Comparative Performance Analysis of Different Bridge Type Fault Current Limiter for LVRT Capability Enhancement in DFIG Based Wind Farm

[1]Md Asaduzzaman Shobug, [2]M.R.I Sheikh, [3]A.H.M. Iftekharul Ferdous
[1,2,3] Department of Electrical and Electronic Engineering
[1,3]Pabna University of Science & Technology (PUST)
[2]Rajshahi University of Engineering & Technology (RUET)
[1]Email: sabs.ruet@gmail.com

Abstract— Rapid reduction of fossil fuel and environment concern, renewable energy is highly considered. Among the various renewable resources, wind energy is one of the most important sources. In recent year doubly fed induction generator (DFIG) is one of the most widely used in wind farms. But the transient stability of DFIG becomes very much sensitive and challenging concern. Three phase line-to-ground fault (3LG) is one of the worst cases of DFIG. During fault at grid side, DFIG is much affected because its stator windings are directly interfaced to grid. So it is important to enhance the transient stability of DFIG during fault. To improve the transient stability and fault ride through capability of DFIG two fault current limiter (FCL), i.e. Parallel Resonance Bridge Fault Current Limiter (PRBFCL) and Non-linear Bridge Type Fault Current limiter (NBFCL) is proposed in this paper. The proposed two FCL limits the fault current but also recovers voltage quickly. Thus improves the transient stability and fulfill the grid code requirements. For simulation analysis, PSCAD/EMTDC software is used. Proposed FCLs performance is compared with the RL-BFCL (RL-type Bridge Fault Current Limiter). Simulation results show that the proposed two FCL enhances the transient stability of DFIG and have better performance than RL-BFCL. Also NBFCL has better performance than PRBFCL which is shown.

Index Terms— DFIG, Fault Current Limiter, Bridge type Fault Current Limiter, Symmetrical Fault, LVRT, Wind Farm, Variable Speed Wind Turbine.

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1 INTRODUCTION

Electrical power demand all around the world has increased. Rapid depletion and limited reserve of fossil fuels and of environmental concerns have made it vital to seek for alternative energy sources. Among the available renewable energy sources, wind energy is the fastest growing and well-known option to generate electric power due to its zero fuel cost, no carbon emission, and low maintenance, cleaner, cheaper and renewable. Due to flexible in operation and enhanced features like higher output power, higher efficiency, improved power quality, variable speed operation, lower mechanical stress on turbine, decoupled control of the active and reactive power, the variable speed wind generators are becoming preferred choice for new installations than the traditional induction machine-based fixed speed wind generators. Lower cost, robustness, simple structure, possibility to cover a wide range of wind speed, partially rated variable frequency ac/dc/ac converter and lower switching loss have made the doubly fed induction machine (DFIM) a superior choice over the other wind generator options [1]. The DFIG is more at risk to grid fault or disturbances from the stability, as its stator windings are directly connected to grid while rotor windings are interfaced to grid via the rotor-side converter (RSC) and the grid-side converter (GSC) that are connected back-to-back through a dc-link capacitor. At the event of grid fault, terminal voltage of the DFIM goes very low and very high current flows through both stator and rotor winding. This is a danger to stable operation and may burn the machine and the converters. Traditionally, to protect from such fault incidents, wind generators were disconnected from the grid, but it is not useful because the impact of a large scale DFIG based wind farms disconnected may disturb the stability, thus need to remain connected to the grid throughout the fault occurrence. This operational behavior is well known as low voltage ride-through (LVRT) capability. To remain connected DFIG must follow grid code. .For these reasons, the DFIG should have better stabilization and fault ride through capability. DVR/STATCOM/SMES/FES can improve the LVRT capability of the DFIG based wind farm, but these solutions need high amount of storage component, which creates the system more complex [2]. Also to overcome these problems many controllers have been proposed such as Bi-2212 superconducting fault current limiter (SFCL) [3], energy storage systems like flywheel energy storage[4], superconducting magnetic energy storage-fault currentlimiter (SMESFCL)[5] but have some disadvantages. In literatures it was found that,some fault current limiters and series devices are employed to improve the LVRT capability and transient stability of the DFIG based wind generators and wind farms, like as CBFCL , NC-NBFCL ,SSFCL-LR, N-SSFCL ,SFCL ,R-type SSFCL, GCSC , SDBR. The bridge-type fault current limiter (BFCL) is a new technique with promising applications in power systems [6], [1, 7] and fault ride through capability enhancement of fixed speed wind turbine generators[8, 9]. In this study, a parallel resonance bridge type fault current limiter (PRBFCL)[10] and non-linear bridge type fault current limiter (NBFCL) is proposed. In this study, performance of the PRBFCL and NBFCL on enhancing the transient stability and low vlotage ride through capability is investigated.

