

APPLICATION OF BRIDGE TYPE FAULT CURRENT LIMITER FOR FAULT RIDE-THROUGH CAPABILITY ENHANCEMENT OF DFIG BASED VARIABLE SPEED WIND TURBINES

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Abstract: Nowadays, wind energy is more prominent option to generate electrical power compared to all other renewable sources. However, their integration into the electrical grid is difficult because of grid code requirements. The Fault Ride Through (FRT) is an important issue related to wind energy conversion systems (WECS). For the power generation by wind uses different types of wind generators like synchronous and induction generators. Currently, the doubly-fed induction generator (DFIG) based wind turbine is most popular technology to generate electric power due to its variable speed operation and to capture more wind energy. According to the grid code requirements, FRT capability augmentation of DFIG based wind turbine is a very important research topic. Doubly fed induction generator-based wind turbines are more affected by the grid faults because its stator windings are directly connected to the electrical grid. However, the wind generators stay connected to the grid during fault as per the grid code requirements. In this work, a bridge type fault current limiter (BFCL) is proposed to enhance the FRT capability of DFIG based wind turbine with the test system considered. The test system consists of a 9MW doubly fed induction generator-based wind turbines connected to an infinite bus through step-up transformers and a double circuit transmission lines. A three phase to ground (3LG) fault is applied to one of the transmission lines to investigate the FRT capability augmentation of DFIG based wind turbine with BFCL. The performance of the BFCL is compared with that of series dynamic braking resistor (SDBR). Simulations are made by using MATLAB/Simulink software. The results show that the proposed BFCL improves the FRT capability of DFIG based wind turbines well. Moreover, the overall performance of the BFCL is better than that of the SDBR in every characteristic.

Keywords: Bridge-type fault current limiter (BFCL), doubly-fed induction generator (DFIG), fault ride through (FRT), grid code requirements, series dynamic braking resistor (SDBR), wind energy conversion system (WECS).

1. Introduction

Day by day, the electrical demand is increasing due to the advancement of technology and industrialization.

To maintain the load demand, power generation is to be increased by means of Conventional and Non-conventional energy sources. Due to environmental constraints and limited reserve of fossil fuels, renewable energy sources play a major role. Now, power generation by the wind is the fastest growing technology due to its low maintenance, clean, cheap, and zero fuel cost. Hence, wind energy is a good research topic around the world. According to the Global Wind energy Council (GWEC), about 12% of the world's total electricity demand will be supplied by the wind energy by 2020[1].

Compared to fixed speed wind turbines (FSWTs), the variable speed wind turbines (VSWTs) are more popular and better choices because they capture more energy from the wind, Flexible in operation, high efficiency, low maintenance, low mechanical stress on turbine, enhanced power quality, and independent control of the active and reactive power. Variable speed wind turbines (VSWTs) employing doubly-fed induction machine (DFIG) are mostly used due to their lower cost, possibility to cover a wide range of wind speed, partially rated power converter (25-30% of the generator capacity), simple structure and lower switching loss [2]. However, the DFIG based wind turbines are more affected by grid faults, as their stator windings are straightforwardly connected to the electrical grid. Usually, to protect from the faults, the wind turbines were disconnected from the grid. As more wind power is integrated into the grid, it has become essential that wind turbines stay connected to the grid during fault from the stability point of view. In addition, this is a requirement by grid codes set by the transmission system operators (TSOs) of different countries [3]. So, the DFIG based wind turbines should

require better fault ride through capability.

Several series and parallel compensators are used to enhance the FRT capability for the wind energy conversion system (WECS). Static synchronous compensator (STATCOM) [4], [5] is proposed but it requires an additional converter, coupling transformer, and harmonic filters. Superconducting fault current limiter (SFCL) [6] and superconducting magnetic energy storage [7] are also proposed, but the high installation cost reduces their good performance.

The Bridge type fault current limiter (BFCL), a new method in power systems[8],[9] is applied to fixed speed wind generators [10] ,[11] where the fault ride through improvement has been done. Now, the BFCL is applied to improve the fault ride through capability of DFIG based wind turbines and it is inspected.

