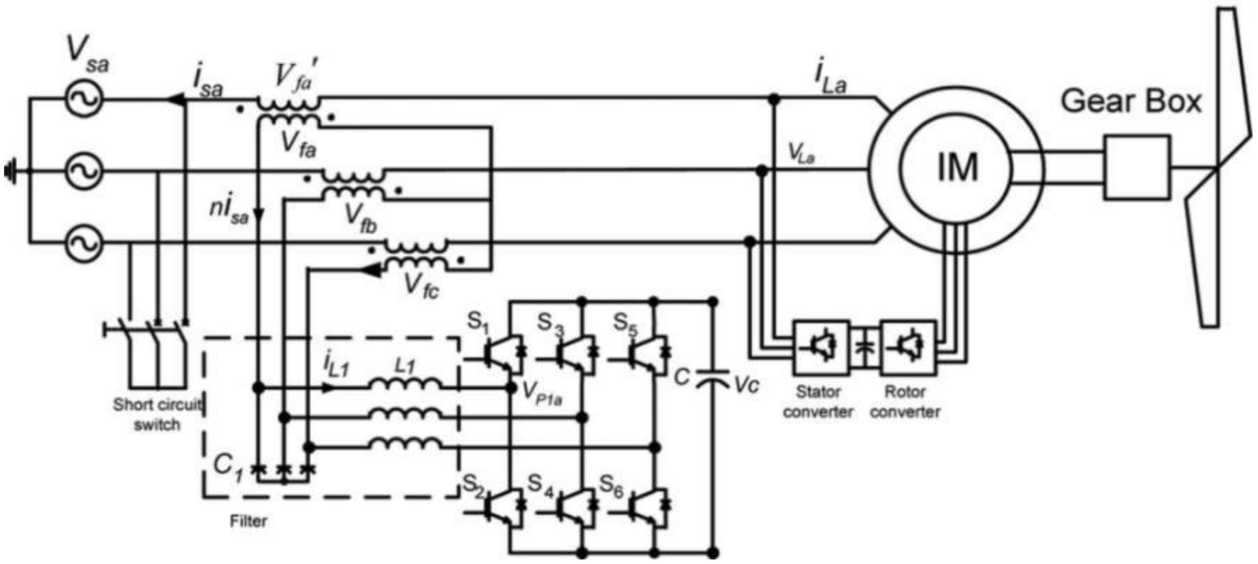



**fig. 2.** Configuration for series converter for the proposed LVRT solution

## DFIG WIND TURBINE

DFIG is an abbreviation for Double Fed Induction Generator, a generating principle widely used in wind turbines. It is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings. It is possible to avoid the multiphase slip ring assembly (see brushless doubly fed electric machines), but there are problems with efficiency, cost and size. A better alternative is a brushless wound-rotor doubly fed electric machine.

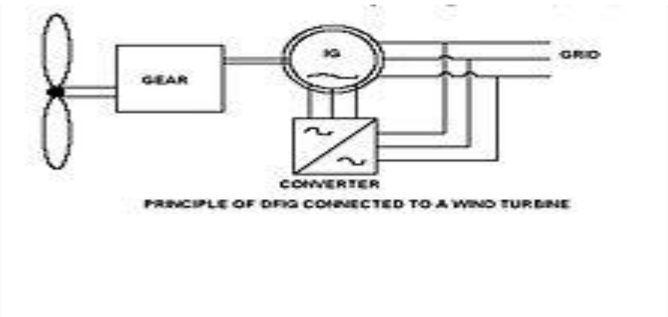



**Fig 2.1** Principle of a Double Fed Induction Generator connected to a wind turbine

The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis current vector control or direct torque control (DTC).[13]DTC has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.[14]

A. **DFIG Modeling Using Dynamic Vector Approach**

Most 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.

