Analysis Of Voltage Ride Through Improvement Using Weibull Parameters For Symmetrical And Asymmetrical Fault

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Abstract: In this paper, a modified dynamic capacitor type fault current limiter configuration is modeled and analyzed for low voltage ride through (LVRT) improvement for a doubly fed induction generator (DFIG). The DFIG is fed with a constant wind speed estimated from Weibull parameters. The proposed crowbar, consisting of a parallel resonance circuit, connected with the capacitor and in shunt with rotor side converter (RSC). There are several crowbar configurations proposed in the literature, and every method is having its own advantages and drawbacks. The rotor side converter is connected to a dc-link capacitor followed by Grid side converter (GSC). The modified crowbar arrangement protects the DFIG, and it further avoids the damage of RSC including capacitor under a grid fault condition. When the crowbar resistance is alone implemented, it will isolate RSC which leads to generator excitation failure. At this instant, the generator works as Squirrel cage-induction generator (SCIG) and thereby absorbs magnetizing current from the grid through stator windings. This creates voltage sag at the point of common coupling (PCC) and it needs to be rectified by modifying the existing crowbar configuration by connecting a capacitor in parallel with the parallel resonance branch. This arrangement is further connected to a crowbar resistance, which will maintain the rotor windings connected with RSC and thus overcoming the LVRT. The proposed model has been performed in MATLAB/Simulink and the DFIG performance has been improved under transient conditions.

Keywords: Low voltage ride through (LVRT); Double-fed Induction Generator (DFIG); Fault ride through (FRT); Capacitor fault current limiter (CFCL); Wind turbine(WT).

1. INTRODUCTION

Nowadays, low voltage ride through (LVRT) is an important issue with respect to wind turbines under grid disturbance, and these can be improved through mechanical devices. This LVRT problem can be overcome by operating the crowbar circuit, consisting of a resistor placed at rotor side of DFIG. This resistor bank will draw the excess power for limiting the generator current. With the improvements made in the grid codes, this type of control leads to loss of control and oscillations in the electromagnetic torque that tends to apply stress over the drive train. This leads to the consumption of reactive power, which is the major reason for voltage dip and further restricts the recovery of the voltage at the grid side [1]. A feedforward transient compensation is presented in [2,3], which obtains the derivatives of rotor current Referenc But this method is only applicable when the reference keeps changing, and is not suitable for external disturbance and this compensation value depends on the disturbance. Resonant controllers [4-6] have been implemented, and are frequently adopted at the grid side to overcome the negative sequence and also transient components. A combination of PI and resonant controller [7] is used for DFIG to overcome the negative sequence oscillating at double the synchronous frequency. Similarly, double resonant PI controller [8] is used to counteracts double synchronous frequency under fault conditions. A demagnetization control is presented in [9] which injects the rotor current against the stator flux which is rotating in a negative sequence.

A simple and effective method for tracking stator and rotor current is proposed in [10]. An inductance control is proposed in [11] for lowering the magnetizing current. There are many modified control methods, that have been presented: demagnetizing current in [12,13], virtual flux damping control [14,15], sliding mode control (SMC) [16], robust control (RC) [17]. A unified interphase power controller (UIPC) is explained and implemented in [18,19], dynamic voltages restorer (DVR) which maintains the rated voltage is presented in [20,21]. Few more solutions in the form of stator damping resistor (SDR) [22] were used to operate under LVRT for DFIG based wind turbine. Though STATCOM [24,25] is used for improving LVRT capability, this cannot limit the DC link voltage and also fault current through RSC of DFIG on the occurrence of a fault. The DVR, UIPC, and SGSC offer greater series voltage injection for restoring stator voltage of DFIG and are presented in [18-22]. For protecting DC-link, energy storage solutions are proposed for limiting the DC link voltage and a series dynamic braking resistor (SDBR) are presented in [23,24].

A supercapacitor type storage device is implemented in [25] for LVRT enhancement and in [26] supercapacitor is connected at DC link of STATCOM for controlling grid side voltage under a grid fault condition. In [27] stator damping resistor, including rotor current control scheme has been explained. In [28,29] a superconducting fault current limiter is introduced, as the cost is high, it is not implemented commercially. Similar work has been investigated in for estimating recovery time for a 440kV/1.2kA system. A bridge type fault current limiter [30-32] for voltage recovery under a fault condition for LVRT is presented. In [33] for the first time, fault current limiter with DC reactor is introduced but, due to the cost of a DC reactor and transformer, some limitations are present in it. Recently superconducting type fault current limiter which has magnetic storage ability has been implemented for LVRT [34], resonant fault current limiters [36] have been proposed and examined for limiting fault current under transient conditions. In this paper, a
A novel modified capacitor type fault current limiter is modeled and tested for DFIG based WT for improving fault ride through capability. The proposed model performance has been analyzed with conventional fault current limiter configurations such as Resistance crowbar (R crowbar), Parallel resonating Fault current limiter (PRFCL), full bridge diode FCL (DBFCL), non-superconducting diode bridge FCL(NSFCL), capacitance diode bridge resonant FCL(CDRFCL).