2. Wind Turbine Modeling

In this work, the horizontal axis wind turbine has been used. The commonly used equation for the mechanical power (P_m), captured by a wind turbine can be expressed as follows

$$P_m = 0.5 * \rho * \pi R^2 * V_w^3 * C_p(\lambda, \beta) \quad (1)$$

Where ρ is the air density in kg/m^3 , R is the wind turbine blade radius in meter, V_w is the wind velocity in m/s, and $C_p(\lambda, \beta)$ is the power coefficient, which is a function of tip speed ratio (λ) and blade pitch angle (β). According to Betz's law, theoretically 59.3% power can be extracted from the wind [12].

The tip speed ratio is expressed as

$$\lambda = \frac{R\omega_r}{V_w} \quad (2)$$

Where ω_r is the angular mechanical speed in rad/sec. The power coefficient $C_p(\lambda, \beta)$ equation [13] can be expressed in (3) is used in this work.

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_1} - C_3\beta - C_4 \right) e^{-\lambda_i} + C_6\lambda \quad (3)$$

Where

$$\lambda_i = \left[\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \right]^{-1} \quad (4)$$

For a particular turbine type, the coefficients from c_1 to c_6 are $c_1=0.5176$, $c_2=116$, $c_3=0.4$, $c_4=5$, $c_5=21$ and $c_6=0.0068$. The C_p - λ characteristics [14] for the different values of blade pitch angle (β) is as shown in

Fig 1. For a fixed blade pitch angle, a maximum C_p is achieved when the tip speed ratio is at the optimum value (λ_{opt}).

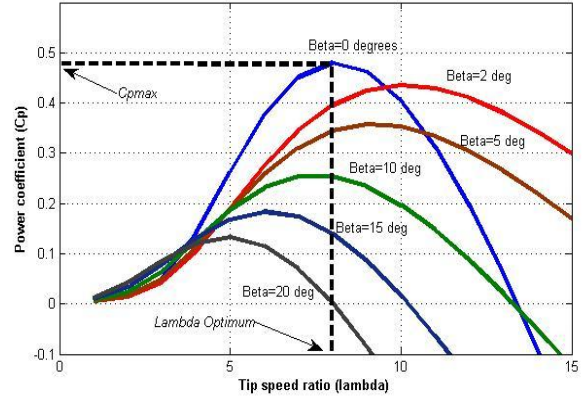


Fig. 1 The C_p - λ characteristics

3. DFIG Modeling

The doubly fed induction machine is a wound rotor induction machine, where the stator windings are directly connected to grid and the rotor windings are interfaced to grid via two converters i.e. the rotor-side converter (RSC) and the grid-side converter (GSC) are connected back-to-back through a common DC link capacitor is shown in Fig. 2. The park's transformation is used to model the DFIG, which is a fourth order state space model. This employs synchronously rotating $d-q$ reference frame, where the d -axis is aligned with the stator flux vector position. An independent control between rotor excitation and the electrical torque is achieved [15].

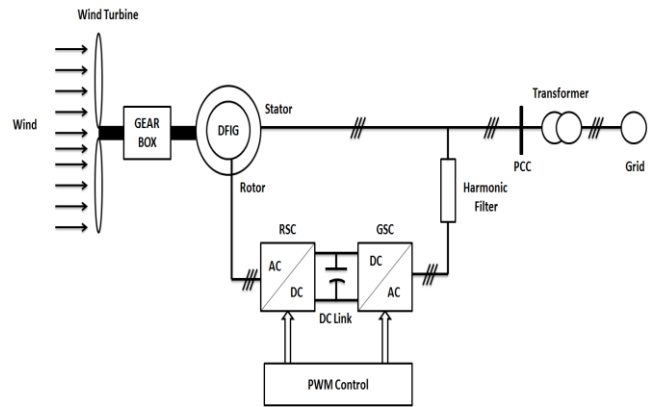


Fig.2 Simplified block diagram for DFIG based wind turbine

A. RSC Controller

The RSC is shown in Fig.3, the name itself defines that it is a controller at the rotor side of DFIG. RSC is nothing but a two level, six pulse based IGBT full bridge AC-DC converter that controls both active and

