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Sustainable operation and performance improvement of grid connected DFIG during symmetrical faults using fuzzy controller based enhanced field oriented control

D.V.N. Ananth1 and G.V. Nagesh Kumar2*

Abstract: According to modern grid regulations, doubly fed induction generator (DFIG) needs to operate without losing synchronism during grid faults. But, severe fault leads to rise in stator and rotor current to a higher value and generator will get damaged. Large oscillations in stator real and reactive power are produced and consequently large torque oscillations get developed. To overcome the above affects due to severe faults, enhanced field oriented control technique (EFOC) is adopted in rotor side control of the DFIG. In EFOC technique, rotor flux reference changes its value from synchronous speed to zero or to a smaller value during fault for injecting current at the rotor slip frequency. In this method, DC-offset component of stator flux is controlled to minimize it. This offset decomposition of flux will be oscillatory in a conventional FOC, whereas in EFOC it can damp quickly. The reference frame for rotor during fault changes with EFOC, so as to make the rotor speed not to deviate much from the reference value. This makes the decomposition of flux during fault to be controlled and make the generator winding current not to exceed to higher values. The proposed EFOC technique with fuzzy controller can damp pulsations in electromagnetic oscillations, improve voltage mitigation and limit surge currents.

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PUBLIC INTEREST STATEMENT
To meet increasing electric power demands, conventional power plants like coal or oil based thermal power stations are alone not sufficient and are not eco-friendly. So, wind power plants are getting importance, as wind is used to drive the wind turbine, which further makes the generator shaft to rotate and produce electricity. The doubly-fed induction wind generators are beneficial as large power ratings are available. These generators are sensitive to faults occurring at the grid. These faults make the generators rotate around higher speed and also the fault currents rushing into the generator will damage the windings. Hence protection and further stability improvement in the operation during and after the fault are important. Nearly 50% of the faults are because of a turbine and 10% by generators and requires more attention for later. For this, enhanced field oriented control scheme is developed to control the generator speed and inrushing currents.
and to have sustained operation of DFIG during voltage sags. The performance of the grid connected DFIG system with voltage sag of 40 and 70% of the rated voltage with symmetrical fault occurring at point of common coupling between 0.1 and 0.3 s are analyzed using simulation studies.

Subjects: Intelligent Systems; Power Electronics; Power Engineering; Renewable Energy; Systems & Controls

Keywords: DFIG; field oriented control (FOC); low voltage fault ride through (LVRT); voltage sag; voltage mitigation, torque oscillations; torque oscillations

1. Introduction

The doubly fed induction generator (DFIG) is preferred due to its small size and higher MVA ratings available in the market. It has low power ratings of converters, variable generator speed and constant frequency operation, robust four quadrant reactive power control. It has better performance during the High and Low Voltage Ride Through (HVRT and LVRT) compared to other generators of the same class. However, DFIG is sensitive to external disturbances like voltage swell and sag as it is directly connected to the grid. If the grid voltage falls suddenly due to any reason, large surge currents enter into the generator terminals which damage the windings and power converters. Apart from this, there will be huge Electromagnetic Torque (EMT) pulsations and increase in rotor speed which may reduce the lifetime of wind turbine gears. Since the occurrence of these faults is high, many researchers got motivated to limit that affects due to grid disturbances.

The status of research on the LVRT issue for DFIG for symmetrical and asymmetrical faults and comparison of different control strategies is given in (Wang, Zhao, Zhao, & Xu, 2010). Understanding the capability of RSC to deliver desired reactive power and withstanding capability during a fault in (Shuai, Hua, Honglin, & Geng, 2013). LVRT enhancement based on flux trajectory (Shuai, Geng, Honglin, & Hua, 2013), enhanced reactive power support (Dong liang, Zha, Lihiu, & Ostergaard, 2013), controlling DC link current of RSC to smoothen DC voltage fluctuations due to grid faults using stored Kinetic Energy (Lihui, Zhao, Ostergaard, Zhao Yang, & Kit Po, 2012), crowbar as passive and RSC strategy as active compensation for LVRT reactive power (Q) compensation (Rahimi & Parniani, 2010). The FFTC schematics with PIR (Jiaqi, Howard, Restrepo, & Harley, 2013) and PI (Jiaqi, Wei, & Harley, 2010) controllers are used for enhanced operation during symmetrical and asymmetrical faults. This scheme is also preferred for improving uninterrupted real and reactive power (P and Q) supply from WT to the grid. Few intelligent control techniques like Genetic Algorithm (GA) (Vrionis, Koutiva, & Vovos, 2014) and bacterial search, etc. were used in control strategies for improving the performance during LVRT.

The LVRT capability using GA through fuzzy controller (FC) is proposed to limit over-currents in the rotor windings. In this, DC side over-voltages with reactive power during and after the fault, contributing to the support of the AC voltage is proposed in (Vrionis, Koutiva, & Vovos, 2014). To limit the rotor side over-currents with the use of a virtual resistance in combination with demagnetization control is proposed in (Hu, Lin, Kang, & Zou, 2011; Zhou, Liu, & Zhou, 2014) but the drawbacks huge inrush fault current to rotor circuit and torque oscillations still cannot be avoided. A comparison is made with well tuned PI and fuzzy logic controller (FLC) and observed that crowbar system can be eliminated by managing fault current if FC is used (deAlmeida, Lopes, & Barreiros, 2004). But for this analysis, a weaker grid is chosen instead of a standard grid system. For tuning PI controller parameters for a rotor converter for enhanced operation during grid faults, genetic algorithm is used (Vieira, Nunes, Bezerra, & Nascimento, 2009). This GA based technique showed a better reduction in over-current in the rotor circuit during faults but there is no analytical explanation of how the performance is achieved. A prototype system was proposed to overcome asymmetrical faults are given in (Hu, He, Xu, & Williams, 2009; Santos-Martín, Rodriguez-Amenedo, & Arnautes, 2009; Wang, Xu, & Williams, 2009; Xu, 2008; Xu & Wang, 2007; Yi Zhou, Bauer, Ferreira, & Pierik, 2009). In (Mak, Ni, & Shen, 2000), DFIG voltage and frequency support in a micro grid system are
exploited using FC. Wind turbine optimal power absorption is evaluated and found that in the transient period, the proposed system can perform well with zero storage devices. Also in (Mak et al., 2000), look-up table method with the FC was designed to damp the inter-area power oscillations and improved dynamic stability of the interconnected power systems. It is found that the FC can damp power oscillations with improved performance under changed system operating conditions. However, in this paper, the major drawback of the FC like based on the knowledge and experience of the designer is not considered for authors. Hence self-learning ability of ANN with the linguistic expression function of fuzzy inference is used in (Jang, 1993; Khuntia & Panda, 2010).