The paper has been organized as: DFIG and Wind turbine modeling including drivetrains are presented in Section 2. This section also deals with grid side converter modeling including PI controller and rotor side converter with PI controller modeling in brief. Now, an important part of induction generator modeling is the transformation between dq-abc and abc-dq and they are presented in section 2. Various configurations and its control schemes with their operations are explained in section 3. The modified crowbar configuration, its reactor and capacitor designing are presented in section 4. The simulation results for different configurations including the proposed are explained in section 5 for different fault cases and the performance is discussed, and the conclusion is provided in section 6.

2. SYSTEM MODELING

The DFIG modeling is a very important aspect while interconnecting wind farm, and as per the grid codes [1], the generator should remain connected under fault conditions for a certain period of time. Grid codes for different countries and the operating times are shown in Fig.1 and its parametric values are given in Table.1. The main objectives are i. The voltage must be constant at dc bus, ii. crowbar must operate in less time to restrict the DFIG to get disconnected from RSC, iii. The terminal voltage transient response must be improved, iv. DFIG dynamic response should be improved, v. rotor fault current minimization must be met.

![Fig.1 LVRT characteristics for different grid codes.](image)

### Table 1

<table>
<thead>
<tr>
<th>Country</th>
<th>Voltage restoration (IR)</th>
<th>Voltage dip (Td)</th>
<th>Voltage level (%vM)</th>
<th>Voltage restoration level (%vR)</th>
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<tbody>
<tr>
<td>UK</td>
<td>1200 msec</td>
<td>140 msec</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>Canada</td>
<td>1000 msec</td>
<td>150 msec</td>
<td>0</td>
<td>95</td>
</tr>
<tr>
<td>Germany</td>
<td>1500 msec</td>
<td>150 msec</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>Denmark</td>
<td>750 msec</td>
<td>140 msec</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>Spain</td>
<td>1000 msec</td>
<td>500 msec</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>USA</td>
<td>3000 msec</td>
<td>625 msec</td>
<td>15</td>
<td>90</td>
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</tbody>
</table>

### 2.1 Weibull parameters estimation

The probability density function through which the dynamic nature of wind can be studied. The occurrence of wind velocity can also be understood with probability density function $f(v)$ and cumulative distribution $F(v)$ tells less than or equal to that wind velocity.

The Weibull distribution function or Weibull probability density function is calculated as:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k}$$

(1)

Where is the probability of wind speed is $f(v)$, wind velocity ($v$), shape and scale parameters are $k$ and $c$.

The Weibull cumulative distribution function is obtained by integrating Weibull probability distribution, is expressed as

$$F(v) = \int_{0}^{v} f(v)dv = 1 - e^{-\left(\frac{v}{c}\right)^k}$$

(2)

After obtaining the $k$ and $c$ parameter the wind power density at 10m and 65m are determined and are shown in Fig.2 and Fig.3.

![Fig.2. Wind power density at 10m](image)
2.2 DFIG modeling

The DFIG stator terminals are directly connected to the grid and rotor being connected through a converter as shown in Fig. 4a. The converters are made up of back to back connected power electronic devices of IGBT and termed as grid side converter and rotor side converters. These two are connected through a capacitor link which serves to provide voltage twice of stator under overload conditions. There is a vast literature in dealing with DFIG modeling and some are presented in [37-38]. A simulation model for the proposed crowbar is shown in Fig. 4b.