reactive powers at the stator side of DFIG. On the other end of RSC, it is coupled to a D.C link capacitor to balance the energy both the sides of RSC and GSC. The generator speed (ω_g), and the reactive power (Q_t), and the terminal voltage of the generator (V_t) are taken as inputs to the RSC such that the outputs are controlled active and reactive powers. The Park's transformation is used to convert the three-phase quantities into two quantities, direct (d) and quadrature (q) components and vice versa. As in the Fig.3, the PI controllers along with park's transformation produces a three-phase output is given to the PWM signal block generator. So, that it can generate pulses to the RSC controller.

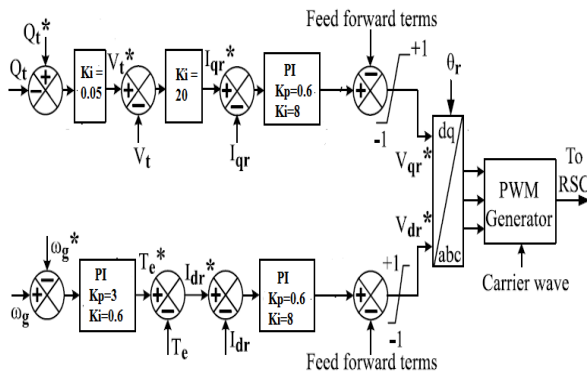


Fig. 3 RSC Controller

B.GSC Controller

The GSC Controller is shown in Fig.4. It also contains a two-level, six-pulse IGBT based power electronic converter. The foremost task of GSC is to control the D.C link voltage at constant level irrespective of the rotor power flow and exchange of reactive power between the grid and GSC. Two cascaded d and q axis control loops exist in GSC, which are similar to RSC. The outer control loops deal with the D.C link voltage and GSC's reactive power and the inner ones deal with current control. GSC takes the inputs, D.C link voltage (E_{dc}) and grid side quadrature current (I_{qg}) and generates the output pulses by means of PWM generator via PI controllers. I_{qg} was set to zero to maintain power factor as unity at the DFIG terminal. RSC and GSC controllers' carrier wave frequency are chosen 1350Hz and 2250Hz respectively to mitigate harmonics. Similarly, the RSC and GSCs' control parameters are adjusted to get the better steady state performance of the DFIG. The D.C link capacitor of 10000 μ F is chosen to smooth out the ripple of the D.C voltage and keep it constant to 1150V.

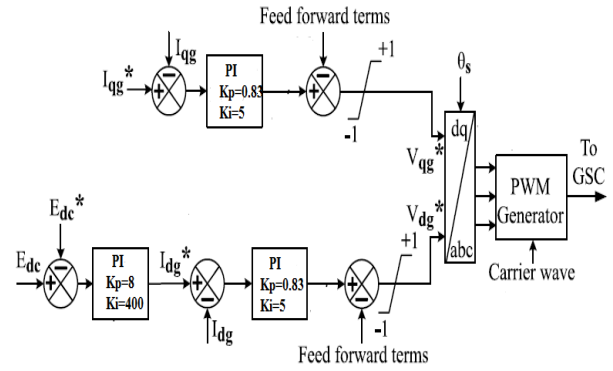


Fig. 4 GSC Controller

4. Bridge Type Fault Current Limiter

The BFCL is composed of two sections: (i) The Bridge Part (ii) The Shunt Part. The bridge part is composed of diodes $D_1 - D_4$, a small-valued d.c inductor L_{dc} and a very small value resistor R_{dc} are connected in series with a parallel free-wheeling diode D_5 placed with an IGBT switch in series. The shunt path composed of a resistor R_{sh} and an inductor L_{sh} , are connected in series and it is in parallel to the bridge part as in Fig. 5.