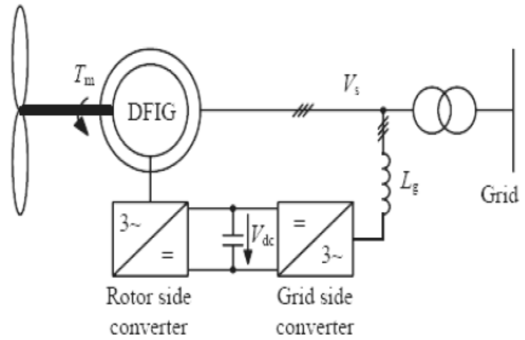



**Fig.3**. Configuration of a DFIG wind turbine system

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, φdsφ'qrφ'dr*in state space form are derived.Substituting the conditions ω = ωr and *V*qr=*V*dr=0 in the flux linkage equation, we get:

$$\boldsymbol{\varphi}qs=\boldsymbol{\omega b}\int(\boldsymbol{Vqs}-\boldsymbol{\omega r}/\boldsymbol{\omega b\varphi}ds+rs/xls(\boldsymbol{\varphi}mq-\boldsymbol{\varphi}qs)) \quad (1)$$

$$\boldsymbol{\varphi}ds=\boldsymbol{\omega b}\int(\boldsymbol{Vds}-\boldsymbol{\omega r}/\boldsymbol{\omega b\varphi}qs+rs/xls(\boldsymbol{\varphi}md-\boldsymbol{\varphi}ds)) \quad (2)$$

$$\boldsymbol{\varphi}'qr=\boldsymbol{\omega b}\int(\boldsymbol{r'r}/xlr(\boldsymbol{\varphi}mq-\boldsymbol{\varphi}'qr)) \quad (3)$$

$$\boldsymbol{\varphi}'dr=\boldsymbol{\omega b}\int(\boldsymbol{r'r}/xlr(\boldsymbol{\varphi}md-\boldsymbol{\varphi}'dr)) \quad (4)$$

The currents can now be calculated

$iqs = (\varphi qs - \varphi mq)/xls$ (5)

$ids = (\varphi ds - \varphi md)/xls$ (6)

$i'qr = (\varphi'qr - \varphi mq)/x'ls$ (7)

$i'dr = (\varphi'dr - \varphi md)/x'lr$ (8)

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

$\varphi mq = xm\ (\varphi qs/xls + \varphi'qr/x'lr$ (9)

$\varphi md = xm\ (\varphi ds/xls + \varphi'dr/x'lr$ (10)

Where $xm = 1/(1/xm + 1/xls + 1/xlr$

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, iqs and i′qr respectively and φqs, iqs arc used in the calculation of electromagnetic torque. The rotor circuit makes use of the φqs, iqs obtained from the q-axis circuit and $\varphi ds$, $iqs$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 $\varphi qs,\ iqs\ and\ \varphi ds,\ ids,$ the electromagnetic torque can be calculated by;

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

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

$$J\left({d\omega_m}/{dt}\right) = T_{em} + T_{mech} - T_{damp}\ (12)$$

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

$$2Hd\ (\omega_\tau/\omega_b)/dt = T_{em} + T_{mech} - T_{damp}\ (13)$$

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

## ANALYSIS OF DFIG DURING GRID FAULT

Whenever any fault occurs in the grid side that effect will falls on the DFIG so we want to analysis the dfig at the time of faults sccording to that faults we want to design it

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

$$\vec{v}_s = R_s\vec{i}_s + \frac{d}{dt}\vec{\Psi}_s\ (14)$$

$$\vec{v}_r = R_r\vec{i}_r + \frac{d}{dt}\vec{\Psi}_r - j\omega_m\vec{\Psi}_r\ (15)$$

The stator and rotor fluxes are given by

$$\vec{\Psi}_s = L_s\vec{i}_s + L_m\vec{i}_r\ (16)$$

$$\vec{\Psi}_r = L_r\vec{i}_r + L_m\vec{i}_s\ (17)$$

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

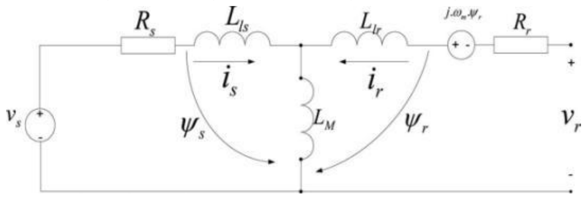



**Fig.4.** DFIG- equivalent circuit for short circuit analysis.

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 is from (16) and substituting into (17).

$$\vec{\Psi}_r = \frac{L_m}{L_s}\overrightarrow{\Psi_s} - \sigma L_r.\vec{i}_r\ , \sigma = 1 - \frac{L_m^2}{L_s.L_r}\ (18)$$

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

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

The first term is the open circuit voltage $vr$ 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 $vr0$:

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

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

wheres is the slip (s = ωr/ωs, ωr = ωs -ωm).