From the equivalent model, the voltage expression is represented as

\[ v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs} \]  \hspace{1cm} (3)

\[ v_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - \omega_r \psi_{qr} \]  \hspace{1cm} (4)

Similarly, we can also obtain the flux expressions from the equivalent model of d-axis SRF and is given by

\[ \psi_{ds} = L_s i_{ds} + L_m i_{dr} \]  \hspace{1cm} (5)

\[ \psi_{dr} = L_m i_{ds} + L_r i_{dr} \]  \hspace{1cm} (6)

where \( V_{ds}, V_{dr} \) are direct axis (d-axis) stator and rotor voltages, \( R_s, R_r \) are stator and rotor resistance. \( \psi_{ds}, \psi_{dr} \) are rotor and stator flux linkages in d-axis. \( i_{ds}, i_{dr} \) are direct axis rotor and stator currents, \( \omega_s, \omega_r \) are supply and rotor angular frequencies. \( L_s, L_r, L_m \) are stator, rotor, and magnetizing inductances respectively.
Here, Fig.7 shows the equivalent model of q-axis for DFIG in SRF, referring to the previous expressions we had written for the voltage for d-axis, now we can write for q-axis reference frame as below

\[
v_{qs} = R_{i_{qs}} + \frac{d\psi_{qs}}{dt} + \omega_{r}\psi_{ds}
\]

(7)

\[
v_{qr} = R_{i_{qr}} + \frac{d\psi_{qr}}{dt} + \omega_{r}\psi_{dr}
\]

(8)

The q axis reference frame flux equations are presented below

\[
\psi_{qs} = L_s i_{qs} + L_m i_{qr}
\]

(9)

\[
\psi_{qr} = L_m i_{qs} + L_r i_{qr}
\]

(10)

where \( V_{qr}, V_{qs} \) are quadrature axis (q-axis) rotor and stator voltages, \( R_s, R_r, R_s \) are rotor and stator resistances, \( \psi_{qr}, \psi_{qs} \) are rotor and stator flux linkages in q-axis, \( i_{qr}, i_{qs} \) are the q-axis rotor and stator currents, \( \Omega_s, \Omega_r \) are supply and rotor angular frequencies. \( L_s, L_r, L_m \) are stator, rotor, and magnetizing inductances respectively.

Now if we combine all the voltage and flux equations in the matrix notation, we will get it as shown below

\[
\begin{bmatrix}
\psi_{ds} \\
\psi_{dr} \\
\psi_{qs} \\
\psi_{qr}
\end{bmatrix} =
\begin{bmatrix}
L_s & 0 & L_m & 0 \\
0 & L_r & 0 & L_m \\
0 & L_s & 0 & L_r \\
0 & L_m & 0 & L_r
\end{bmatrix}
\begin{bmatrix}
i_{ds} \\
i_{dr} \\
i_{qs} \\
i_{qr}
\end{bmatrix}
\]

(11)

\[
\begin{bmatrix}
v_{ds} \\
v_{dr} \\
v_{qs} \\
v_{qr}
\end{bmatrix} =
\begin{bmatrix}
R_s & 0 & 0 & 0 \\
0 & R_{ij_{qr}} & 0 & 0 \\
0 & 0 & R_s & 0 \\
0 & 0 & 0 & R_r
\end{bmatrix}
\begin{bmatrix}
i_{ds} \\
i_{dr} \\
i_{qs} \\
i_{qr}
\end{bmatrix}
\]

(12)

\[
\begin{bmatrix}
v_{ds} \\
v_{dr} \\
v_{qs} \\
v_{qr}
\end{bmatrix} =
\begin{bmatrix}
R_s & 0 & 0 & 0 \\
0 & R_{ij_{qr}} & 0 & 0 \\
0 & 0 & R_s & 0 \\
0 & 0 & 0 & R_r
\end{bmatrix}
\begin{bmatrix}
i_{ds} \\
i_{dr} \\
i_{qs} \\
i_{qr}
\end{bmatrix}
\]

(13)

where “m” is the mutual component, “s” and “r” subscripts represents stator and rotor quantities, therefore stator, rotor inductance values are represented as \( L_s \) and \( L_r \).

The power expression across the capacitor is given by

\[
P_{dc} = V_{dc} C_{dc} \frac{dV_{dc}}{dt}
\]

(14)

Similarly, we can also calculate \( P_s, P_r, Q_s, Q_r \) i.e. active and reactive power of DFIG as shown below

\[
P_s = 1.5\left(V_{qs}i_{qs} + V_{ds}i_{ds}\right),
\]

(15)

\[
P_r = 1.5\left(V_{dr}i_{dr} + V_{qr}i_{qr}\right)
\]

(16)

\[
Q_s = 1.5\left(V_{qs}i_{ds} - V_{ds}i_{qs}\right),
\]

(16)

\[
Q_r = 1.5\left(V_{qr}i_{dr} - V_{dr}i_{qr}\right)
\]