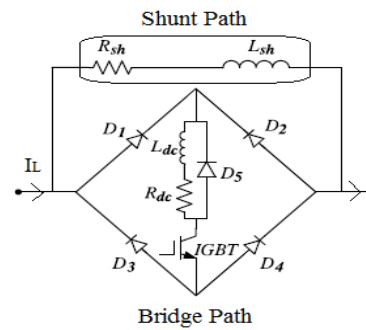


Fig.5 Bridge Type Fault Current Limiter

A. BFCL Operation

The BFCL operation is shown in Fig.6. The IGBT switch in the bridge part remains closed during normal operating condition. During the positive half cycle of electrical frequency, the line current flows from $D_1 - R_{dc} - L_{dc} - D_4$ and for the other half cycle, the line current flows from $D_2 - L_{dc} - R_{dc} - D_3$. Therefore, the current through the inductor (L_{dc}), flows in the same direction and this current is the d.c current (I_{dc}). The inductor (L_{dc}) is charged with the peak current and acts as a short circuit. In steady-state operation, the IGBT turn-on resistance, the inductor (L_{dc}) inherited resistance and the diode forward voltage drop cause

some voltage drop, but this voltage drop is quite negligible compared to line drop.

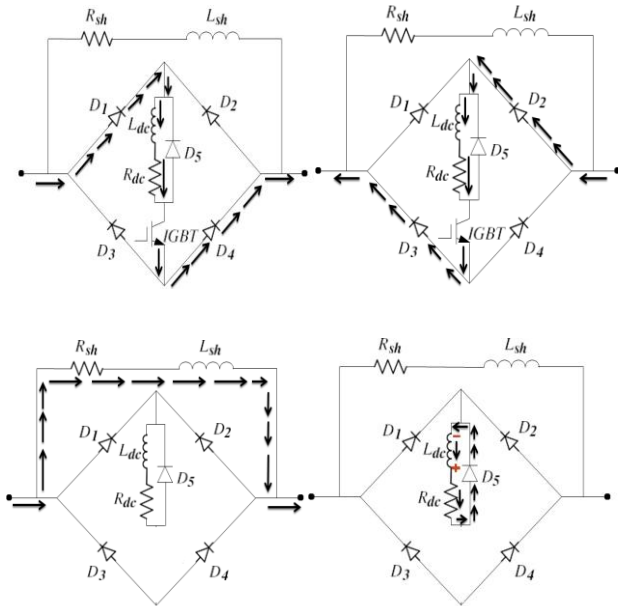


Fig. 2 BFCL operation

The shunt path impedance is chosen high enough, the complete line current to flow through the bridge except a very small leakage current. When a fault occurs, initially the line current tends to increase suddenly, but the inductor (L_{dc}) limits the increasing rate of line current. The safe operation is maintained because the IGBT switch is saved from high value of di/dt .

B. BFCL Control Strategy

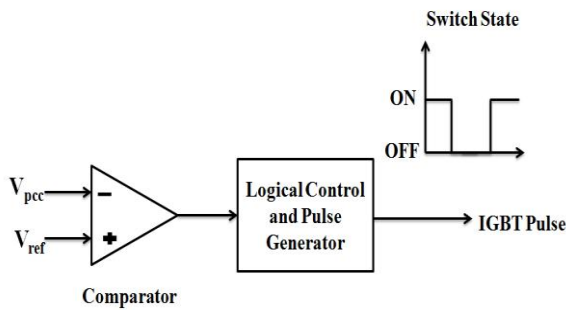


Fig. 7 BFCL Controller

The BFCL controller is shown in Fig. 7. It is composed of a single comparator and a pulse generator. Signal from the comparator is collected, and an appropriate IGBT gate signal is sent via pulse generator.

The PCC voltage of the wind farm (V_{pcc}) is compared with the threshold reference (V_{ref}). At the

event of fault, V_{pcc} goes low and becomes lower than V_{ref} . The IGBT switch opens and current is bypassed to the shunt path having high impedance and suppresses the fault current. When V_{pcc} is restored due to fault isolation and becomes greater than the threshold value (V_{ref}). The IGBT switch is closed and normal operation continues.