Recently few papers are proposed novel control schemes that do not require a crowbar (Huang, Zhu, & Kang, 2015). These papers used fault current limiters SMES etc. to limit surge currents (Huang et al., 2015; Shen et al., 2015; Zhou et al., 2014; Zhu, Chen, Wu, & Deng, 2015). The LVRT with external devices like fault current limiter are used to suppress surge currents produced in the rotor during severe faults (Guo et al., 2014, 2015; Xiao, Yang, & Geng, 2011). In the above control schemes, the torque is fixed to zero and the reactive power must be drawn from the grid. This makes the DFIG system to more prone to the fault and weakens the system. The demagnetization control technique is widely used to suppress the natural stator flux components which help in damp flux oscillations. However, from literature it is found that demagnetization technique is sensitive to variation in the system parameter as stator resistance knowledge is required. The above sensitivity can be reduced by combining with virtual resistance methodology or arbitrary change in the RSC phase locked loop (PLL) reference in changing the arbitrary value of speed of stator and rotor reference. The above effects are reduced by changing mostly the inner current control loop with surge current limiters and fast acting control strategy. Hence for this, our EFOC technique is adopted with fast changing inner control loop with arbitrary changing speed reference with surge current limiter technique. The flux decomposition is also controlled with our proposed control scheme.

In the Section 2, design of converters for EFOC is explained. In Section 3, mathematical modeling of wind turbine and generator converters for the grid connected DFIG was explained during transient state. In this section, effect of the system during symmetrical fault, EFOC control technique and behavior of mechanical and electrical system with variation in rotor speed is explained in subsections. In Section 4, rules for FC are described briefly. Further Sections 5 describe the simulation results with voltage sag of 40 and 70% of the rated voltage with FC is verified using the MATLAB environment. The conclusion is given in Section 6 followed by Appendix A and references.

2. Design of rotor side converter control for EFOC
RSC controller helps in improving reactive power demand at grid and to extract maximum power from the machine by making the rotor to run at optimal speed. The optimal speed of the rotor is decided from machine real power and rotor speed characteristic curves from MPPT algorithm. The stator active and reactive power control is possible with the RSC controller strategy through $i_r$ and $i_q$ components controlling respectively. The rotor voltage in a stationary reference frame (Hu et al., 2011) and further analysis from (Ananth & NageshKumar, 2015) is given by

\[ V_r^s = V_{br}^s + R_i^s + \sigma L_r \frac{di_r^s}{dt} - j\omega_i f_i^s, \]  

with $\sigma = 1 - \frac{L_r}{L_s}$ and $\omega_i$ is the rotor speed, $f_i^s$ is the rotor current in a stationary frame of reference, $L_s, L_r$ and $L_m$ are stator, the rotor and mutual inductance parameters in Henry or in per-unit (pu). $V_{br}^s$ is initial rotor voltage in stationary frame. $R_i$ is rotor resistance in ohms or in per-unit (pu). The initial rotor voltage in stationary frame can be written as

\[ V_{br}^s = \frac{L_m}{L_s} \left( \frac{d}{dt} - j\omega \right) \Phi_s^r \]  

is the rotor voltage induced in to the stator windings with $\Phi_s^r$ and $\Phi_r^s$ as stationary reference frame stator and rotor flux.
\[ \Phi_s^* = L_s i_s^* + L_m i_s \]  \hspace{1cm} (2)

\[ \Phi_r^* = L_r i_r^* + L_m i_r \]  \hspace{1cm} (3)

Here \( i_s^* \) is the stator current in a stationary frame of reference.

The Equation 1(a) in terms of rotor current and rotor flux can be written as

\[ V_r^* = R_i i_r^* + \frac{d}{dt} (\Phi_r^*) - j \omega_s \Phi_r^* \]  \hspace{1cm} (4)

From the basic equations of DFIG available in the literature, the Equation (4) can be rewritten as

\[ V_r^* = R_i i_r^* + \frac{d}{dt} \left( \frac{L_m}{L_s} \Phi_s^* + \sigma L_s i_r \right) - j \omega_s \left( \frac{L_m}{L_s} \Phi_s^* + \sigma L_s i_r \right) \]  \hspace{1cm} (5)

Also,

\[ \Phi_s^* = \frac{V_s}{j \omega_s} e^{j \omega_t t} \]  \hspace{1cm} (6)

is the stator flux under normal conditions.

Rewriting the above Equation (5), we get

\[ V_s^* = \left( R_i i_r^* + \sigma L_s i_r \frac{di_r^*}{dt} - j \omega_s \sigma L_s i_r \right) + \left( \frac{L_m}{L_s} \frac{d\Phi_s^*}{dt} - j \omega_s \frac{L_m}{L_s} \Phi_s^* \right) \]  \hspace{1cm} (7)

Substituting Equation (6) in (7)

\[ V_s^* = \left( R_i i_r^* + \sigma L_s i_r \frac{di_r^*}{dt} - j \omega_s \sigma L_s i_r \right) + \left( \frac{L_m}{L_s} s V_s^* e^{j \omega_t t} - j \omega_s \frac{L_m}{L_s} V_s^* e^{j \omega_t t} \right) \]  \hspace{1cm} (8)

Here “s” is slip speed, \( \omega_s \) is slip rotor speed and \( \omega_s \) is synchronous speed of stator.

From the literature, the \( d \) and \( q \) axis rotor voltage equations and the stator and rotor two axis fluxes are given by

\[
\begin{align*}
V_{dr} &= \frac{d\Phi_{dr}}{dt} - \left( \omega_s - \omega \right) \Phi_{qr} + R_i i_{dr} \\
VV_{qr} &= \frac{d\Phi_{qr}}{dt} - \left( \omega_s - \omega \right) \Phi_{dr} + R_i i_{qr} \\
\Phi_{dr} &= \left( L_d + L_m \right) i_{dr} + L_m i_{ds} \\
\Phi_{qr} &= \left( L_q + L_m \right) i_{qr} + L_m i_{qs} \\
\Phi_{ds} &= \left( L_d + L_m \right) i_{ds} + L_m i_{dr} \\
\Phi_{qs} &= \left( L_q + L_m \right) i_{qs} + L_m i_{qr}
\end{align*}
\]  \hspace{1cm} (9)

From the basic equations of DFIG (Hu et al., 2011), the rotor \( d \) and \( q \) axis voltages are expressed as

\[ V_{dr} = \left( R_i + \frac{dL_i}{dt} \right) i_{dr} - s \omega_s L_i i_{qr} + \frac{L_m}{L_s} V_{ds} \]  \hspace{1cm} (10)

\[ V_{qr} = \left( R_i + \frac{dL_i}{dt} \right) i_{qr} - s \omega_s L_i i_{dr} + \frac{L_m}{L_s} \left( V_{qs} - \omega \Phi_{ds} \right) \]  \hspace{1cm} (11)
where $\omega$ is rotor speed, $\omega_{q_s}$ is speed of stator flux, $\omega_s$ is synchronous speed.

The block diagram based on the control circuit of RSC for enhancing performance for LVRT issues are given in Figure 1. The right side corner with subsystem 2 is a sub-circuit of the controller for EFOC technique and its design is shown later in flow chart Figure 3. The above Equations (10) and (11) can be rewritten in terms of decoupled parameters and are designed for RSC controller as in Equations (12) and (13).

\[
\sigma V_{dr} = \sigma L_r \frac{dI_{dr}}{dt} - \omega_s \Phi_{ds} + \frac{L_m}{L_s} \left( V_{ds} - R_s i_{ds} + \omega_1 \Phi_{qs} \right)
\]

(12)

\[
\sigma V_{qr} = \sigma L_r \frac{dI_{qr}}{dt} - \omega_s \Phi_{dr} - \frac{L_m}{L_s} \left( R_s i_{ds} + \omega_1 \Phi_{ds} \right)
\]

(13)

In general the rotor speed $\omega_r$ is and the synchronous speed of stator is $\omega_s$. But this synchronous frequency has to be changed from $\omega_s$ to a new synchronous speed value as described in flowchart later $\omega_1$, as it is represented commonly by $\omega_1$. Under ideal conditions, reference stator $d$-axis flux $\Phi_{d}^*$ is zero and $q$-axis flux $\Phi_{q}^*$ is equal to the magnitude of stator flux $\Phi$ for given back emf and rotor speed. The transient rotor $dq$ axis current is given by Equations (14a) and (14b) as

\[
\frac{di_{dr}}{dt} = -\frac{R_r}{\sigma L_r} i_{dr} + \sigma \omega_s i_{qr} + \frac{1}{\sigma L_r} V_{dr}
\]

(14a)

\[
\frac{di_{qr}}{dt} = -\frac{1}{\sigma} \left( \frac{R_r}{L_r} + \frac{R_m L_s^2}{L_r L^2} \right) i_{qr} - \sigma \omega_j i_{dr} + \frac{1}{\sigma L_r} V_{qr}
\]

(14b)

The reference rotor voltages in $dq$ transformation can be rewritten from Equations (12) and (13) and from the control circuit are given below. This is the output voltage from rotor windings during normal and transient conditions.

\[
V_{dr}^* = \left( i_{qr} + \frac{R_r}{\sigma L_r} i_{dr} - \sigma \omega_j i_{dr} \right) \sigma L_r
\]

(15a)
The Equations (12)–(15) describe the design procedure for RSC and the necessity to control the rotor and voltage parameters. The Equations (16)–(24) are helpful in understanding the behaviour of DFIG during and after the faults. The Equation (16) describes the flux change during sudden transient and its exponential decay. The interaction between stator and rotor flux during the fault and control in the decay in stator flux understanding are important for effective operation during faults. The Equations from (17) to (21) are back emf component in the rotor during normal and transient conditions and is represented with equivalent diagram as in Figure 2. The Equations (22)–(24) describes how the stator flux changes during the fault. To control the flux interaction between stator and rotor, rotor reference flux need to be changed. This can be achieved by controlling more effectively the decay of flux during a fault. For this, rotor speed has to be changed as described by Equations (23) and (24) to make the rotor to rotate at different speed other than at slip speed described by $\omega_f$. The procedure for this is described in Figure 3 and in Section 3.2 with internal control circuit.

The dc voltage maintenance across the capacitor is also very important during the fault. Also, GSC need to supply reactive power like a shunt compensator to improve voltage profile after the fault instant. Hence the robust GSC controller strategy needs to be adopted. The future scope can be, decrease in surges and maintenance of constant stator and rotor current value during any disturbance. With the proposed control strategy, smooth transition in electromagnetic torque is achieved during symmetrical fault based transient state of drop in grid voltage and restoring is possible. The dynamic stability of DFIG was improved and thereby mitigation of generator stator and rotor voltages and current are superior with EFOC fuzzy technique. The output power from the generator is better damping the transient stator flux. This is possible by changing the reference flux reference value by choosing particular stator flux ($\lambda_s$) value. Otherwise over current in the rotor winding makes the system performance and lifetime to degrade under these situations.

The overall block diagram of the RSC is presented in Figure 1. The rotor speed is multiplied with pole numbers and is subtracted from angular grid synchronous frequency. Later integrated and given a 90° phase shift to get rotor slip injection frequency angles ($\theta_s$). At this slip frequency RSC converter injects current into the rotor circuit to control the rotor speed for optimum value and to control grid reactive power. The stator voltage magnitude is compared and controlled using PI or FC controller to get $q$-axis current. Similarly rotor actual speed and optimal speed reference are controlled using PI or FC to get $d$-axis reference current. They are compared with an actual rotor $d$ and $q$ axis currents and controlled with tuned PI controllers to get the rotor injecting $d$ and $q$ axis voltages. The $d$ and $q$ voltages are converted into three axis abc voltage by using a PLL with inverse Park's transformation and are given to a PWM pulse generator for getting pulses to RSC converter.

The flux derivation technique helps in understanding the operation of DFIG during steady state and transient state. The accuracy of system performance during steady state depends on accuracy of wind speed measurement action of the pitch angle controller, measurement of stator current, voltage, flux and other important parameters. The more accurate these measurements, the more can be a real power extracted from the DFIG wind turbine system. The Equations (14)–(17) plays a vital role in understanding the behavior of DFIG during steady state and accuracy of RSC control action depends on control of the $d$ and $q$ axis voltages.

\[
V_{qr}^* = \left( i_{dr}^* + \frac{1}{\sigma} \left( \frac{R_r}{L_r} + \frac{R_r L_m^2}{L_r^2 L_{dr}} \right) i_{qr}^* + \sigma \omega_f i_{qr} \right) \sigma L_r
\]  

(15b)
3. Mathematical analysis of RSC and GSC converters for the grid connected DFIG during transient state

3.1. Three Phase Symmetrical Faults
The stator voltage will reach zero magnitude during severe three phase's symmetrical faults of very low impedance and stator flux $\Phi_s$ gets reduced to zero magnitude. The decay in flux is not as rapid as in voltage and can be explained from the flux decay theorem available in literature and further can be explained as; delay is due to inertial time lag $r_s = \frac{1}{L_s R_s}$ effecting the rotor induced Electromotive Force (EMF) $V_{or}$. The flux during fault is given by

$$\Phi_{sf}^s = \Phi_s^s e^{-t/r_s} \quad (16)$$

and $\frac{d\Phi_{sf}^s}{dt}$ is negative, indicating its decay. By substituting (16) in (1b)

$$V_{or}^s = -\frac{L_m}{L_s} \left( \frac{1}{r_s} + j\omega_s \right) \Phi_s^s e^{-t/r_s} \quad (17)$$

Figure 2. The rotor equivalent circuit.