(16)

due to the direct axis and quadrature axis current and flux in the rotor axis, electromagnetic torque is produced and is calculated using the following expression

\[
T_{em} = \frac{3}{2} p \left(\psi_{qr} i_{dr} - \psi_{dr} i_{qr}\right)
\]

(17)

Now coming to the rotor connection, the rotor side of DFIG is connected through a bidirectional converter made of IGBT power electronic circuit. As already mentioned, these two converters are separated by a dc-link which serves to maintain the voltage variations to a minimum. Another function of this converters is that it has the ability to transfer active, reactive power through vector control approach. The DFIG active, reactive power control is achieved by controlling RSC and it is obtained by varying d-q axis currents (idr, idr). The GSC is regulated to achieve voltage across the capacitor for reactive power flow in both the direction at PCC irrespective of rotor power. To determine the voltage angle, phase locked loop is used and rotor current and voltages are estimated by implementing a PI controller.

2.3 Rotor side converter control

The persistence of orientation control makes us control stator reactive power and torque by utilizing both d, q rotor currents independently. In Fig.8 a speed control with stator reactive power control loops is presented. By implementing reactive control, the magnetization of the machine can be controlled, since the stator of DFIG is connected to the grid side directly. So, stator flux level can be maintained by controlling of ids and iqr values. The reference control signals are generated from the PI controller that is fed to pulse width modulation (PWM) for generating signals for IGBT as shown in Fig.8. The MPPT controller has been included for generating Tem which is further used to get iq reference. The PWM block is operated with a switching frequency of 4 kHz.

Fig.8. Rotor side controller block diagram

For the rotor side converter, we consider speed reference and actual speed as the input signals for torque and MPPT
controller. Now, the stator voltage is utilized for obtaining angle and by using the rotor current we achieve actual idr and iq reference currents respectively.

The rotor side converter controller parameters i.e, kp_id and ki_id, kp_iq and ki_iq values are determined using the following equations.

Rotor side direct axis and quadrature axis proportional gains are calculated using the following expressions

\[
k_{p_{id}} = 2 \cdot \omega_{m} \cdot \sigma \cdot L_r - R_r
\]

(18)

\[
k_{p_{iq}} = K_{p_{id}}
\]

(19)

In the same manner, rotor side direct and quadrature axis integral gains are formulated using the below expressions

\[
k_{i_{id}} = \omega_{m} \cdot 2 \cdot L_r \cdot \sigma
\]

\[
k_{i_{iq}} = k_{i_{id}}
\]

(20)

The proportional and integral gains for torque controller is calculated as follows

\[
k_{p_{n}} = 2 \cdot \omega_{m} \cdot j / p
\]

\[
k_{i_{n}} = \omega_{m} \cdot 2 \cdot J / p
\]

(22)

(23)

The closed loop current control by implementing PI controller for the rotor side converter in d-axis can be expressed as second-order system with the values calculated from above equations as shown below

\[
i_{dq}^{*}(s) / i_{dq}(s) = \frac{sk_{p_{id}} + k_{i_{id}}}{\sigma L_s^2 + (k_{p_{id}} + R_r)s + k_{i_{id}}}
\]

(24)

Similarly, for q-axis rotor current loop the expression can be modified as below

\[
i_{iq}^{*}(s) / i_{iq}(s) = \frac{sk_{p_{iq}} + k_{i_{iq}}}{\sigma L_s^2 + (k_{p_{iq}} + R_r)s + k_{i_{iq}}}
\]

(25)

The output of current regulators are Id and Iq and it is fed through voltage regulators for achieving Vabc_ref, this is fed to PWM signal generator for generating pulses for rotor side converter.

2.4 Grid side converter control

In this, the function of GSC is for maintaining the voltage at the dc bus within permissible limits irrespective of rotor power. The GSC model is shown in Fig.9, the inputs for GSC are measured Vbus, Qg, and Ig. These are fed to the PI controller for generating reference signals for the PWM block. This GSC controls reactive power requirement and voltage at dc bus to the rated value. For GSC also the switching frequency is chosen to be 4 kHz for harmonic elimination. In this GSC three PI controllers are used and among them, two PI controllers are used for generating idg and iqg reference currents and another for Vbus.

Fig.9. Grid side controller block diagram

The grid side converter parameters are estimated using the expressions given below.