In this paper, to get the good performance of the considered system, the value of R_{sh} and L_{sh} is considered as 0.46 p.u and 0.04 p.u.

5. Series Dynamic Braking Resistor

The SDBR is shown in Fig.8. In this work, the effectiveness and performance of the proposed BFCL is compared with the SDBR. The SDBR is a proved solution to improve the fault ride through capability of DFIG based wind turbine [16]. The SDBR is a combination of IGBT switch with a parallel resistor. During the normal operating condition, the IGBT switch remains closed and the line current flows through the IGBT switch. At the event of fault, the IGBT switch will open and the line current flows through the braking resistor until the desired condition will be satisfied. The same control strategy is used for both the BFCL and the SDBR. To make the comparison, the same value of 0.46 p.u resistance as the BFCL is also considered for the SDBR.

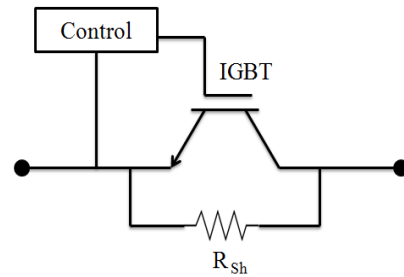


Fig. 8 Series Dynamic Braking Resistor

6. Test System Model

In this work, a 9 MW 0.575 KV DFIG based wind Farm has been modeled to investigate the fault ride through capability improvement. The DFIG parameters used in this work are listed in Table 1. The series-compensating device i.e., the BFCL or the SDBR, is connected in series at the point of common coupling (PCC). The effectiveness of the proposed BFCL is tested by considering most severe fault (3LG) at point F_1 in the considered power system network as shown in Fig.9.

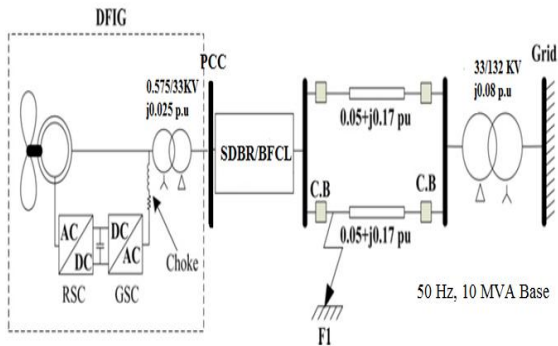


Fig.9 Schematic diagram of test system considered

The MATLAB/Simulink implementation of DFIG based wind turbine with test system considered is as shown in Fig.10. The DFIG wind turbine is connected to an infinite bus through two step-up transformers and a double circuit transmission line. A zig-zag grounding transformer is used for harmonic elimination. Fig.11 shows MATLAB/Simulink implementation of DFIG with back to back converter. To lessen the harmonics generated by the PWM converters, choke coil is inserted in series with the GSC. Filter is used to eliminate the harmonics produced by the power electronic converters. Fig.12 depicts the MATLAB/Simulink implementation of BFCL and its controller. Fig.13 shows the MATLAB/Simulink implementation of SDBR and its control circuit. The BFCL and SDBR controller generates gate pulse to the IGBT with the help of relational operator.

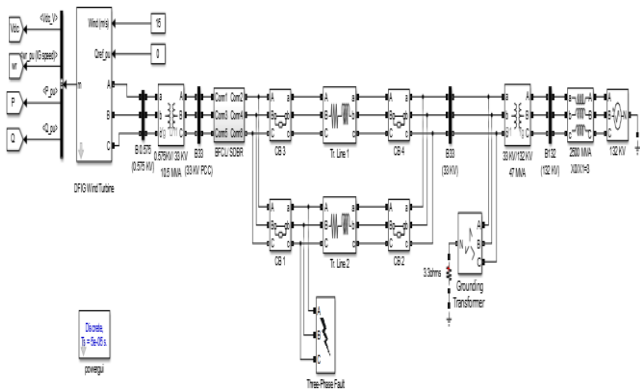


Fig.10 MATLAB/Simulink implementation of DFIG based wind turbine with test system considered