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 (21) is smaller than Vr0 . The rotor voltage due to the stator flux can be written as [10].

$$\vec{v}_{ro} = j\omega_r \frac{L_m}{L_s}\vec{\Psi}_s = \frac{\omega_r}{\omega_s}\frac{L_m}{L_s} V_s e^{-j\omega_s t} \quad (22)$$

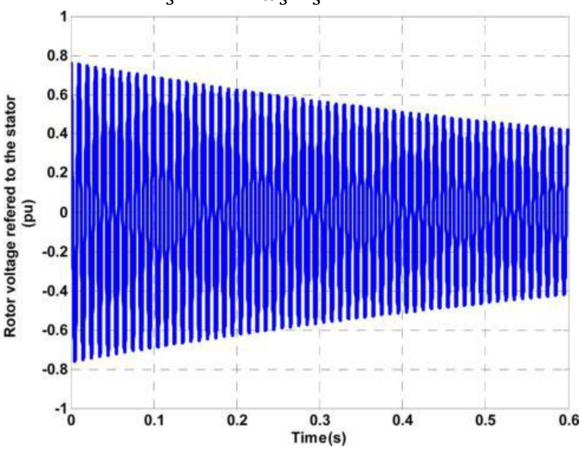



**Fig.5.** Rotor voltage with-0.2 slip and 1s stator time constant

The amplitude of the voltage $vr0$ can be described as a function of the amplitude of the stator voltage as follows:

$$v_{ro} = \frac{L_m}{L_s} s V_s \quad (23)$$

During the normal operating condition, the rotor voltage $vr0$ 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

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

where ψ0 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 *ωm.*

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

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 $vr0$ 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

$$v_{ro} = \frac{L_m}{L_s}\frac{\omega_m}{\omega_s} V_s = \frac{L_m}{L_s}(1 - S)V_s. \quad (26)$$

According to (26), $Vr0$ 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 super synchronous 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 $vs{-}n$ to , where $vs{-}n$ is the nominal stator voltage:

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

$$\vec{v}_s = r_s \vec{\iota}_s + \frac{d\vec{\Psi}_s}{dt} \quad (28)$$

Solving for $is$ from (16) and substituting into (28) yields

$$\frac{d\vec{\Psi}_s}{dt} = \vec{v}_s - \frac{r_s}{L_s}\vec{\Psi}_0 \quad (29)$$

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

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

Replacing phasor of $vs-n$ with $Vs-n$ , we achieve

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

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:

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

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

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

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

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

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:

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

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

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

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

## PROPOSED LVRT SOLUTION WITH SERIES COMPENSATOR

In electricity supply and generation, low voltage ride through (LVRT), or fault ride through (FRT), is a capability of electrical devices, especially wind generators, to be able to operate through periods of lower grid voltage. Similar requirements for critical loads such as computer systems and industrial processes are often handled through the use of anuninterruptible power supply (UPS) to supply make-up power during these events.

To start analyzing the proposed solution, it is assumed that the generator is operating under normal condition when at time $t0$ a three-phase short circuit occurs:

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

As soon as the short circuit is detected, we apply a voltage vector of $vc$via the series converter on the stator, where $|vc|$ = $|vs|$ at $t$ = 0, and $\tau$ 1 is the time constant to be quantified later from energy equations of the system. Vector $vc$ is rotating with the speed of $\omega$sand its magnitude is declining with the time constant of $\tau$ 1 :

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

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

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

Substituting $vs$= , 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:

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

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

This voltage is a space vector that rotates at synchronous frequency. Its amplitude decreases exponentially with the time constant of $\tau 1$ . 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:

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

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

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

The initial magnitude of the new rotor voltage at the moment of the short circuit ($t \geq t0$ ) 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 $\tau 1$ . 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 $\tau 1$ . 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.