The grid side resistance and inductance are considered as given below

\[
R_g = 20e - 6
\]

(27)

\[
L_g = 400e - 6
\]

(28)

\[
k_{p_{idg}} = 2 \cdot \omega_{mg} \cdot L_g - R_g
\]

(29)

\[
k_{p_{iqg}} = K_{p_{idg}}
\]

(30)

\[
k_{i_{idg}} = \omega_{mg} \cdot 2 \cdot L_g
\]

(31)

\[
k_{i_{iqg}} = k_{i_{idg}}
\]

(32)

The Kp and Ki gains for voltage controller are considered as given below

\[
k_{p_{v}} = -1000
\]

(33)

\[
k_{i_{v}} = -300000
\]

(34)

By using the grid side angle and grid side current, it is fed to the voltage regulator which generated reference voltage Vabc_ref, the reference voltage is further sent to the PWM generator as input for producing pulses for the rotor side converter.

2.5 Wind turbine modeling

\[
P_r = \frac{1}{2} \rho \pi R^2 V_w^3 C_p
\]

(35)
Based on the wind turbine speed (Ωtm), power coefficient value varies and also due to wind speed Vw and pitch angle β, the exact expression for Cp is defined as

$$C_p = f(\lambda, \beta) = k_c \left( \frac{k_2 - k_3 \beta - k_4}{\lambda^2} \right) e^{\lambda \lambda} + k_5 \lambda$$

(36)

The coefficient values that decide the wind turbine characteristics are k1 to k6 (k1=0.5176, k2=116, k3=0.4, k4=5, k5=21, k6=0.0068) [35]

2.6 Drive train
The dynamic analysis of drivetrain of wind turbine connected to the grid can be studied [29]. The drive train model is shown in Fig.10 and its motion can be modeled using the following expression

$$\frac{d\theta}{dt} = \omega_i - \omega_g$$

(37)

$$\frac{d\omega_i}{dt} = \frac{1}{2H_i}(T_i - K_s \theta_i)$$

(38)

$$\frac{d\omega_g}{dt} = \frac{1}{2H_g}(-T_c + K_s \theta_i)$$

(39)

Fig.10 Drive train model

Where $T_i$, $T_c$, $\omega_i$ and $\omega_g$ are electromagnetic torque, available torque at the generator side, generator and turbine speed respectively. $K_s$ is the stiffness constant of the shaft and $H_t$ is the inertia of the turbine blade, $H_g$ is generator inertia whereas $\theta_i$ is the angular displacement of the shaft.

3. CONVENTIONAL FAULT CURRENT LIMITERS
For examining the effectiveness of proposed LVTR configuration, it is compared with existing topologies of DBNSFCL, RCrowbar, BFCL, PRFCL, CDBRFCL. The operation of these configurations has been explained below.

3.1 Diode bridge Non-superconducting fault current limiter
Here we present the configuration of fault current limiter for one phase as shown in Fig.11a. It consists of three subparts and they are i. The diode bridge is made of diodes numbered D1 to D4, ii. non-superconducting coil with a very small resistance of (rd) and inductor (Ld) which is cascaded with IGBT switch, iii. Shunt resistance with a large value is used in parallel with IGBT for absorbing large currents during faults. Let us consider the system is operating under a normal condition with rated voltage and current. The IGBT will be in the closed state, and the diodes carry the line current. In the positive cycle, the current takes the path of D1-rod-D4 path, and in the negative cycle, the current takes the path of D2-rod-D3. The bridge converters AC to DC so the inductor acts as a short circuit for DC current and the ripples present in the system can be minimized by increasing the value of Ld. Due to a high shunt resistance value, the current will not take this path under steady operation without any fault. Whenever a fault occurs, the reactor doesn’t allow to change the current suddenly and this IGBT serves as protecting the device.

3.2 Resistance crowbar
This is one of the conventional protection circuit made of a simple resistor connected at the output of dc in series with an IGBT switch is presented in Fig.11b. Whenever a disturbance exists in the form of fault occurs in the system, the R-crowbar is being short-circuited to generator rotor terminals. This model is having a large drawback of reduction in the voltage at PCC and this violating the grid codes that must be met by the system. A typical value of crowbar resistor will be around 10 times as that of rotor resistance. As this protection is having limited application further modifications can be done for improving its performance.

3.3 Bridge type fault current limiter
As it can be seen from Fig.11c BFCL is the dual combination of full bridge diodes circuit and a limiting reactor Lsh and resistor Rsh for diverting current when a fault occurs in the system. Under normal operation of the system, the IGBT is under turn-on condition and the current enters into the dc reactor. Now the current flows through shunt path Rsh thereby limiting the huge fault current. When the fault has been removed, the controller once again turns on the IGBT.