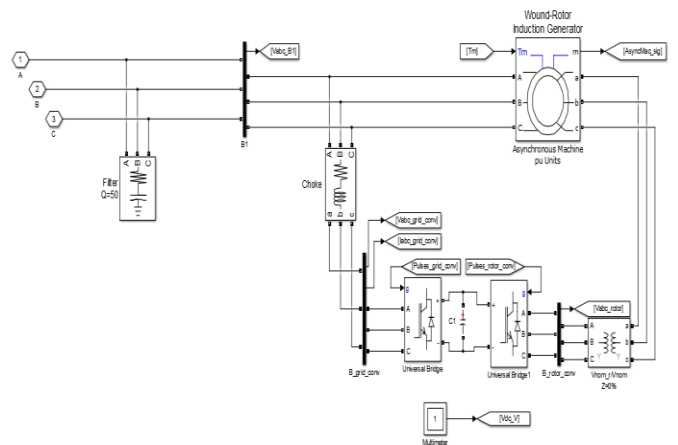


Fig.11 MATLAB/Simulink implementation of DFIG with back to back converter

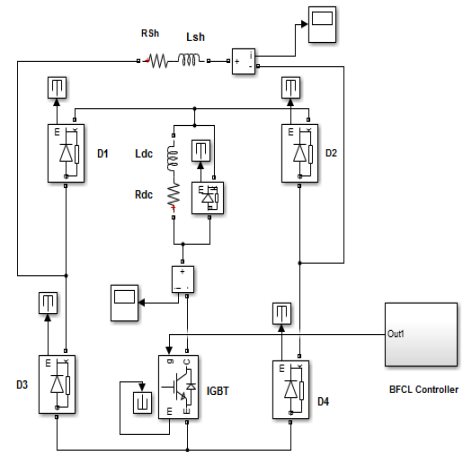


Fig.12 MATLAB/Simulink implementation of BFCL and its controller

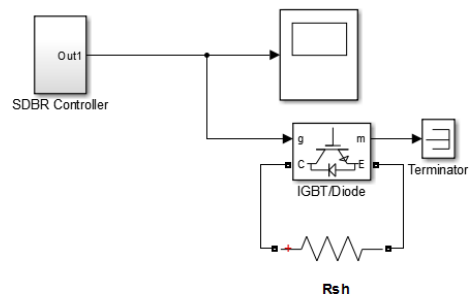


Fig.13 MATLAB/Simulink implementation of SDBR and its control circuit

Table 1 Parameters of the DFIG simulated

Rated Power of DFIG	1.5 MW
Rated Voltage	0.575 KV
Rated frequency	50 Hz
No. of wind turbines	6
Stator Resistance (R_s)	0.023 p.u
Rotor Resistance (R_r)	0.016 p.u
Stator Inductance(L_s)	0.18 p.u
Rotor Inductance(L_r)	0.16 p.u
Mutual Inductance(L_m)	2.9 p.u
Lumped Inertia constant(H)	0.685s
No.of pole pairs	2

7. Simulation Results and Discussions

A. Simulation Considerations

In this work, the wind speed is considered as constant (15m/s), as the duration of the fault is too small for the wind speed to make any considerable effect. The most severe (3LG) fault is applied on the test system considered at point 'F₁' near the PCC at 1sec as shown in Fig.9.Circuit breakers on the faulted line open at 1.1sec and reclose successfully at 2sec.The nature of fault is temporary. The simulation time is 2 sec and the simulation step time of 50 μ s is used in this study. During the simulation, three different situations are considered, they are as follows:

Situation -1: with no auxiliary device

Situation -2: with SDBR

Situation -3: with BFCL

B. FRT capability augmentation for 3LG

Fig.14 shows the outputs of generator PCC voltage, current, active power, reactive power, D.C link Voltage and rotor speed respectively with no auxiliary device and with two auxiliary devices SDBR and BFCL. Fig. 14 (a) shows the DFIG's PCC voltage when a symmetrical fault (3LG) is applied. In no auxiliary device case, during fault time the voltage dip is higher almost at 0.1p.u. Whereas in SDBR, even the dip is lower than no auxiliary device case as shown in Fig.14 (b) where the voltage dip is at a value of 0.4. As shown in Fig. 14 (c), the DFIG PCC voltage returns nearer to the nominal value 0.8 p.u at a faster rate than no auxiliary device and SDBR.

With no auxiliary device case, the DFIG's current is

at 2.5 p.u during the fault period as shown in Fig.14 (d). Fig.14 (e) exhibits that the fault current is reduced to 1.5 p.u because of SDBR, even the current is minimized to 1.2 p.u because of better operation of BFCL as shown in Fig.14 (f).

In Fig. 14(g), the active power from DFIG is almost zero during the fault period under no auxiliary device operation. From Fig.14 (h), SDBR just improves the power profile to 0.5 p.u. BFCL provide better operation as it has improved the power profile as shown in Fig.14 (i).

During normal operating conditions, DFIG does not draw reactive power from the grid (0 p.u). In the event of fault, Induction machine draws huge amount of reactive power (0.75 p.u) due to its inductive nature as shown in Fig.14 (j) under no auxiliary device situation. From Fig. 14 (k), it visualizes that the reactive power demand from the DFIG is lower in case of SDBR. The oscillation of the reactive power output is lower for the BFCL compared to the SDBR as shown in Fig.14 (l).

In the event of Fault, the D.C Link voltage increases from 1150V (1.0 p.u) to 2093V (1.82 p.u) as shown in Fig.14 (m) under no auxiliary device case. In case of SDBR, the D.C link voltage is almost settled at the reference value with more fluctuations as shown in Fig. 14(n). However, with BFCL, the D.C link voltage is settled at the reference value with slight fluctuations as shown in Fig. 14(o).

With no auxiliary device case, there is a sudden rise of rotor speed of the DFIG due to a gap between the generated power and the demanded power at the event of fault as shown in Fig.14 (p).With the application of SDBR, the rotor speed deviation is lower compared with the no auxiliary device case as shown in Fig.14 (q).But the BFCL lowers the rotor speed deviation better than the SDBR is as shown in Fig.14(r).

At the event of fault, the d.c reactor, placed within the bridge of the BFCL limits the sudden rise of fault current. Also, the IGBT switch is protected against the severe di/dt at the instant of fault. The SDBR lacks these merits. Without proper protective devices for IGBT switch, the SDBR may stop to operate. From the simulation results, the BFCL provides enhanced performance than the SDBR.

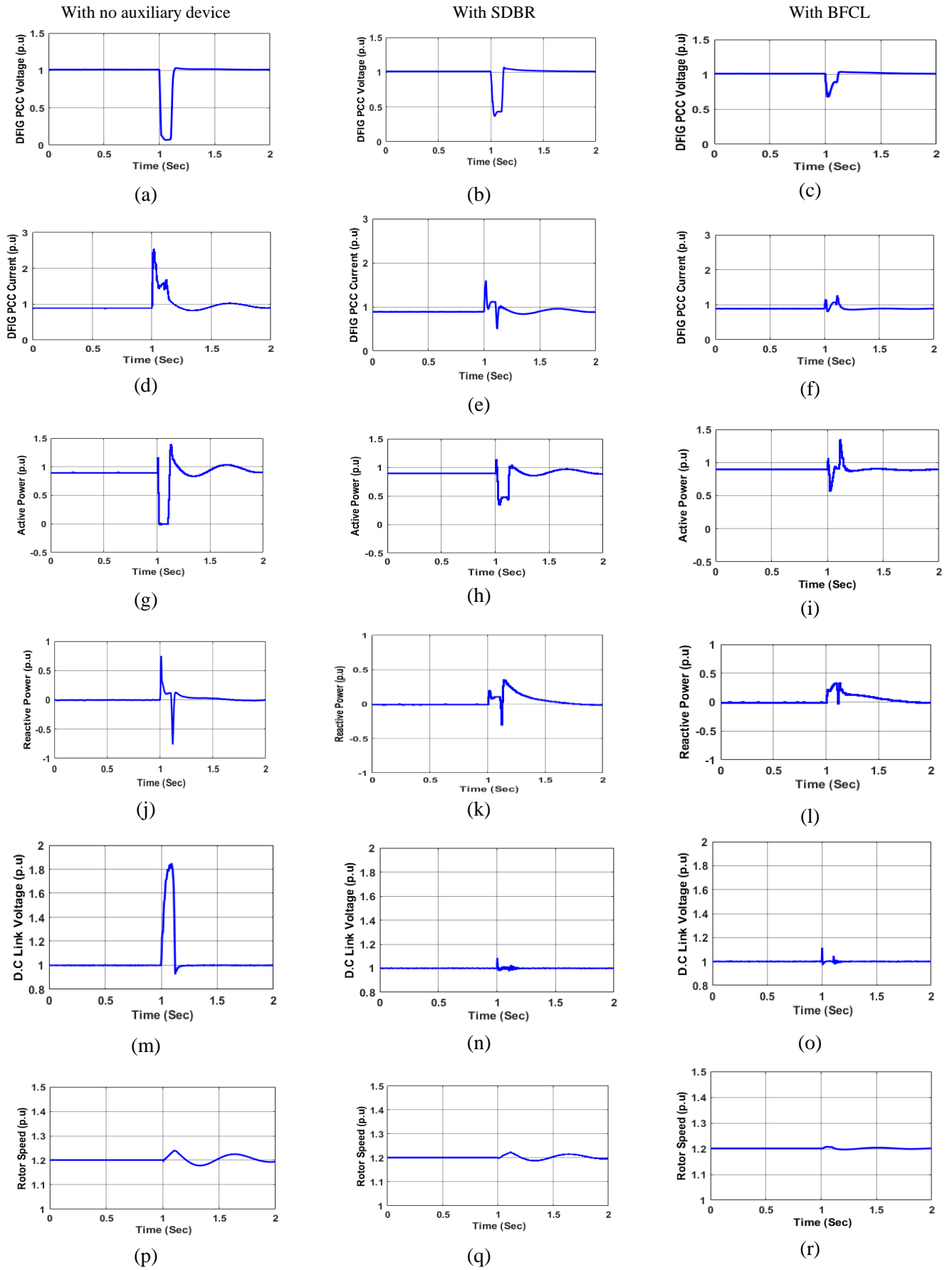


Fig.14 Simulation results during 3LG fault (a),(b) and (c) DFIG PCC Voltage(p.u) (d),(e)and (f) DFIG PCC Current (p.u) (g),(h) and(i) Active Power (p.u) (j),(k) and (l) Reactive Power(p.u) (m),(n) and (o) D.C Link Voltage(p.u) (p),(q) and (r) Rotor Speed(p.u)

8. Conclusion

In this paper, the application of BFCL is proposed to augment the FRT capability of DFIG based wind generator. The performance of the BFCL is compared with that of SDBR. Based on the simulation results, the following points are noteworthy in BFCL compared to SDBR:

1. The BFCL is a very effective means to augment the FRT of DFIG based wind generator.
2. Suppression of the fault current is achieved by using the BFCL.
3. The BFCL prevents huge instantaneous voltage drop at the event of fault, so the generator faces lower stress.
4. The BFCL minimizes the fluctuation of rotor speed and enhances stability better than the SDBR.
5. The BFCL works better than the SDBR in every characteristic.

In our future work, the effectiveness of the proposed BFCL can be extended to asymmetrical faults and the BFCL can be applied and tested for the permanent magnet synchronous generator (PMSG) based variable speed wind generator.

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