Figure 3. Scheme of enhanced flux oriented control where, DCOC = dc offset component of flux, $R\Phi_s$ = radius of flux trajectory.
The above Equation is converted into a rotor reference frame and neglecting $\frac{1}{r_s}$

$$V_{0r}^s = -\frac{L_m}{L_s} (j\omega) \Phi_s^s e^{j\omega t}$$  \hspace{1cm} (18)

By substituting $\Phi_s^s = \frac{V_s^s}{j\omega}$ in (18)

$$V_{0r}^s = -\frac{L_m}{L_s} (1 - s)V_s$$  \hspace{1cm} (19)

$$|V_{0r}^s|$$ is proportional to $(1-s)$

The converting Equation (1a) into the rotor reference frame

$$V_r' = V_{0r} e^{-j\omega t} + R_r i_r' + \rho L_r \frac{di_r'}{dt}$$  \hspace{1cm} (20)

Thus rotor equivalent circuit derived from (18) is as shown in Figure 2 (Hu et al., 2011).

From the equivalent circuit in Figure 2, the rotor voltage during fault is given by

$$V_r = i_R R_r + \sigma L_r \frac{di_r}{dt} + V_{0r}$$  \hspace{1cm} (21a)

Or

$$V_r = i_R R_r + \sigma L_r \frac{di_r}{dt} + \frac{L_m}{L_s} \frac{d\Phi_s}{dt}$$  \hspace{1cm} (21b)

In the above Equation (21b), the first two terms on RHS determine the voltage drop by rotor current due to passive elements and the last term determines the EMF induced by the stator flux.

A considerable decrease in pre-fault steady state voltage $V_{0r}^s$ to certain fault voltage during a three phase fault was explained in above analytics. However, RSC converter is designed to meet $V_r'$ to match $V_{0r}^s$ for rotor current control and the design has to be made for rating of only 35% of stator rated voltage. The voltage dip during fault can be adopted independently or in coordination by using two techniques is explained below.

During fault, at first instant, $\Phi_s$ does not fall instantly (18) as shown in the flux and voltage trajectories (Zhou et al., 2014). If the machine is running at super synchronous speed with slip (s) near to $-0.2$ pu, during fault, rotor speed further increases based on the term $(1-s)$ as given by (18). The above speed change is uncontrollable for a generator having higher electrical and mechanical inertia constants. In order to control the rotor current change, $V_r'$ has to be increased. Based on the first reason listed above, a voltage $V_{qs}$ has to be injected in the feed forward path for improving the rotor dip to reach to its near steady state value. Converting the Equation (18) into a synchronous reference frame and by considering direct alignment of $\Phi_{ds}$ with $\Phi_s$ we get,

$$V_{qs} = -\frac{L_m}{L_s} \omega \Phi_{ds}$$  \hspace{1cm} (22)

The second technique for voltage increase requirement in a rotor is, dip can be compensated by replacing $\omega\Phi_s$ with $(\omega_{qs} - \omega)$ in cross coupling terms $\omega_s L_s i_q r$ and $\omega_s L_s i_d r$, respectively. The reduction
in magnitude and frequency of flux $\Phi_s$, and alignment of flux with the stator voltage without the rate of change in flux angle $\theta_{qs}$ indicates DC offset component in flux.

$$\frac{d\Phi_s}{dt} = \omega_{qs} = 0 = \omega_f$$  \hfill (23)

Here, $\omega_f$ is the speed of stator flux during fault and this value can be made to zero as offset.

The voltage injection components (22), (23) and compensating components as discussed above are estimated using enhanced flux oriented control (EFOC scheme whose flow chart is shown in Figure 3 and the determined values are incorporated in the RSC controller shown in Figure 1.

$$\frac{d\Phi_s}{dt} = \omega_{qs} = \frac{V_{\beta s}\Phi_{\alpha s} - V_{\alpha s}\Phi_{\beta s}}{\Phi_{\alpha s}^2 + \Phi_{\beta s}^2} = \omega_f$$  \hfill (24)

When dynamic stability has to be improved, the proposed technique controls the decrease in stator and rotor flux magnitude and also damp oscillations at the fault instances. To achieve better performance during transients, this paper proposes a strategy for stator frequency reference to change to zero or other value depending type and severity of disturbance. The accurate measurement of stator and rotor parameters like flux, current helps in achieving better performance during transients. The DC offset stator current reduction during transients and making the two axis flux and voltage trajectories circular also improves the efficacy of the system performance during any faults. The Equations (13)-(18) help in understanding DFIG behaviour during transient conditions and accuracy of its working depends on measurement of rotor current and flux parameters.

### 3.2 Proposed EFOC control technique

The EFOC method of improving field flux oriented control technique helps in improving the performance of the RSC controller of DFIG during fault conditions is described in Figure 4. The DCOC observer does two actions.

The change in flux values of stationary frame stator references ($\Phi_{\alpha s}, \Phi_{\beta s}$) for tracking radius of the trajectory and the DCOC for offset change in stationary fluxes ($\Phi_{dc\alpha s}, \Phi_{dc\beta s}$) during fault conditions and controlling them. The first action helps in not losing the trajectory from a circle point, and to reach its pre-fault state with the same radius and centre of the circle and hence improving the same rate of flux compensation even during fault without losing stability. The second action helps in controlling and maintaining to nearly zero magnitude using the DCOC technique.

Based on above two actions, if former one is greater with change in trajectory which generally happens during disturbances from an external grid, stator synchronous frequency flux speed ($\omega_{qs}$) changes to synchronous grid frequency flux ($\omega_f$) otherwise $\omega_{qs}$ changes to fault angular frequency value and is injected to RSC voltage control loop as error compensator.

The stator three phase voltages and current are used as inputs for extracting a new arbitrary reference frame for RSC during different fault levels. Here “$z$” is the internal resistance of the stator winding. The voltage and current with impedance multiplication are subtracted to get reference voltage as shown in Figure 4. Under normal conditions, the difference will be nearly zero. During fault conditions, the voltage decreases and current increases, which make the difference between these two parameters to the picture. Now the reference three phase voltages are converted to stationary alpha, beta ($V_{\alpha}, V_{\beta}$) voltages using Clark’s transformation. This voltage is integrated and manipulated to get stator flux $\Phi_{\alpha}, \Phi_{\beta}$. The angle between these two fluxes is flux angle reference $\theta_{\alpha\beta}$. This angle is used to convert $\Phi_{\alpha}, \Phi_{\beta}$ to $\Phi_{\alpha1}, \Phi_{\beta1}$ and also the two stationary voltages $V_{\alpha}, V_{\beta}$ are also converted to rotating voltages $V_{\alpha1}, V_{\beta1}$ using parks transformation. The magnitude of these two voltages is $V_{r}$. The reference voltage magnitude of stator is $V_r$. During normal conditions, $V_{\alpha}$ and $V_{\beta}$ are same. But during voltage dips, there exists a difference between the two voltages $V_1$ and $V_2$. During
faults, if $V_1$ is greater than $V_2$, RSC inner control loop and speed reference changes from $W_{\lambda s}$ to $W_1$. Else in another case, with $V_2$ greater than $V_1$, the speed reference varies from $W_{\lambda s}$ to 0 or $W_1$. Under severe fault, where voltage dip will go beyond the rating of converters, the $W_{\lambda s}$ will be zero. Else it will have certain value specified by flowchart and controller as shown in Figures 3 and 4.