3.4 Parallel resonance fault current limiter
In Fig.11d, PRFCL block for one phase is shown and this structure consists of two major parts: i. a full bridge diode circuit and output of full bridge circuit is connected to IGBT in series with another subcircuit. This subcircuit is made of dc reactor and resistor in parallel with the diode. The purpose of the diode at this location is for the safe operation of Ldc. ii. This is the resonant part consisting of shunt capacitor and inductors forming a resonant part operating at a system frequency. Under the normal operating condition, the switch is closed and the direction of current takes the path D1-Ldc-Rdc-D4 in the first half cycle and in the next half cycle, the current direction will be D2-Ldc-Rdc-D3. The drop across the Rdc is negligible compared to line drop. The Ldc restricts the rise of line current during fault condition and makes the IGBT to operate safely.
3.5 Capacitor diode bridge resonant fault current limiter
This fault current limiter is presented in [33] consisting of a combination of a capacitor and full bridge circuit and its schematic circuit for a single phase is shown in Fig.11. Though it improves the LVRT it has few drawbacks like transient over-voltages are introduced in the system due to IGBT switching which further damages the switch. The reactor values increase with the fault current flowing under a fault condition. The transformer rating should be made equal to that of line voltage of the bridge circuit which induces high cost. The configuration consists of the bridge circuit of diodes D1 to D4 and a switch at the dc side. A freewheeling diode is connected in parallel with the reactor of small value in series with a resistor. Here a discharging resistance is placed in such a way that the bridge circuit and resistor are in parallel at the dc output.

4. PROPOSED CAPACITIVE TYPE FAULT CURRENT LIMITER

4.1 Configuration and Operation of proposed model
The modified crowbar model is achieved in two stages: in the first stage, a basic RCrowbar is modeled consisting of resistance at the output of diode bridge with D1 to D4. In the second stage, a capacitor is connected in parallel with reactor and resistor combination. For this, a free-wheeling diode is placed after the switch for avoiding the voltage spikes. The proposed model is presented in Fig. 12a. The complete circuits diagram for one phase is shown in Fig.12a, it constitutes a diode bridge and current limiting reactor \( L_d \) and resistor \( R_d \). Under normal operating condition, the IGBT is in the closed condition, so the current flows in the resonant path. Once the fault is cleared, the controller initiates the signal to switch for closing its contact and the bridge is brought back to its normal operation.

4.2 Designing of the proposed model
The presence of resistor \( R_d \) is to dissipate the power of DFIG under fault condition. This avoids DFIG from accelerating the rotor speed and avoids over voltage of dc link. As shown in Fig. 12a shunt capacitor \( C_{sh} \) injects reactive power during a fault, the reason is that torque is proportional to voltage square. So, the reactive power prevents reduction of electrical torque and rotor acceleration. The capacitor also provides sufficient reactive power required by DFIG after clearing the fault thereby avoiding the reactive power absorption from the grid \( (Q_g) \).

4.2.1 Reactor design \( (L_d) \)
While designing a reactor threshold value of current \( (i) \) and its time \( (t) \) must be taken into consideration. The value of DC reactor should damp the DC current prior to fault meeting the condition \( i_d < i \). The main advantage of placing reactor on DC side is to reduce the ramp rate of fault current for turning off the IGBT switch. At this stage the current is linearly incremented and is given by

\[
\frac{d}{dt}V_i(t) = \frac{V_{dc}}{L_d}(t - t_0) + i_0
\]

(40)

where \( V_d \) is dc side voltage and \( i_0 \) is DC reactor current at \( t = t_0 \), now the dc side voltage \( V_d \) can be written as

\[
V_d = \frac{2V_m}{\pi}
\]

(41)

where \( V_m \) is source voltage. From (38 ) the value of inductance is calculated as

\[
L_d = \frac{t_1 - t_0}{i_1 - i_0} V_d
\]

(42)

4.2.2 DC Resistor \( (R_d) \) design
The resistor value is selected in such a way that the power transferred in the fault line should get dissipated without reaching DFIG. Power discharged in \( R_d \) is given by

\[
P_d = \frac{V_{dc}^2}{2R_d} = \frac{P}{2}
\]

(43)
where $P_1$ is the active power and using the above expression minimum value of Rd can be determined as

$$R_d = \frac{2V_{pcc}^2}{P_1}$$  \hspace{1cm} (44)

### 4.2.3 Capacitor design ($C_d$)

The reactive power necessary for DFIG under fault condition must be supplied by the capacitor ($C_d$), so the reactive power and capacitor value is related as follows

$$Q_d = C_d\omega I_c^2 = Q_1$$  \hspace{1cm} (45)

Now the capacitor current $I_c$ is expressed as

$$I_c = C_d\omega V_{pcc}$$  \hspace{1cm} (46)

from the above two equations, $C_d$ can be written as

$$C_d = \frac{Q_1}{V_{pcc}\omega}$$  \hspace{1cm} (47)

So, it is clear that the capacitor value depends on the reactive power of DFIG.