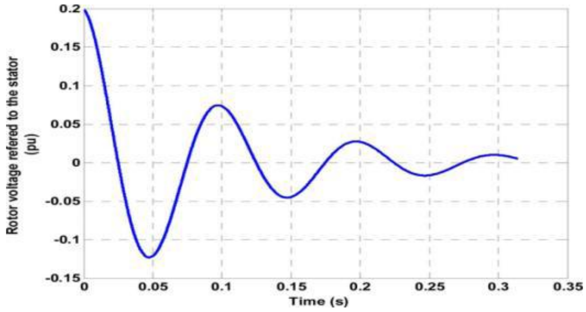



**Fig. 6.** Open circuit rotor voltage during short circuit with slip of –0.2 and τ1 of 0.1 s at t ≥ t0 .

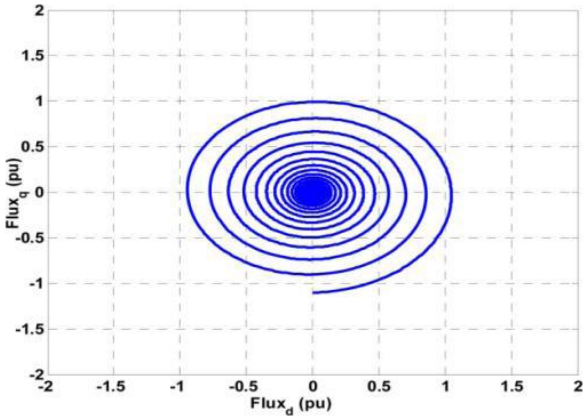



**Fig. 7.** Stator flux trajectory transients with compensation.

the stator circuit to keep the stator flux rotating at synchronous speed but its magnitude decreases exponentially with the time constant of $\tau 1$ . 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.

## CONTROL TECHNIQUE

In order maintain the DFIG without any problem we want to design a control technique for the series converter so it is as follows. In this section, the control technique for the series converter is described. The measured grid voltages ($Vsa$,$Vsb$, and $Vsc$) are converted into the stationary reference frame voltage quantities ($Vs\alpha$ and $Vs\beta$ ) using the following transformation [7]:

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

A phase lock loop (PLL) is used to generate the grid voltage angle

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

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.

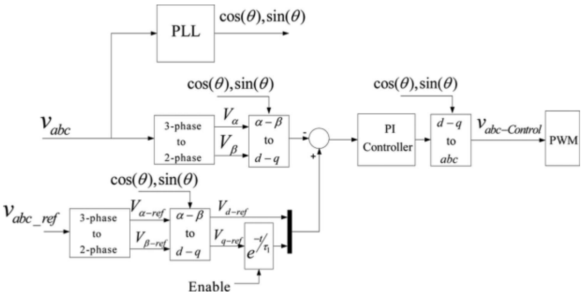



**Fig. 8**. Block diagram of the converter control technique.

*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 ($\tau$ 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. $VC$ 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

$$C = \frac{2\int_0^{0.2} \sqrt{3} V_c I}{\Delta V^2} \quad (48)$$

where $\Delta V$ 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 $\tau 1$ is introduced for the voltage compensation. Substituting $Vc = Vc\ e{-}t/\tau 1$ into (48), we get

$$C = \frac{2E}{V^2} = \frac{2\int_0^{0.2} \sqrt{3}\, V_c I e^{-t/\tau_1}}{V^2} (49)$$

From the aforementioned equation, it can be found that the energy delivered is a function of the time constant $\tau 1$ 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 of the turbine during short circuit with compensation. Both power decline to zero after a fast transient.

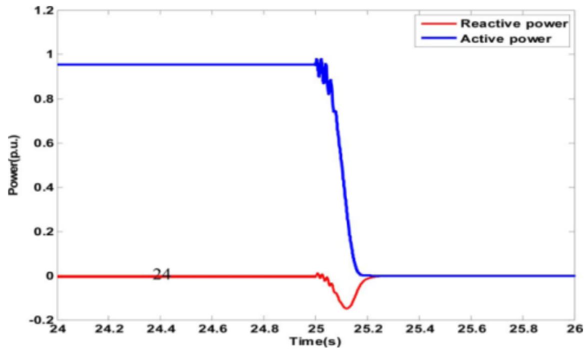
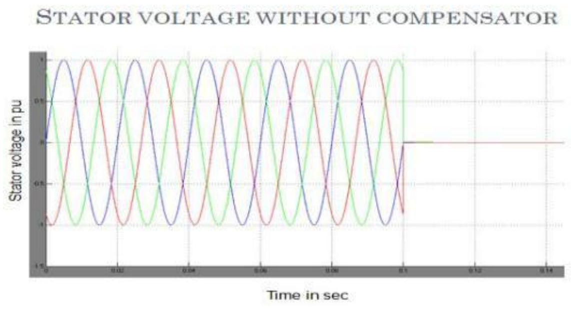



**Fig. 9.** Active and reactive power delivered with exponentially decaying voltage compensation (Vc = Vc e−t/ τ1 ).

## SIMULATION RTESULTS

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 transientis shown Fig.10. These short circuit characteristics are what make the system very venerable to short circuit.



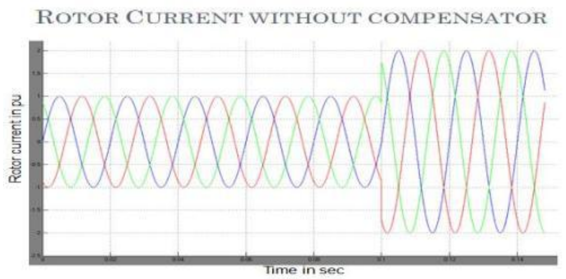
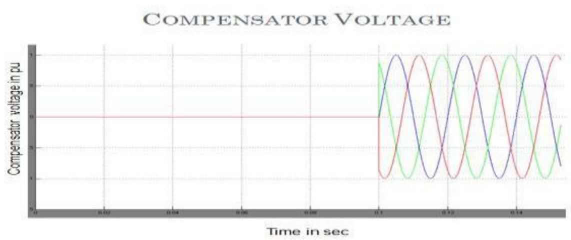
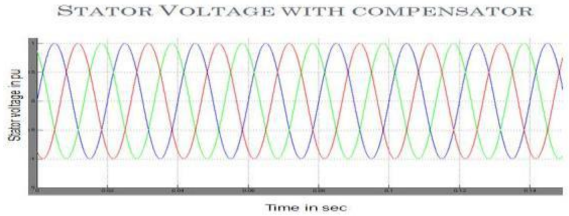



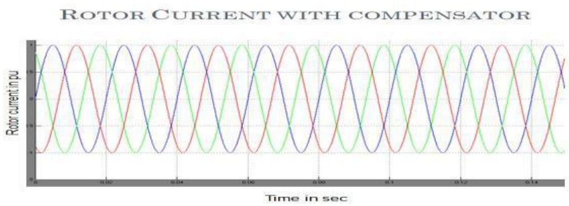

**Fig. 10.** Simulation results for a three-phase short circuit on the terminal of a 1.5-MW DFIG wind turbine.

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.



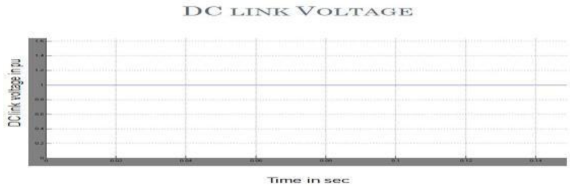




**Fig. 9.** Simulation results for a three-phase short circuit on the terminal of a 1.5-MW DFIG wind turbine when a full compensation is applied.

## CONCLUSION

High penetration of WTs imposes a big challenge to the safe operation of power systems. To ensure the security of electricity supply with substantial wind power, the WTs must ride through during voltage dip caused due to different grid faults. The effect of three phase short circuit fault on grid voltage is most severe. Fluctuations with regard to grid voltage, rotor speed, real power, reactive power, rotor andstator current , dc link voltage, shaft torque and pitch angle ismaximum for three phase short circuit fault followed bydouble line to ground fault and then single line to groundfault. While connecting a local load in between DFIG and grid LVRT requirements should be confirmed which otherwise may lead to LVRT failure during fault. 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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