2 SYSTEM MODEL

The system consists of wind turbine based DFIG, transformer, double circuit transmission lines connected to the infinite bus and fault occurs at point F as shown in Fig.1. In this model, DFIG consists of a wound rotor induction machine is used. The detailed model of DFIG was described in [11, 12]. The equation (1), (2), and (3) represents the characteristics of wind turbine.

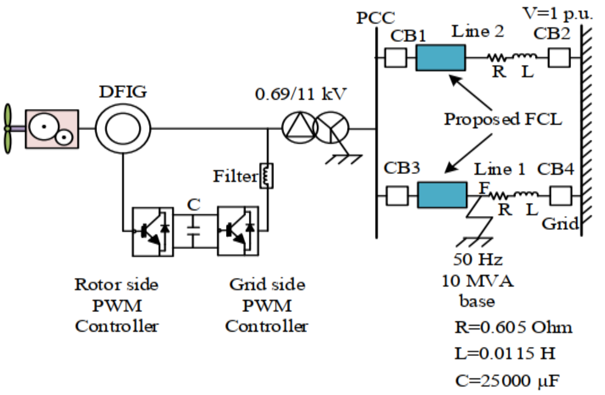

Fig.1. Schematic diagram of DFIG with proposed

$$P_w = \frac{1}{2}\pi\rho R^2 V_w^3 Cp(\lambda)\text{.............................}(1)$$

$$\lambda = \frac{\omega R}{V}\text{..}(2)$$

$$C_p(\lambda) = 0.5(\tau - 0.022\beta^2 - 5.6)e^{-0.17\tau}\text{...}(3)$$

Where, P_w is the wind turbine output [W], λ is the tip speed ratio, R is the radius of the blade [m], ω is the wind turbine angular speed [rad/s], β is the blade pitch angle [deg], V_w is the wind speed [m/s], ρ is the air density [kg/m3], and τ is the wind turbine output torque [N-m]. C_p, is the power constant.

In [8]–[11] many works described the modeling of the DFIG. The DFIG parameter used in this study is described below in Table-1.

TABLE I. WIND GENERATOR DATA

No.	Wind Generator Data Summary	
	Generator Characteristic	*Value*
i.	Rated Power	10[MVA]
ii.	Rated Voltage(L-L)	.69[KV]
iii.	Rated Frequency	50 [Hz]
iv.	Stator/Rotor Turns Ratio	1
v.	Angular Moment Of Inertia (J = 2H)	1.5
vi.	Graphics Display	3- Phase View
vii.	Stator resistance	0.01[pu]
viii.	Wound Rotor Resistance	0.01[pu]
ix.	Stator Leakage Inductance	0.15[pu]
x.	Wound Rotor Leakage Inductance	0.15[pu]

3 FAULT CURRENT LIMITERS

The details of three fault current limiter is described below:

3.1 PRBFCL Fault Current Limiter Model

A configuration of parallel resonance bridge type fault current limiter (PRBFCL) was found in [10]. Fig.2 shows the proposed configuration of PRBFCL. It consists of the shunt path includes a resistor (*Rpr*), an inductor Lpr, a capacitor C_{pr} all are connected in

ISSN 2229-5518

parallel with the bridge circuit. The bridge circuit includes a full diode bridge (*D1-D4*), an IGBT switch (*T*) connected in series with a small DC reactor parallel with a freewheeling diode (*D5*). The DC reactor consists of resistance *Rdc* and inductance L_{dc}. The basic operating principle of this PRBFCL is to insert impedance of RLC branch limiting the fault current.

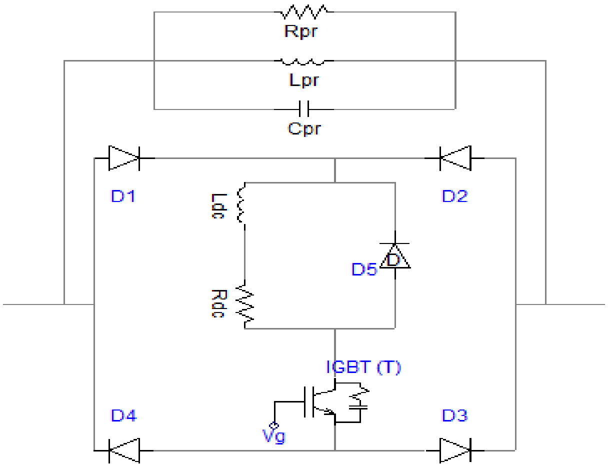

Fig.2. Configuration of PRBFCL

3.1.1. PRBFCL Operation

i. Normal operation mode:

In normal operation mode, the IGBT (T) switch is closed and full line current flows through the bridge circuit path. The bridge circuit converts the AC line current to DC, which flows through the DC reactor. After a few cycles, the DC reactor current charged to the peak value of the line current (I_0), and the PRBFCL enters its steady state operation[13]. The DC reactor current (i_{dc}) offers no impedance. Since, the impedance of shunt path is relatively large, the full line current flows through the bridge circuit path. The R_{dc}, the IGBT switch and diodes of bridge circuit switching produce some voltage drop and power losses, but they are negligible compared to line drop and losses[13].

ii. Fault operation mode:

During the fault operation mode, the PRBFCL operation is divided in two modes before and after fault detection as shown in Fig.3 [14]. The first mode begins at $t=t_0$ and continued until $t=t_1$. During this mode, the IGBT switch is closed and a large short circuit current flows through the bridge circuit and the DC reactor. The instantaneous change of the short circuit fault current is impeded by DC reactor without any delay. In this mode, the DC reactor current increases with a constant rate, as shown in fig.3. The current i_d is given by the following equation (4).

$$i_d = \frac{\sqrt{2}\,V_s}{Z}\left[\sin(wt-\theta) + \frac{2}{1-e^{-\left(\frac{R_{dc}}{L_{dc}}\right)(\pi/w)}}\sin\theta\; e^{-\left(\frac{R_{dc}}{L_{dc}}\right)t}\right]. \qquad \text{…………..……..….. (4)}$$

For $0 \le (wt-\theta) \le \pi$ and $i_d \ge 0$.

Where $Z = [R_{dc}^2 + (wL_{dc})^2]^{1/2}$ and $= \tan^{-1}(\frac{wL_{dc}}{R_{dc}})$

The current i_d is shown in fig.4 , where i_L is used to define i_d , and V_L is used to define voltage across R_{dc} and L_{dc} .

When the DC reactor current reaches to the threshold current i_T, the PRBFCL control system generates low voltage gate signal to make the IGBT turn off as shown in Fig.5 [14]. After, turn off the IGBT, the second mode begins at $t=t_1$ and the bridge path is open circuited. Therefore, the limiting impedance of the PRBFCL is inserted in series with the line and short circuit fault current is limited during this mode. Also, the energy stored in the DC reactor is discharged in freewheeling diode D4, DC reactor resistance R_{dc} and DC reactor inductance L_{dc} path.