The dc reactor ($L_{dc}$) value is selected to be small which is about (1mH) and Rd value is taken as 0.1mohm which is the internal resistance of Ldc. For comparing the performance of various LVRT techniques these values are preferred in most of the cases. The shunt resistance value is found to be approximately 0.628 p.u for getting good performance.

### 4.3 Controller operation

As shown in Fig.10b the input parameter for the controller are dc current (idc) i.e. the output of full bridge rectifier, reference current (iref), and another comparator takes the input as the voltage at PCC and the reference voltage. Now, the modified capacitive configuration as shown in Fig.10a, when it is under a normal operating condition, the IGBT is in on condition and the current iL flows in the direction D1-Ld-rd-D4-Q during first half cycle, and D2-Ld-rd-D3-Q in the negative cycle. It was mentioned in the previous section that the impedance of Rd and Cd are large so current flows in the reactor path which offers low impedance., so, the current is approximately zero in Cd and Rd. Since the rd value is small the voltage drop is negligible compared to line losses. Due to the occurrence of a fault in the system, the current goes beyond the threshold value and the controller generates a gate signal to turn off the IGBT. At this moment the Rd will be connected to bridge circuit and thus limiting short circuit current. When the system is under normal condition, energy present in the reactor gets discharged in the freewheeling diode. After the fault clearance, the PCC voltage is restored to the rated voltage. The comparator now compares predefined voltage and measured PCC voltage and when both values are equal a high signal is sent to IGBT to operate, and the system brought to normal operation.

### 5. Simulation Results and Discussion with Performance Comparison

Here in the simulation, a constant wind speed with a magnitude of 8.5 m/sec is considered for analysis. We create a 3LG and 1LG fault in order to study the performance of various LVRT configurations. The fault is usually created near the PCC i.e. at the grid side as it is considered as the severe case. The fault is created at time 3 s and drawn at 3.1 s and the breaker connected in the line operates. For better visualization, the fault section is zoomed and shown. In order to analyze the LVRT six different cases have been simulated and presented here and they are

1. Case A: CDRFCL
2. Case B: DBNSFCL
3. Case C: BFCL
4. Case D: PRFCL
5. Case E: R Crowbar
6. Case F: Capacitor diode bridge DC reactor PRFCL

The LVRT enhancement analysis for DFIG based WT is performed through MATLAB/Simulink. The performance for symmetrical fault and asymmetrical fault by implementing different cases mentioned above are presented in the following sections.

#### 5.1 Analysis of symmetrical three phase-ground (3LG) fault

The analysis of three-phase- ground fault and its various performance measures are presented in this section. Fig.13a shows the stator voltage when a transient 3LG fault is initiated at the PCC. Due to this fault, the voltage has been reduced to 10% of the nominal value from 3s to 3.15s and the voltage recover starts from 3.15s to 3.85s with a ramping voltage of volts and settles to a steady-state value of 690V at 3.85s. The voltage reaches to almost zero at the fault instant and it continues till the breaker contacts are separated. By implementing capacitive diode bridge dc reactor parallel resonant fault current limiter (CDDRPRFCL) the voltage is restored quickly for meeting the grid code limits compared to CDRFCL, BNSFCL, BFCL, PRFCL, RCrowbar. This shows the performance improvement by using the proposed modified configuration for 3LG fault.

From Fig.13b it is clear that Speed of the generator is having fewer oscillations by placing proposed CDDRPRFCL during fault when compared to CDRFCL, BNSFCL, BFCL, PRFCL, RCrowbar for symmetrical 3LG fault. By using a crowbar, the rotor speed jumps at the fault instant and the proposed model is able to reduce these oscillations.