The general form of speed regulation is given by

$$T_e = J \frac{d\omega_r}{dt} + B\omega_r + T_1 \tag{25a}$$

$$T_e = (J + B)\omega_r + T_1 \tag{25b}$$

Where $T_e$ is electromagnetic torque, $J$ is moment of inertia and $B$ is friction coefficient, $T_1$ is considered to be disturbance. Multiplying both sides with $\omega_{error}$, the equation becomes

$$T_e \omega_{error} = (J + B)\omega_r \omega_{error} + T_1 \omega_{error} \tag{26}$$

Considering $\omega_r$ constant and change in speed error is $\omega_{error}$ is control variable, the above equation becomes.

$$P_s^* = (K_{in}s + K_{pn}) \omega_{error} + P_1 \tag{27}$$

As product of torque and speed is power, stator reference power and disturbance power are given below.

$$P_s^* - P_1 = (K_{in}s + K_{pn}) \omega_{error} \tag{28}$$

where $K_{in} = J\omega_r$ and $K_{pn} = B\omega_r$.

Finally direct axis reference voltage can be written by using Equation (28) and from Figure 1 is

$$V_{rd}^* = -\omega_{error} \left(K_{pn} + \frac{K_{in}}{s}\right) + \left(P_s + \frac{K_{it}}{s}\right) \tag{29}$$

$$V_{rq}^* = Q_{error} \left(K_{pQ} + \frac{K_{iq}}{s}\right) \tag{30}$$
The rotating direct and quadrature reference voltages of rotor are converted into stationary abc frame parameters by using inverse Park’s transformation. Slip frequency is used to generate sinusoidal and cosine parameters for inverse Park’s transformation.

In general, during fault and after fault, the DC link voltage across the capacitor at the DFIG back-to-back converter, terminal falls and rises, the STATCOM helps in improving the operation and assist in regaining its voltage value respectively to get ready for the operation during next fault. However, STATCOM provides efficient support for the grid-generator system under severe faults by fast action in controlling reactive power flow to grid by maintaining the DC link voltage at the capacitor terminal of DFIG converters constant particularly during transient state. Hence it helps in improving the dynamic stability of the overall system. The standard general DFIG based power system for study is shown in Figure 5.

The GSC converter is shown in Figure 6(a). the reference real power is extracted from lookup table based on wind speed. The error in this reference to actual power is controlled using PI controller. The difference in square of DC reference voltage to actual DC voltage is controlled using a tuned PI controller. The difference in the above two PI controllers and multiplied with stator d-axis current vector to get reference d-axis stator current. This current and actual stator output current is maintained to zero using PI controller. Using decoupling voltage vector control method, referenced-axis decoupled voltage will be extracted. In the similar way q-axis decoupled voltage vector is obtained. The d and q axis voltages are converted to 3 phase by using inverse park’s transformation and further given to PWM to get pulses to the grid side converter circuit. The general internal PLL angles for RSC controller to operate at slip frequency are described in Figure 6(b).

In the control schemes used earlier, the torque is fixed to zero and the reactive power must be drawn from the grid. This makes the DFIG system to more prone to the fault and weakens the system. The demagnetization control technique is widely used to suppress the natural stator flux components which help in damp flux oscillations. However, from literature it is found that demagnetization technique is sensitive to variation in the system parameter as stator resistance knowledge is required. The above sensitivity can be reduced by combining with virtual resistance methodology or arbitrary change in the RSC phase locked loop reference in changing the arbitrary value of speed of stator and rotor reference. The above effects are reduced by changing mostly the inner current control loop with surge current limiters and fast acting control strategy. Hence for this, our EFOC technique is adopted with fast changing inner control loop with arbitrary changing speed reference with surge current limiter technique. The flux decomposition is also controlled with our proposed control scheme.

This paper proposed an improved demagnetization approach to suppress stator and rotor flux oscillations. For this a new arbitrary reference frame is chosen in the inner RSC control scheme for controlling fault current entering into the system. The flux referees for stator and rotor are derived by using input terminal voltage and current parameters instead of taking from machine parameters.

\[
V_{gd}^* = K_{gp} \left( i_{gd}^* - i_{gd} \right) + k_{gi} \int \left( i_{gd}^* - i_{gd} \right) dt - \omega_L L_g i_{gd} + k_1 V_{sd} \tag{31}
\]

\[
V_{gq}^* = K_{gp} \left( i_{gq}^* - i_{gq} \right) + k_{gi} \int \left( i_{gq}^* - i_{gq} \right) dt + \omega_L L_g i_{gd} + k_2 V_{sq} \tag{32}
\]

\[
i_{gq}^* = K_q \sqrt{V_{dc}^2 - V_{dc}^2} + k_{qi} \int \left( V_{dc}^* - V_{dc} \right) dt + R_{dc} V_{dc} \tag{33}
\]

\[
i_{gd}^* = K_d \sqrt{V_{s}^2 - V_s^2} + k_{di} \int \left( V_s^* - V_s \right) dt \tag{34}
\]
This makes the control action faster and accurate. This technique helps in overcoming the effect of rating of converters for DFIG. The main objective is suppressing the exponentially increasing DC offset component (DCOC) of current during faults, thereby controlling the back emf of DFIG. In general, PI controller is slower in action, so for faster action and better damping of oscillations, FC is used. The EFOC technique is designed for improving dynamic and transient stability margin during and after faults. In EFOC technique, rotor flux reference changes its value from synchronous speed to zero or to a smaller value during fault for injecting current at the rotor slip frequency. In this method, DC-offset component of stator flux is controlled to minimize it. This offset decomposition of flux will be oscillatory in a conventional FOC, whereas in EFOC it can damp quickly. The reference frame for rotor during fault changes with EFOC, so as to make the rotor speed not to deviate much from the reference value. This makes the decomposition of flux during fault to be controlled and make the generator winding current not to exceed to higher values. This technique was adopted in the inner control loop of RSC.

3.3. Behaviour of mechanical and electrical system with the variation in rotor speed and reactive power

The rotor speed can be expressed as

\[ \omega_r = (1 - s) \omega_s = p \eta \omega_{wt} \]  

(35)

where \( s \) is slip of DFIG, \( p \) is a pair of poles of DFIG; \( \eta \) is gear box ratio and \( \omega_{wt} \) is wind turbine speed. With the change in wind speed and depending on gears ratio and number of field poles, the rotor speed variable is shown in Equation 33. When rotor speed varies, reference quadrature axis current changes, thereby current flow in the rotor circuit varies. The stator output also varies with variation in wind turbine speed and DFIG output power. When slip varies, the voltage in the rotor circuit also varies which can be explained as per Equations (8) and (9). Further change in rotor voltage leads to change in rotor current, thereby rotor power flow also varies. When a disturbance like symmetrical fault occurs, rotor speed increases so as to compensate the change in electrical power and the mechanical power. During faults, rotor tries to accelerate and reaches a new operating load point which can be under stable with equal area criteria.

The mechanical turbine tip speed ratio (TSR) can be written in terms of the radius of turbine wings (\( R \)), angular stator speed (\( \omega_s \)), pole pairs and gear box ratio as

\[ \lambda = \frac{R \omega_s}{p \eta \omega_{wt}} (1 - s) \]  

(36)

Increase in the stator or grid frequency, TSR increases and vice versa. Similarly with an increase in rotor speed or wind speed, TSR decreases and vice versa. Hence, when an electrical system gets disturbed, mechanical system also will get some turbulence and electrical mechanical system is tightly interlinked. The steady state behaviour of the overall system must satisfy the relation below.
Figure 6. (a) Grid side controller for DFIG and (b) Internal circuits design of RSC for extracting rotor Parks transform PLL block for dq to abc conversion.

\[ \Delta P = \frac{-P_{me}}{1-s} - P_{em} = 0 \]  

(37)

Under normal conditions, the change in turbine output has to be compensated by electrical power output from DFIG. Otherwise slip gets changed and thereby rotor speed changes. Hence imbalance in mechanical to electrical power output ratios, the slip changes. With the change in coefficient of power \( C_p \), the mechanical power varies. The mechanical power changes mostly when wind speed or air density around the turbine wings changes. The electrical power from DFIG changes, when mechanical power changes or rotor speed changes or load demand from grid varies.

4. Rules for FLC for DFIG based system for improved LVRT operation

The major problem with a DFIG system during fault is torque and stator flux reduction to a smaller value with large oscillations. Using sophisticated EFOC techniques (Ananth & NageshKumar, 2015) or FFTC (Jiaqi et al., 2013) with conventional PI controller cannot damp these oscillations quickly. So, a need of fast processor to control effectively the duty cycle is required to overcome the above
problems and the solution is a FLC. In Figure 1, the error from \( \text{idr}^* \) and \( \text{idr} \) and also \( \text{iqr}^* \) and \( \text{iqr} \) is given to two FLCs to achieve a faster rate of error diminishing and stable operating environment. The FLC has two inputs and one output. The inputs are \( d \)-axis stator current error and rate of change of \( d \)-axis stator current error and output is \( d \)-axis stator voltage. A MAMDANI FC with fuzzy control rules and a set of fixed parameters are shown in Figure 7 is used to control the current flow such that ripples and surges because of sudden inrush current can be minimized. It also helps in supplying rapid reactive power to grid provided by generator easily.

This technique determines the desired direct and quadrature axis component of the current. The DFIG stationary current 3 phase components are converted into rotating direct and quadrature components and these two actual components are compared with direct axis and above produced quadrature axis reference currents. The error to determine the correct voltage vector to obtain control switch state, such that the output voltage from the converter circuit can perform effectively even under transient conditions. The \( d \) and \( q \) axis error controlled by PI, is now replaced with appropriate rules based FLC to produce desired direct axis voltage to regulate the real power flow to the machine such that the speed is maintained, torque ripples reduced and reactive power can be compensated quickly at desired value and not to go out of step.

5. Result analysis
The system performance is studied under two fault cases with 40% and 70% decrease in grid voltage during 0.1 to 0.3 seconds symmetrical fault occurs near point of common coupling (PCC). The voltage and current parameters at rotor, stator and DFIG electromagnetic torque, speed of the rotor are analyzed for the two cases with different voltage dips. The proposed EFOC method is applicable to LVRT issues for improving current and voltage profile at stator and rotor terminals during disturbances with FC. In general, when a severe grid under voltage occurs, there will be oscillations with stator terminal voltage, rapid increase in winding currents, DC link capacitor voltage increases, speed of rotor increases and electromagnetic torque magnitude decreases. All these effects are intended to minimize in this paper with an improved FOC technique called EFOC.

5.1. Case 1: with 40% decrease in grid voltage
The performance of an EFOC based test system in Figure 5 with FC is considered for analysis. A total 0.3 seconds three phases to ground fault occurred at PCC is considered for the study with fault resistance of 0.0061 Ω. During fault, stator voltage decreased from 1 to 0.6 pu with a 40% decrease compared to normal during 0.1 to 0.3 seconds as shown in Figure 8(a). The decrease in grid voltage during fault depends mainly on location, fault resistance and type of fault. The efficacy of the proposed EFOC system can be compared with [(9)–(13), (21) and (22)] for the operation and reactive power control during faults.

The stator current is nearly constant with 0.8 pu at healthy conditions to 0.56 pu during fault and regains instantly without surges, its normal value once fault is cleared as in Figure 8(b). Due to unpredictable surge current entering into the system, at fault instant, there will be current surges. But due to faster action of controllers, this surge current is limited. The surges at these instants are due to sudden change in capacitor voltage at the back to back converters and also due to a sudden inrush of fault current into the stator and rotor windings. The rotor current in Figure 8(c) which is initially under steady state without fault is 0.70 pu. There is a very small surge current in the rotor at fault instant making the current to increase and then decreased and maintained at 0.50 pu from 0.1 to 0.3 s. This current has a decrease in magnitude during fault, but no change in rotor slip frequency because of the proposed control scheme. It reached its pre-fault value after the fault is cleared. From the Equations (15)–(18), with the change in the stator and rotor flux linkage value and rotor slip, the rotor voltage increases slightly exponentially to certain value because of change in back emf of DFIG. Because of this, based on Figure 3, it can be observed that rotor current, thereby stator current will decrease with a proposed scheme instead of increasing during a fault. The rotor voltage is almost constant at 0.4 pu before, during and after fault is shown in Figure 8(d).
The Electromagnetic Torque (EMT) is constant at −0.8 pu before the fault occurrence as shown in Figure 8(e). But at fault instant, a torque surge up to −1.08 pu is produced at 0.1 s and this torque reached −0.325 pu during 40% dip in the voltage. The oscillations are damped due to the fast acting FC, hence is preferred over the PI controller. A conventional FC with rules available in the literature are used in the paper. The increase in torque initially is because of the decrease in electrical power and constant mechanical power. The unbalance between these two energies make the torque and speed to increase. It shows the performance improvement during and after a fault and has better working conditions than in available literature. There is a surge in torque at 0.1 s at fault occurring instant. Based on Equation (22b), moment of inertia J, mechanical torque does not vary, but the rotor speed varies. The rotor speed remained almost constant with this type of fault from 1.20 pu under normal conditions to 1.210 pu during fault and reached slowly to 1.2 pu after the fault is cleared. This is another major advantage with the proposed system to maintain a constant speed of the rotor during a fault. To satisfy the equality constraint with change in rotor speed, EMT also varies. The variation in mechanical torque is low compared to electrical torque because electrical system operates faster than a mechanical system as explained by equal area criteria. Due to the inertia in the machine, rotor speed will increase during fault and decreases to normal once fault is cleared. The role of FC helps in damping out oscillations during fault and to reach steady state quickly. This FC also helps in controlling the flux decay desired by proposing an EFOC technique to stubborn control over d and q axis currents in RSC circuit.

The DC link voltage across capacitor between the back to back converters of DFIG is shown in Figure 8(f). Under normal conditions, the DC voltage is constant at 1.0 pu. The GSC control technique with square of error control technique help in controlling and maintaining the voltage constant. This voltage control by GSC is achieved by coordinating control of RSC with proposed EFOC technique. At fault instant 0.1 s, the voltage dip from 1 to 0.9 pu is observed. remaining time during and after fault, this voltage remained constant.

The stator real and reactive powers are shown in Figure 8(g). In this before the fault occurrence, the stator power is constant at 0.98 pu. During a fault, this power reached to 0.46 pu without oscillations and immediately reached to pre-fault value. The reactive power of stator before the fault is 0.0 pu and during fault, it reached 0.15 pu. The reactive power control adopted in RSC will control the change in reactive power. If this reactive power control is done in GSC, the reactive power compensation can be better. With the change in Electromagnetic Torque (EMT), rotor speed and impedance at PCC, the real and reactive power flow from the generator to grid changes.

The rotor speed is almost constant during and after symmetrical fault with 30 % dip in grid voltage as shown in Figure 8(h). The rotor speed is initially 1.2 pu before fault and reached to 1.210 pu during fault period from 0.1 to 0.3 s and slowly decreased and reached to 1.2 pu once fault is cleared. This speed control is possible with the proposed RSC control scheme.

5.2. Case 2: With 70% decrease in grid voltage
In this case, much severe fault occurred at PCC near grid, which makes the grid voltage decreased to 0.3 pu from 1 pu during 0.1 to 0.3 s. The results of proposed system are compared with the results...
from the reference (Shuai, Geng, et al., 2013). This decrease is 70% for stator voltage compared to rated voltage under healthy conditions as shown in Figure 9(b)(i). Because of this fault, the stator and rotor current surges are produced at the instant of fault at 0.1 s. After 0.012 s, these currents decreased and reached a smaller and safe value with the proposed technique. The dip in voltage with proposed and reference paper (Shuai, Geng, et al., 2013) are same. The stator current in Figure 9(b)(ii) which is initially 0.80 pu before fault, reaches to 0.4 pu during fault between 0.1 and 0.3 s. the rotor current at fault instant in (Shuai, Geng, et al., 2013) reaches about 2 pu and with DC offset components in stator current sustained upto 0.1 s of fault and reached steadstate with sustained oscillations. These DC offset components and oscillations are eliminated in our proposed system. A surge current of magnitude 1.5 pu is produced at fault instant 0.1 s and lasts for one cycle. Compared
Figure 9. (a) Waveforms snapshot from reference Shuai, Geng, et al. (2013) and (b) Performance of DFIG with 70% dip in grid voltage with EFOC (i) stator voltage, (ii) stator current, (iii) rotor current, (iv) rotor voltage, (v) actual electromagnetic torque, (vi) DC link voltage across capacitor at back to back converters, (vii) stator real and reactive power, (viii) rotor speed.
to the work in literature (Shen et al., 2015; Shuai, Geng, et al., 2013), the offset DC components (DCOC) in flux during fault are minimised even with severe fault with a fault resistance of 0.00125Ω. The decrease in DC offsets current oscillations, limiting surge currents, maintaining current waveform, all are considered advantages with proposed EFOC. A steady state is reached and stator current maintained as in pre-fault state. With EFOC technique, continuity of current, thereby power flow is improved. The overall system stability and performance are improved. The results obtained with FC is placed in inner control circuit of RSC helps in achieving faster control action with sustained oscillations and the EFOC limits the decoupled current control parameters. This FC helps in sustaining the system without much severe oscillations due to severe faults with the membership function adopted.

The rotor current decreased from 0.70 to 0.3 pu during fault and regained to 0.7 pu after the fault is cleared as shown in Figure 9(b)(iii). The rotor current oscillations with proposed system is less than that in (Shuai, Geng, et al., 2013). The frequency of rotor waveform is constant during this fault. With proper switching control action by RSC and GSC ensures the system sustaining capability by limiting the surge current. The proposed RSC control technique with optimal speed reference control scheme, flux decay control and improved demagnetisation control action makes the rotor current not to increase naturally during a fault. Without the need for any external real or reactive power sources or crowbar arrangement and with the same converter rating, the rotor and stator current surge control is possible. Compared to work in (Shen et al., 2015; Shuai, Geng, et al., 2013), the distortions in the rotor and stator parameters are very less with the proposed control scheme. The rotor voltage is almost constant during and after the fault with the proposed control action. The rotor voltage is also almost constant at 0.40 pu as shown in Figure 9(b)(iv).

The EMT at fault instant 0.1 s has surged −1.4 pu and reaches a steady value during fault to −0.1 pu at 0.105 s is shown in Figure 9(b)(v). Later, when the fault is cleared, reaches a steady state value at 0.3 s at fault clearing as shown here. With the results in (Shuai, Geng, et al., 2013), the EMT oscillations after fault lasts for more than 0.1 s as shown in Figure 9(a). With a proposed EFOC technique with FC, the torque oscillations are eliminated and stability was improved.

The DC voltage in Figure 9(b)(vi) at converters is maintained constant at 1.0 pu during and after the fault without oscillations. A sag up to 0 pu volts at fault instant 0.1 s in DC voltage dip is observed at fault instant, due to unexpected occurrence of fault. With fast acting control strategy, the voltage dip can be mitigated. Even if the fault exists for more than 0.5 s time period, the system can sustain stability as DC capacitance voltage is maintained constant at back-to-back converters. The DC capacitor rating at back-to-back converters will also play a vital role in storing and delivering this excess current during the faults. The GSC circuit, helps in controlling the decay in DC link voltage, thereby overall stability is improved.

The stator real and reactive powers are shown in Figure 9(b)(vii). Before the fault occurrence, the stator real power is 0.98 pu, during a fault, it reached to 0.13 pu between 0.1 to 0.3 s and regain to pre-fault value once fault is cleared. Similarly, the reactive power changed from 0 to 0.18 pu during fault and reaches −0.02 pu after the fault is cleared. It can be observed that, there are no oscillations in real and reactive power and hence there are no distortions in the voltage or current waveforms. The rotor speed is maintained nearly constant during this type of severe fault. The rotor speed increases to 1.214 pu as shown in Figure 9(b)(viii) and reaches steady state once fault is cleared.

Compared to previous case with a 40% dip in grid voltage, the deviation from normal value is little higher. It is due to severity of fault which is occurring with a very low impedance value. To much decrease in grid voltage, inrush current entering into the stator and rotor winding will increase very rapidly and produces surges in current waveforms. If these surges are not limited, both the windings and the converters will get damaged. For the protection of the rotor winding and further stator winding from severe inrush current surges, the crowbar is generally used. But with the proposed control circuit, this crowbar scheme can be eliminated. No need of external real or reactive power...
sources. However, limiting surges at fault instances are not completely eliminated and can be said to be future scope of the work. Compared to the work discussed previously in the literature, this method can have better sustainable operation and continuity of current flow with improved performance in all respects.

The Table 1 gives a detailed picture of parameter variation under steady state, at the instant of fault with sag value and during the fault. Under normal conditions grid voltage is 1 pu, when voltage decreased to 40 and 70%, the voltage is 0.6 and 0.3 pu voltage. The electromagnetic torque (EMT) during steady state is −0.8 pu in Nm, at the instant when the volatage dropped to 60% nearly, this reached to −0.325 pu. It again reached to pre-fault value of −1 pu after the fault is cleared. In the same case with 40 % of voltage dip, the stator real power decreased to 0.46 pu and stator and rotor current reached at 0.56 and 0.50 pu amperes. The same explanation holds good for other parameters.

### Table 1. Showing the parameter variation before and during voltage swell

| Parameter under consideration | Normal system (at steady state) (pu) | Grid voltage 40% drop with fault resistance 0.0061 Ω | Grid voltage 70% drop with fault resistance 0.0021 Ω |
|--------------------------------|-------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Grid voltage (pu)              | 1.0                                 | 0.6                                          | 0.3                                           |
| EMT (pu)                       | −0.8                                | Surge = −1.0 at start of 0.1 s and −0.8 after clearing | Surge = −1.38 at start and −0.8 once fault is cleared |
|                                |                                     | During fault = −0.325                         | During fault = −0.1                           |
| Speed (pu)                     | 1.2                                 | During fault it is 1.210                      | During fault 1.214                            |
| Stator voltage (pu)            | 1.0                                 | No surges are produced                       | No surges                                     |
|                                |                                     | During fault 0.6 pu                          | During fault 0.3 pu                           |
| Rotor voltage (pu)             | 0.40                                | No surges, dip or swell during or after fault | Dip at fault occurring instant = 0.1 s to 0.15 pu |
|                                |                                     | During fault it is 0.40                      | During fault, it is 0.40 pu                   |
| Stator current (pu)            | 0.80                                | Surge at fault occurring instant = 1.0 pu    | Surge at fault occurring instant = 1.4 pu     |
|                                |                                     | During fault = 0.56                         | During fault = 0.3                            |
| Rotor current (pu) (as per 35% rated converter value) | 0.70 | Surge at fault occurring instant = 1.12 pu | Surge at fault occurring instant = 1.3 pu |
|                                |                                     | During fault = 0.50                         | During fault = 0.6                            |
| DC link capacitor voltage across the converters (pu) | 1.0 | Sag at fault occurring instant = 0.8 pu | Surge at fault occurring instant = 0 pu |
|                                |                                     | During fault = 1.0                          | During fault = 1.0                           |
| Real power delivered           | 0.98                                | During fault = 0.46                         | During fault = 0.13                           |
| Stator reactive power          | 0.0                                 | During fault = 0.15                         | During fault = 0.18                           |

6. Conclusion
A conventional DFIG wind turbine system connected to the grid was considered in the analysis. A three phase fault is imagined to occur at PCC between 0.1 and 0.3 s, making the grid voltage to decrease to 30 and 70% compared to normal. With the proposed EFOC technique, rotor current during fault is maintained at certain value without increasing or getting zero. The stator and rotor current dip is observed with proposed control scheme. The waveforms are sinusoidal without DC offset components and the system is maintained synchronism at 70% dip in the voltage. The reduction in torque is observed at 70% dip in grid voltage, but regained to normal value without oscillations after the fault is cleared. The rotor speed is constant without much swell during severe fault with the proposed control scheme. The overall secured operation can be guaranteed during and the fault with proposed EFOC technique. The torque ruiipple and surges in current waveform possible with the
help of a FC, as it is a fast device than a conventional PI controller. The post fault recovery in machine voltage and current waveforms have taken place without any surges. The dip in DC link voltage is minimised and hence stator and rotor voltage and current profiles were improved using an EFOC technique with FC. The electromagnetic torque output from DFIG have less oscillations and reached immediately to steady state even, during faults and also after fault clearing. There are few surges in torque and current at the starting and clearing of faults. It is due to symmetric decrease in flux value and with EFOC it recovers very rapidly without any fluctuations.

In recent works, meta-heuristic type techniques or with PR, PIR, there will be much mathematical complexity to improve reliability and sustainability during faults. Our proposed system with EFOC alone can improve the performance during and after fault with improved security. For more promising results, FC was used in inner control loop to control the current errors and thereby decoupled voltage components are controlled. The stator winding or terminal current has to improved for better continuity of current. This can be achieved by controlling more effectively the decay of flux during a fault. Hence the robust GSC controller strategy needs to be adopted. The future scope can be, decrease in surges and maintenance of constant stator and rotor current value during any disturbance. With the proposed control strategy, smooth transition in electromagnetic torque is achieved during symmetrical fault based transient state of drop in grid voltage and restoring is possible. The dynamic stability of DFIG was improved and thereby mitigation of generator stator and rotor voltages and current are superior with EFOC fuzzy technique. The output power from the generator is better damping the transient stator flux. This is possible by changing the reference flux reference value by choosing particular stator flux ($\lambda_s$) value. Otherwise over current in the rotor winding makes the system performance and lifetime to degrade under these situations.

Hence, with the proposed EFOC fuzzy technique, a control over stator transient flux is possible so as to suppress rotor current surges and helps in achieving better LVRT operating characteristics. EMT is smooth with suppressed oscillations, thereby prolong lifetime of the generator turbine system during voltage dip and recovery. The behavior during and post-fault conditions were improved with mitigation in stator and rotor current waveforms. The overall performance is improved and can sustain to severe faults with ensured stability.

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Appendix A

The parameters of DFIG used in simulation are:

Rated Power = 1.5 MVa, Rated Voltage = 690 V, Stator Resistance Rs = 0.007 pu, Rotor Resistance Rr = 0.0049 pu, Stator Leakage Inductance Ls = 0.171 pu, Rotor Leakage inductance Llr1 = 0.156 pu, Inertia constant = 4.54 pu, Number of poles = 4, Mutual Inductance Lm = 2.90 pu, dc link Voltage = 1200 V (1 pu), dc link capacitance = 20 mF, Operating Wind speed (in this paper) = 14 m/sec. Grid Voltage = 25 kV, Grid frequency = 60 Hz, Grid side Filter: Rfg = 0.3 Ω, Lfg = 0.6 nH, Rotor side filter: Rf = 0.3 mΩ, Lf = 0.6 nH, Grid transformer at PCC: 0.690/25 kV, Y-Δ, 5 MVA, 60 Hz.