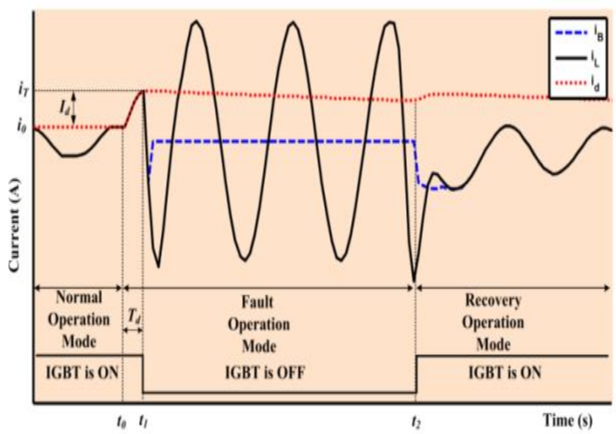

Fig. 3: Effect of the PRBFCL during fault.

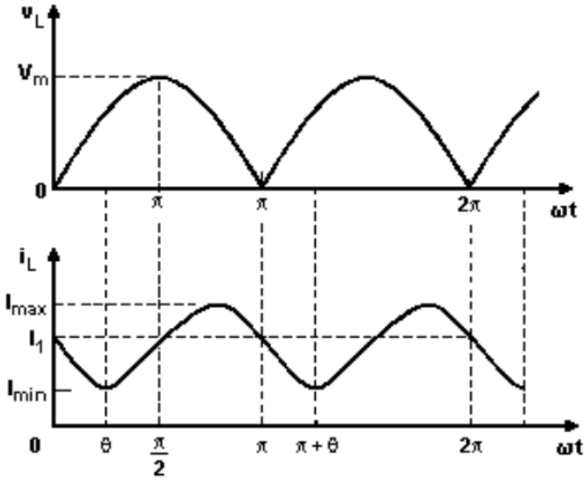

Fig 4: waveform of i_d and V_L.

iii. Recovery operation mode:

After fault clearing at t=t_2, the PCC voltage(Vpcc) starts to recover to the pre-fault value[14]. Voltage dip at PCC has been used to sense recovery operation mode and generate the IGBT gate control signal. As shown in Fig.5, a comparator compares the PCC voltage(V_{pcc}) and predefined threshold voltage(V_T)[13]. When the V_{pcc} reaches to the V_T due to fault clearance, the IGBT receive high voltage gate signal and turns on, hence the system returned to normal operation mode.

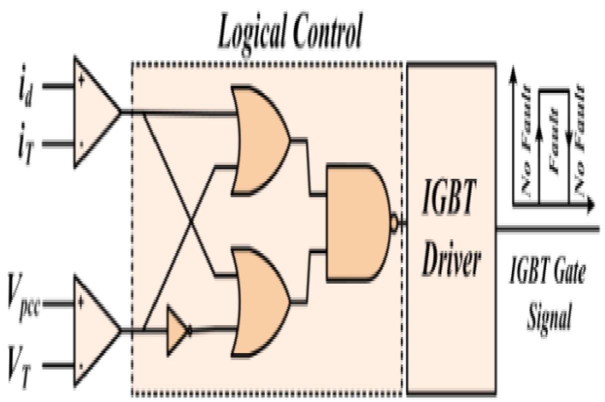

Fig. 5. Control system of the PRBFCL.

3.1.2 DC Reactor Design

DC reactor current increases linearly [13] due to DC reactor. A small value of R_{dc} is considered which is 0.3 mΩ. The value of $L_{dc}$to be 1 mH gives a time constant (τ =L_{dc} /R_{dc}) of 3.33 s which is good enough for smoothening the dc reactor current increases linearly.

3.1.3 PRBFCL Design

The PRBFCL is placed in each phase of three-phase line[10] near to the PCC. The power consumed by the PRBFCL at post fault is given by[10]:

$$P_{PRBFCL} \leq \frac{P_g}{3}$$

$$P_{PRBFCL} = I_{fault}^2 R_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

$$R_0 \leq \frac{P_g}{3 \times I_{fault}^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Where P_g represents the rated power generated by the source; R_0 is the PRBFCL equivalent resistance required to consume the generated source power. A capacitor (C_{pr}) value of 220.2634 μF is selected. An inductor (Lpr) value of 0.046 H is computed considering the resonance condition with 50Hz operating frequency. The value of R_{pr} is calculated is 7.0019014Ω.

3.2 RL-BFCL FAULT CURRENT LIMITER MODEL

For determining the effectiveness of proposed two FCL, it is compared with RL-BFCL[1] shown in figure 6

3.2.1 RL-BFCL Configuration

The RL-BFCL configuration and operation is same as PRBFCL shown in fig 6. RL-BFCL has two sections, the bridge part and the shunt path same as PRBFCL only the shunt path consists of a resistor Rs and an inductor connected in series. The bridge path is same as PRBFCL.

3.2.2 RL-BFCL Operation

The basic operating principle of this RL-BFCL is nearly same as PRBFCL, unlikely to insert the impedance of RL branch in series with the faulted line during fault condition. Before and after the fault, the operation is same as PRBFCL. The bridge circuit and its operation are same as PRBFCL.

ISSN 2229-5518

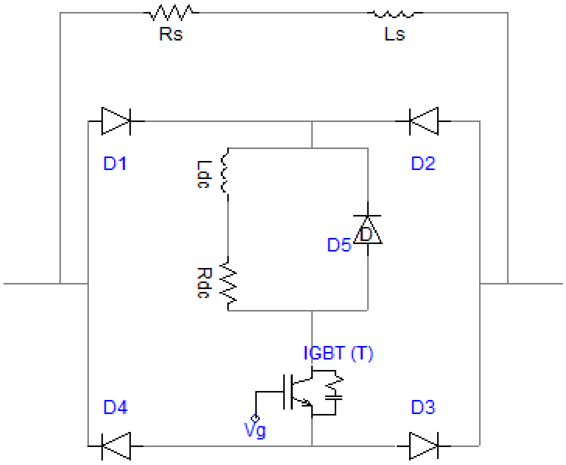

Fig.6: configuration of RL-BFCL.

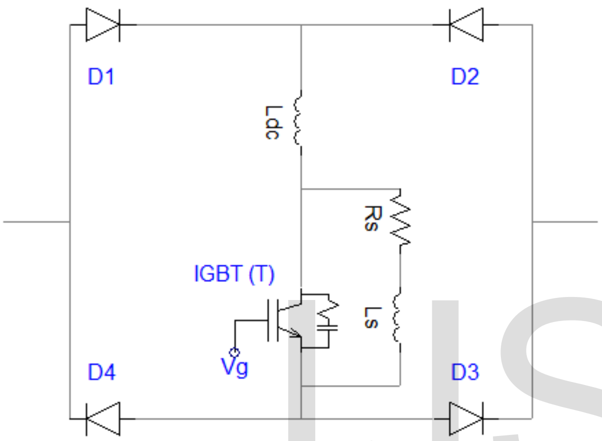

Fig. 7: proposed single-phase new bridge type fault current limiter

3.3 N-BFCL FAULT CURRENT LIMITER MODEL DESCRIPTION

3.3.1 NBFCL Configuration and Operation

A configuration of NBFCL was found in [14]. The configuration of the proposed NBFCL is shown in Fig.7.The NBFCL consists of four diodes D1-D4. It is generally based on diode-bridge rectifier and a high impedance of resistor R_s in series of an inductor L_s is connected in parallel with the semiconductor IGBT switch Ts as shown in fig 7.Dc current i_{dc} flows in each phase and the inductor of L_{dc} acts as a short circuit. No current will flow thorough the parallel path as its impedance is high. In the event of fault the dc current i_d becomes greater than the predefined maximum permissible current i_T shown in fig 5 and the controller of NBFCL opens the IGBT switch from the closed mode. After opening the IGBT, the line current is bypassed to the parallel path. Therefore, the high impedance parallel path limits the fault current and the shunt resistor Rs consumes the excess energy from the DFIG, helping to ensure system transient stability.

After fault clearing, the PCC voltage starts to recover to the pre-fault value. As shown in Fig 5, a comparator compares the PCC voltage (*Vpcc*) and predefined threshold voltage (V_T). When the *Vpcc* reaches to the V_T due to fault clearance, the IGBT receive a high voltage gate signal and the IGBTs switch is turned on, and the system returned to normal operation mode

4 SIMULATION OUTPUTS AND DISCUSSION

The performance of the proposed two FCL is compared with RL-BFCL to determine the effectiveness of proposed FCL. Resistance value of RL-BFCL, proposed PRBFCL and NBFCL is taken same of 7 ohm and inductance value is taken same of 0.046 H for proper comparison. Both the model is simulated by PSCAD/ EMTDC software. For the purpose of transient analysis, A 10 MVA DFIG based wind turbine and a three phase line-to-ground (3LG) fault is occurred at point F near the PCC as shown in Fig.1.The 3LG fault at point F is occurred at t=10s for 0.5s. Circuit breaker of CB3 and CB4 in the faulted line is opened at 10.1s and again reconnected successfully at 11s. Fig.8 represents terminal voltage response of DFIG when a temporary 3LG fault is occurred at point F. Using the proposed two FCL, it maintains the voltage level near to ±0.9 p.u of nominal voltage where RL-BFCL maintains the voltage level near to 0.87 p.u shown in fig 9. But NBFCL has better performance than PRBFCL shown in fig 9. In Fig.10 shows the active power response of DFIG for 3LG fault. Using the RL-BFCL and NBFCL output power goes low near to 0.85 p.u, both have nearly same graph and performance. But PRBFCL has less good performance than both RL-BFCL and NBFCL at faulty condition. Fig.11. shows the comparison between PRBFCL, NBFCL and RL-BFCL for active power response for 3LG fault in per unit (p.u). Fig.12 shows the faulted line current (C phase current) response for 3LG fault. Fig.13 shows that using RL-BFCL, after the fault occurs, faulted line current is less than pre-fault condition which is undesirable. From fig.14 PRBFCL limits the faulted line current to satisfied value.

Fig.15 shows that using NBFCL faulted line current after the fault. NBFCL has better performance than PRBFCL shown in fig.15. Fig. 16 shows the reactive power response of all controller.

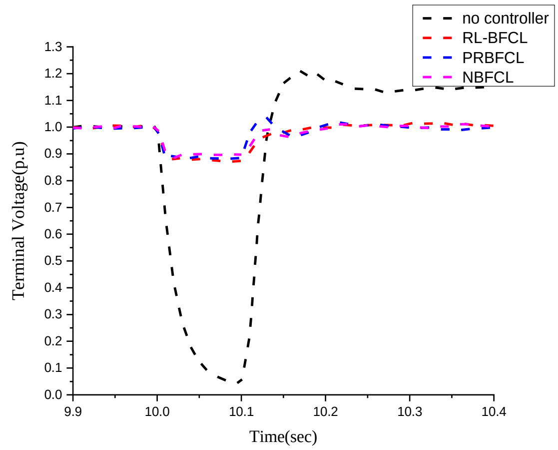

Fig .8: Terminal voltage response for 3LG fault.

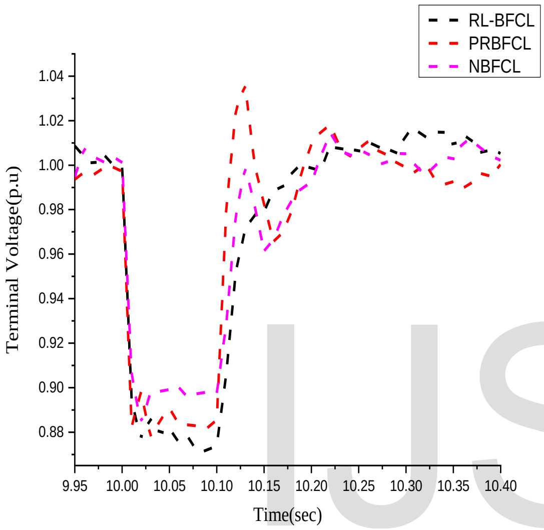

Fig.9: Comparison among NBFCL, PRBFCL and RL-BFCL for terminal voltage response for 3LG fault.

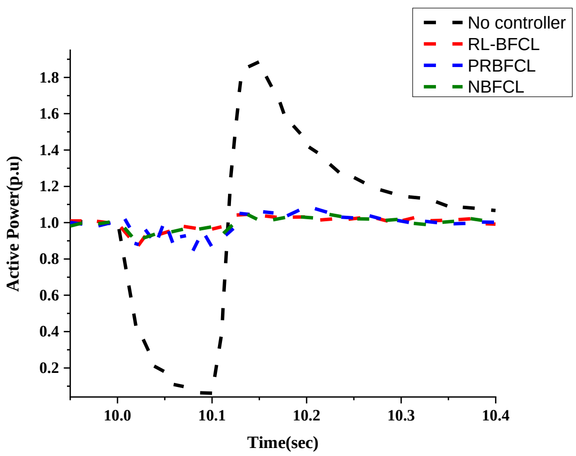

Fig.10 Active power response for 3LG fault in per unit (p.u).

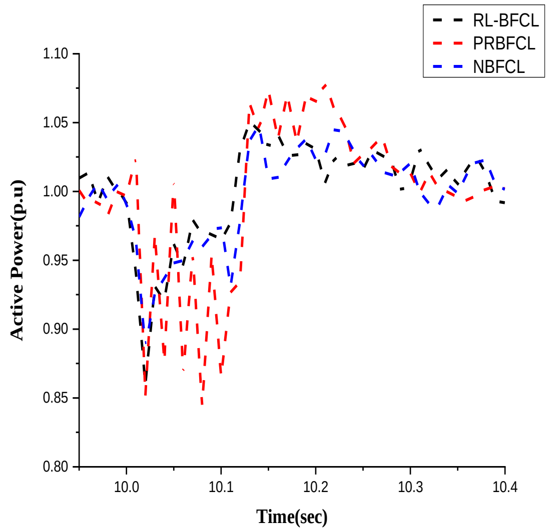

Fig.11 .Comparison among PRBFCL, NBFCL and RL-BFCL for active power response for 3LG fault in per unit (p.u).

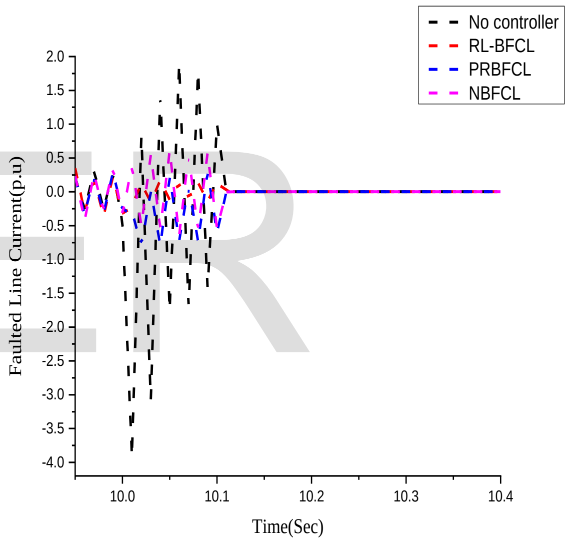

Fig.12 Faulted line current for 3LG fault (only for phase C

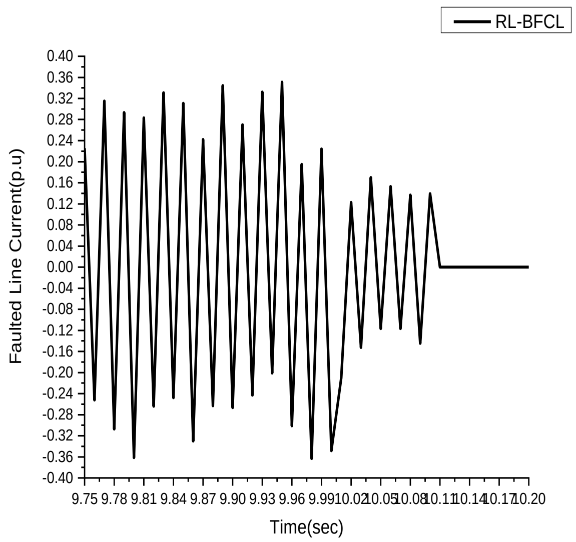

Fig 13: Faulted line current for RL-BFCL.

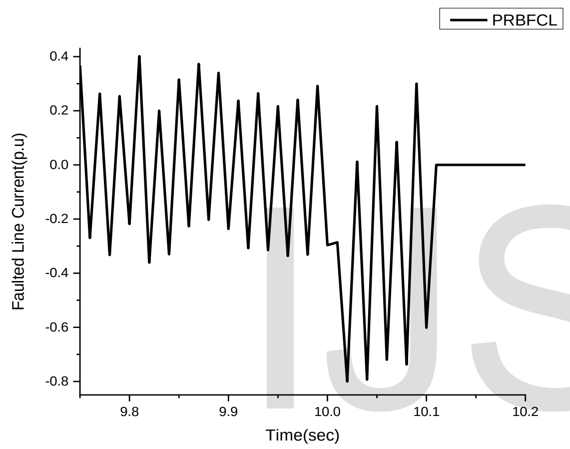

Fig .14: Faulted line current for PRBFCL.

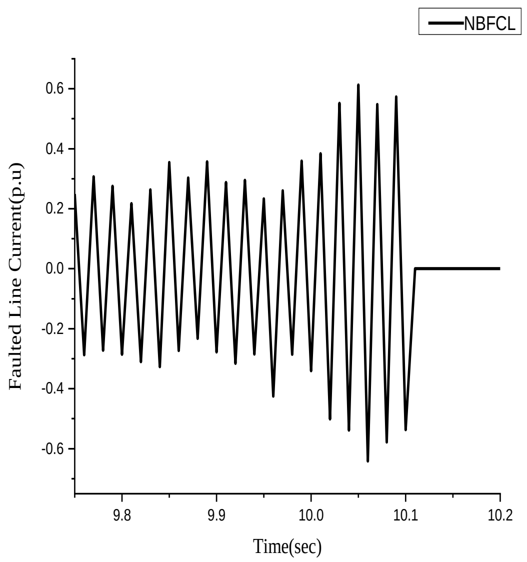

Fig.15: Faulted line current for NBFCL

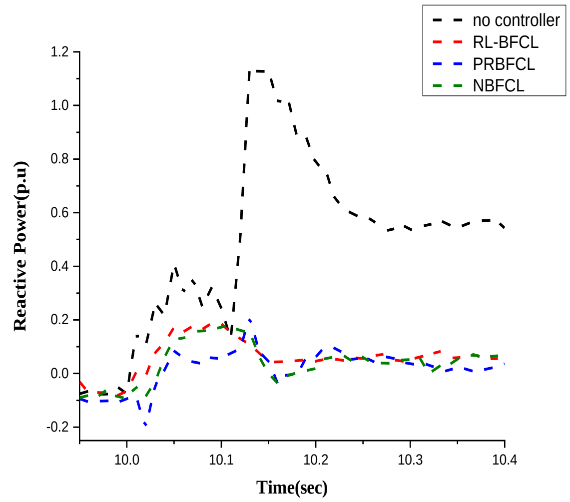

Fig.16: Reactive power response for 3LG fault in per unit (p.u).

5 CONCLUSION

In this paper two FCL is proposed to improve the transient stability and low voltage ride through capability of DFIG. The proposed two FCLs performance is compared with RL-BFCL. Simulation results show that the proposed two FCL model is more capable to respond to a fault and return back to the normal state within a shortest possible time. The Proposed FCL gives lower voltage drop and limits the fault current close to pre-fault condition where RL-BFCL limits the fault current more than the pre-fault current which is undesirable.

The impact on power quality in normal condition of the two proposed FCL can be analyzed. Harmonic in steady state fault current limitation mode is needed to under consideration. Harmonic content of the system can also be analyzed for different conditions in practice. From simulation results of the two proposed FCL model give a smooth curve for voltage, active power, reactive power and faulted line current during normal condition which means less distortion and less loading effect of two proposed model during normal operation.

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