The dc bus voltage is shown in Fig.13c for a 3LG fault for all the cases. The proposed fault current limiter maintains the voltage at the dc link near to rated value when compared CDRFCL, BNSFCL, BFCL, PRFCL, RCrowbar and therefore the voltage profile has been improved significantly. Some other parameters that show the performance improvement by using proposed configuration are Tem as shown in Fig.13d is having more oscillations during the starting due to inertia and it slowly settles down to a steady value. But on occurs of fault, the proposed CDDRPRFCL is capable of reducing the oscillation is the torque and brings the electromagnetic torque to steady.
state in less time. The $T_{mech}$ as seen from Fig.13e is the mechanical input given to DFIG.

![Fig. 13. Dynamic analysis of DFIG for a three-phase fault at the reduction of 10% of nominal voltage (a) to (e).](image)

On fault detection, the rotor speed varies and the MPPT controller changes its path and brings the system to steady state with fewer oscillations with the proposed configuration. Similarly, the rotor current and stator current are shown in Fig.14a to Fig.14d for both $d$-axis, $q$-axis and stator flux, rotor flux in Fig.14e and Fig.14f. Once the flux gets reduced and the voltage is able to stabilize the machine the crowbar comes to its original position and the RSC is reconnected to the machine.
But, the flux is not damped completely and it is required to inject demagnetizing rotor current by the rotor side controller. This rotor current injecting is achieved by providing reactive power by increasing rotor current $d$ component. This process continues until the grid voltage gets restored and normal operation is presumed. The three-phase rotor current, stator current, $V_{dr}$, $V_{qr}$ active and reactive power are shown in Fig. 15a-15f.

Fig. 14. Dynamic analysis of DFIG for a three-phase fault at the reduction of $10\%$ of nominal voltage (a) to (f).
5.2 Analysis of asymmetrical single line-ground fault

Here the performance of the proposed model with other fault current limiters available in the literature has been analyzed for a single line-ground (1LG) fault. The severity of 1LG is less when compared to a 3LG fault and it is the most frequently occurring fault among other faults. Fig. 16a shows the stator voltage for the 1LG fault for 10% of nominal voltage or 90% voltage dip in one of the phase. The rotor speed has fewer oscillations by employing the proposed (CDDPRFCL) as shown in Fig. 16b and the dc-link voltage is depicted in Fig. 16c also having fewer variations with the reference value when compared with another case A-E. The electromagnetic torque and mechanical torque both are having good performance with the proposed dynamic model and is shown in Fig. 16d and Fig. 16e.

Fig. 16. Dynamic analysis of DFIG for single phase fault at the reduction of 10% of nominal voltage (a) to (e).

In a similar way, the rotor current, stator current are shown in Fig. 17a to Fig. 17d in both d-axis and q-axis and stator flux, rotor flux in Fig. 16e and Fig. 16f.
Fig. 17. Dynamic analysis of DFIG for single phase fault at the reduction of 10% of nominal voltage (a) to (f).

From Fig. 18a-18f rotor current, stator current, Vdr, Vqr, active and reactive power are shown.
Fig.18. Dynamic analysis of DFIG for single phase fault at the reduction of 10% of nominal voltage (a) to (f).

The values of 3LG and 1LG faults for different configurations are presented in Table 2 and Table 3.

6. CONCLUSION
A modified capacitor type diode bridge fault current limiter is proposed for DFIG based wind turbine for voltage ride through improvement under symmetrical and asymmetrical fault conditions. The proposed fault current limiter performance has been compared with RCrowbar, BFCL, PRFCL, CDRFCL, and diode bridge NSFCL models. The results as presented in Table 2 and Table 3 show that the proposed configuration is better than other models as mentioned above. All the simulation results and explanations are given by comparing with conventional LVRT models. For a 3LG fault, Voltage at PCC for the proposed model is having least deviation of about 0.2493 p.u and more deviation for CDRFCL. While the active power is also maintained at 0.0731 p.u of deviation for the proposed model and the highest deviation is observed in the case of PRFCL. Similarly, DC bus voltage and speed are 0.0413 p.u and 0.0312 p.u deviations respectively for 3LG fault. The proposed model also assured better performance for LG fault also as shown in Table 3.

- The proposed CDDRPRFCL limited the ramp rate of fault current without delay through DC reactor for DFIG connected to wind turbine subjected to symmetrical and unsymmetrical voltage dips.
- It provides voltage support at PCC by providing sufficient reactive power under fault and post-fault conditions.

So, the proposed CDDRPRFCL is having good improvement compared to CDRFCL, BNSFCL, BFCL, PRFCL, RCrowbar under symmetrical and asymmetrical voltage dip in the system. This work can also be extended for large wind farm system for LVRT improvement and integrating to the smart grid.
REFERENCES:


