Mitigation of Fault Current Level using Super Conducting Fault Current Limiter in Wind Turbine Generation Systems

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Abstract— With the continuous increase of power demand, the capacities of renewable energy generation systems are being expanded. With the increased penetration of wind energy as a renewable energy source, there is a need to keep wind turbines connected to the grid during grid faults. The ability of WTGS (Wind Turbine Generation System) to remain connected to the grid during faults is termed as Fault-Ride Through capability (FRT) of the system. In this paper, the use of superconducting fault current limiter (SFCL) is proposed to improve the FRT capability of WTGS thus improving reliability of the system. A Doubly-Fed Induction Generator (DFIG) is considered as a wind-turbine generator for analysis. Detailed simulation results are obtained with and without SFCL considering the stator and rotor currents. Also, the voltage profile, real and reactive power magnitudes are analyzed. The computed results ensure that SFCL is effective in mitigating the fault current magnitude which would enhance the reliability and stability of the system as a whole.

Index Terms— Doubly fed induction generator(DFIG), Wind Energy Conversion System(WECS), Superconducting Fault Current Limiter(SFCL), Resistive SFCL(RSFCL).

1 INTRODUCTION

With the interconnection of modern power system networks to meet the increasing power demand, the renewable energy sources has greatly penetrated in power systems. The renewable energy sources reduce global warming and other environmental related problems [1]. The wind turbine generation system (WTGS) is one of the best renewable energy system to satisfy the above said problems.

Recently, doubly-fed induction generator (DFIG) operated as a variable speed generator, has been widely implemented in all wind energy conversion systems. But, DFIG suffers from more sensitivity to grid side disturbances like grid faults [2-4]. When fault occurs into the grid, stator current increases and a voltage dip will appear at the generator terminals. Also, excessive rotor current will flow due to the magnetic coupling between stator and rotor. This will cause failure of the rotor side converter (RSC) of the DFIG system. Due to this, RSC will be blocked and wind turbine will be tripped. This problem becomes more severe with large penetration of wind energy and will cause a worst effect on the stability of the system.

Hence, there is a need to improve the ability of wind turbines to remain connected to the grid during faults.

The short-circuit fault current will increase beyond the rating of the existing protective components in the system [5-7]. To overcome these drawbacks, a superconducting fault current limiter (SFCL) has been proposed in this paper for effective solution to improve the stability of the wind system. The proposed SFCL has quicker response and minimum recovery period when compared to other conventional protective devices. Further incorporating SFCL into the grid prevents the damage of the components in the power system which controls the interruption of power supply to the utilities.

MATLAB tool is incorporated for all the simulations done in this paper to show the effectiveness of the fault current limiter. The stability of the test wind energy conversion system (WECS) has been improved due to the implementation of the proposed SFCL in the system.

2 SYSTEM DESCRIPTION

Figure.1. illustrates a DFIG-based wind turbine, where the stator is directly connected to the grid, while the rotor is connected to a controlled back-to-back converter. The back-to-back converter consists of the rotor-side converter and the grid-side converter. The rotor-side converter controls the torque and the speed of the DFIG and the grid-side converter keeps the dc link voltage constant between the two converters[8].

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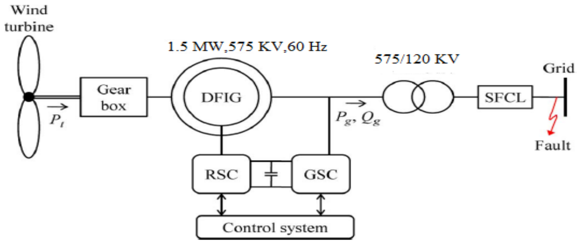

Fig 1. DFIG system

Under normal operating conditions, the active power is generated based on wind speed and wind turbine characteristics, while the reactive power is set at zero. The grid is represented as an infinite bus of 120KV rating. The DFIG is connected to the grid through a 575/120 KV step-up transformer and the SFCL is introduced after the transformer. The system has been simulated and analyzed using MATLAB software.

3 DESIGN FEATURES OF PROPOSED WECS

3.1 Design of Wind Turbine

Detailed modeling of DFIG-based wind turbine is explained in the literature [9],[10],[11],[12]. The mechanical power extracted from the wind turbine is given by the following equation:

$$P_w = 0.5 C_P A \rho V^3 \quad (1)$$

where C_P is the power coefficient, A is the swept area of rotor, ρ is the air density and V is the wind speed. The voltage equations of the stator and rotor circuits of the generator are expressed in the d − q reference frame as follows:

$$v_{ds} = R_S i_{ds} - \omega_s \lambda_{qs} + \frac{d\lambda_{ds}}{dt} \quad (2)$$

$$v_{qs} = R_S i_{qs} + \omega_s \lambda_{ds} + \frac{d\lambda_{qs}}{dt} \quad (3)$$

$$v_{dr} = R_r i_{dr} - (\omega_s - \omega_r)\lambda_{qr} + \frac{d\lambda_{dr}}{dt} \quad (4)$$

$$v_{qr} = R_r i_{qr} + (\omega_s - \omega_r)\lambda_{dr} + \frac{d\lambda_{qr}}{dt} \quad (5)$$

where λ is the flux linkage, ω is the angular frequency and R is the resistance per phase. The subscripts d and q denote the direct and quadrature axes, respectively, while the subscripts s and r denote the stator and rotor quantities respectively.

4 SUPER CONDUCTING FAULT CURRENT LIMITER (SFCL)

The phenomenon of using the superconductors to carry electric power and to limit peak currents has been practiced in systems as they possess highly non-linear properties. More specifically, the current limiting behavior depends on their nonlinear response to temperature, current and magnetic field variations. Increasing any of these three parameters can cause a transition between the superconducting and the normal conducting regime. The characteristics are shown in fig. 2.

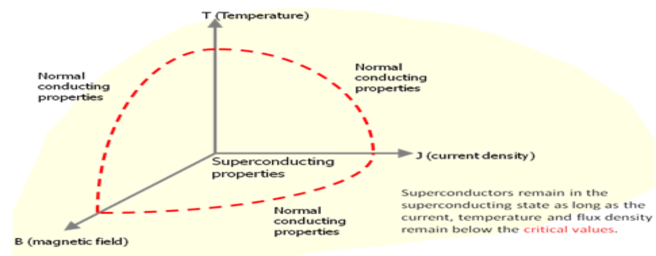

Fig. 2 T-B-J Characteristics of superconducting material

The current increase can cause a section of superconductor to become so resistive that the heat generated cannot be removed locally. This excess heat is transferred along the conductor, causing the temperature of adjacent sections to increase. The combined current and temperature can cause these regions to become normal and also generate heat [13],[14]. Figure 3 shows the behavior of SFCL in limiting the fault current magnitude.

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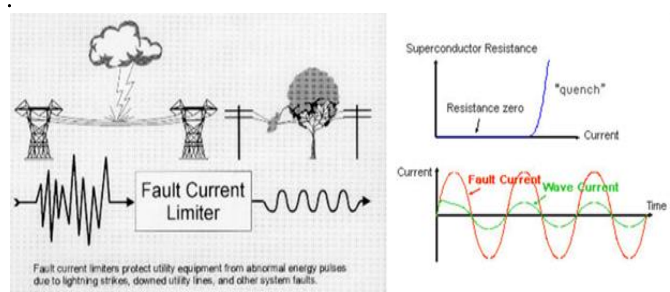

Fig. 3 Characteristics of SFCL

4.1 Features of SFCL

The following are the properties of SFCL namely:

- High impedance in fault operation
- Low impedance in normal operation
- Limits fault current before first peak
- Operational before circuit-breaker re-closes etc

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4.2 SFCL Model

In this paper, the resistive type SFCL is considered due to its compact size and simple principle of operation. RSFCL is to limit the fault current effectively. Resistive SFCLs utilize the superconducting material as the main current carrying conductor under normal grid operation. The principle of their operation is shown in Fig 4. It is a normalized plot of voltage across RSC as a function of the ratio of current through the device, I Line, to the "critical current", IC, of the superconducting element. When a fault occurs, the current increases and causes the superconductor to quench thereby increasing its resistance exponentially. The current level at which the quench occurs is determined by the operating temperature, and the amount and type of superconductor. The current limiting behavior of the resistive type SFCL can be characterized by the resistance transition in terms of temperature and current density as described by the following equation [6].

$$R_{SFCL} = \begin{cases} 0 & (J < J_c, T < T_c) \quad \text{Superconducting state} \\ f\left[\left(\frac{J}{J_c}\right)^n\right] & (J > J_c, T < T_c) \quad \text{Flux flow state} \\ f(T) & (T > T_c) \quad \text{Normal state} \end{cases}$$

Where J and T are the current density and temperature, respectively, while Jc and Tc are their critical values and n represents the exponent of E − J power law relation. From the dynamic point of view for DFIG, the flux flow resistance will play an important role in the present study, where after the first cycle of the fault current, the control action becomes active and the current drops rapidly. Therefore, the developed model of SFCL on MATLAB is represented as a constant resistance.

The quench process in resistive SFCLs results in heat that must be carried away from the superconducting element by the cryogenic cooling system. Typically, there is a momentary temperature rise in the superconducting element that causes a loss of superconductivity until the cryogenic system can restore the operating temperature. This period of time, known as the recovery time, is a critical parameter for utility systems.

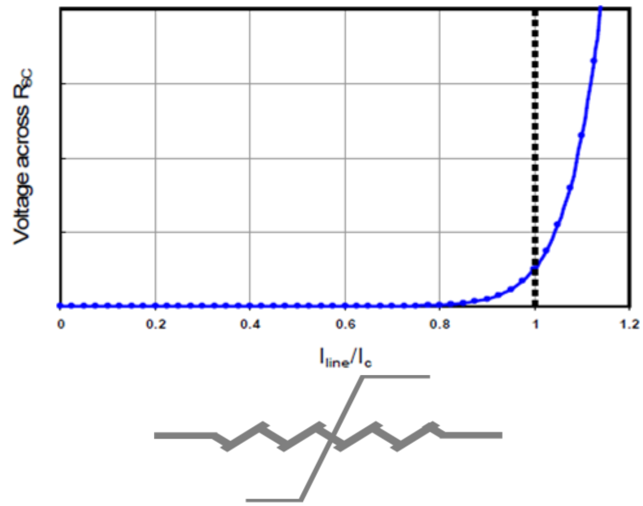

Fig.4 Plot of voltage and current in a superconductor at constant temperature and magnetic field and equivalent circuit

Some resistive SFCLs include a fast switching component in series with the superconducting element. This switch quickly isolates the superconductor after most of the current has transitioned to the shunt element, allowing the superconducting element to begin the recovery cycle while the limiting action is sustained by the shunt. The fast-acting switch reduces the peak temperature within the superconductive material and allows for faster recovery times than for purely resistive SFCLs. This type of SCFL is sometimes referred to as a hybrid SFCL.

4.3 Advantages of RSFCL

- It mitigates the voltage dip in the machine terminal during the fault condition [12].
- RSFCL causes no power loss in the steady state condition and improves the transient stability of the power system
- The response time is fast and it has a quick recovering capablity

5 SIMULATION RESULTS AND DISCUSSION

In order to evaluate the effectiveness of SFCL for current limitation of DFIG-based wind turbine, a three phase and ground fault is considered at the integration point with the grid as shown in Figure 5 and 6, the fault is created at 0.5 seconds.

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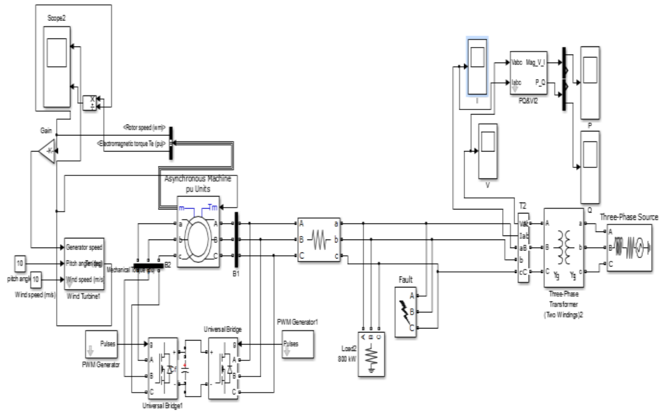

Fig. 5 Simulation without SFCL Fault At 0.5 Seconds

5.1 Current

In order to evaluate the effectiveness of SFCL for current limitation of DFIG-based wind turbine, a symmetrical fault was considered at the integration point with the grid as shown in Fig. 1. The fault is created at 0.5s. For the results in this paper, the wind turbine operates at a wind speed of 12 m/s.

Fig 9 shows the current limitation capability of the SFCL. A 200 Ω current limiting resistance was considered in this analysis. Without connecting SFCL as shown in Fig. 8, the first peak of the current signal reaches about 109.95 kA for phase a, 32.8 kA for phase b and has a negative peak of 87.5 kA for phase c. After inserting the SFCL as represented in Fig. 9, the fault peak current was limited effectively to reach 90.2kA for phase a, 30 kA for phase b and 75.5 kA for phase c. The difference of peak currents and corresponding limiting behavior between phases is attributed to the different fault starting angles. It is important to note that the inverse peak after fault clearance has also been decreased for all phases after connecting SFCL. So, the overall dynamic performance of DFIG has been improved.

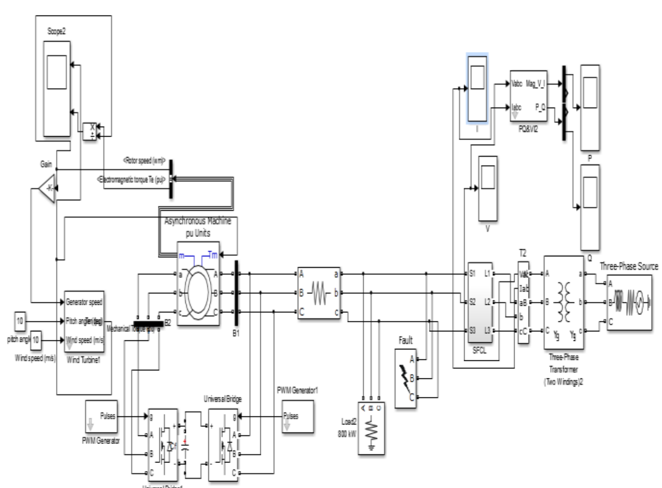

Fig. 6 Simulation with SFCL Fault At 0.5 Seconds

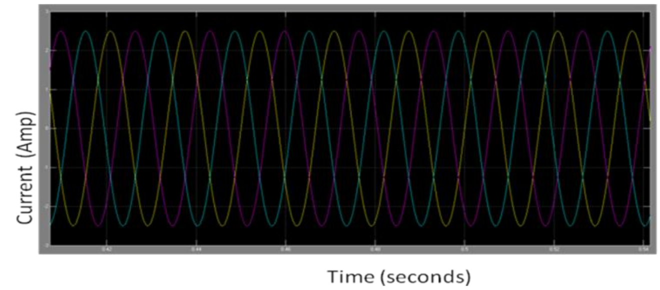

Fig. 7 Current waveform without Fault

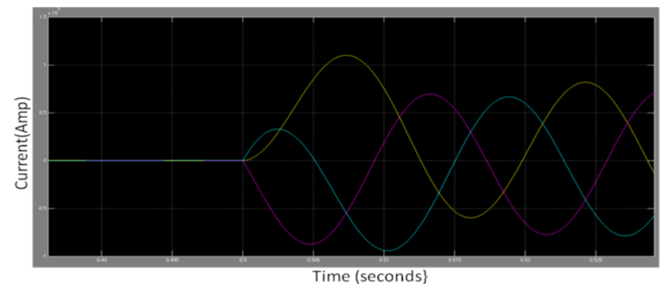

Fig. 8 Current waveform with Fault at 0.5 Sec

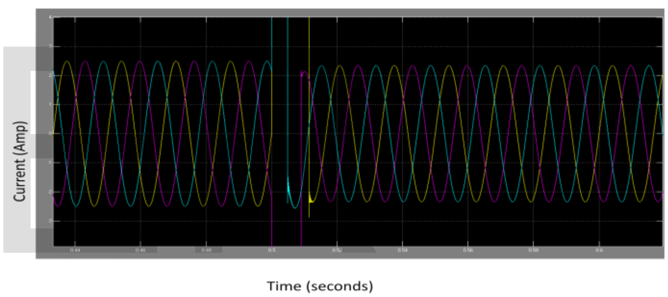

Fig. 9 Current waveform with SFCL Fault at 0.5 Sec

5.2 Voltage Dip Characteristics

Figure 10 shows the voltage waveform of the system without fault. The evaluation of voltage in volts at the terminals of the wind turbine generator is shown in Figure11. Without SFCL, it is shown that the voltage is decreased to 140 volts during fault from 812.9 volts. After adding the SFCL, the voltage dip is decreased, where the voltage reaches 360.4 volts during fault. Thus the effective operation of SFCL has avoided the excessive voltage dip during fault.

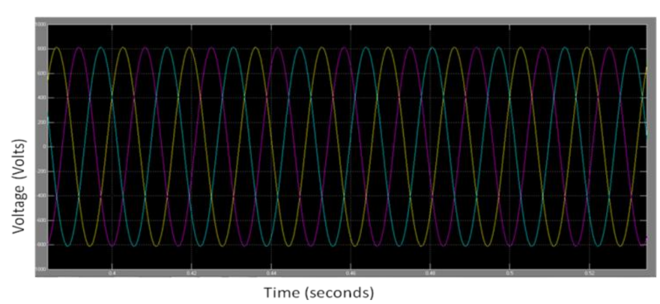

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Fig. 10 Voltage waveform without Fault

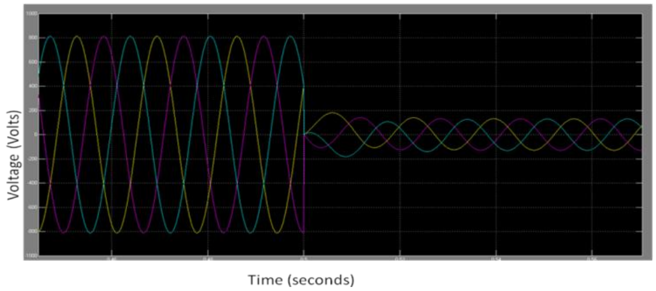

Fig. 11 Voltage waveform without SFCL with Fault at 0.5 Sec

5.3 Active and Reactive Power

Figures. 13 and 16 show the active and reactive power responses without fault, the active power is constant and reactive power is all most zero. The fig 14 and 17 shows the active and reactive power responses without connecting SFCL, the system will observe more active power and reactive power. After connecting SFCL the consumption of active power has been reduced to 8 Mw from 20.3Mw as shown in fig 15. The fig 18 shows SFCL limits the deviation of reactive power at the fault instant, and also limits the reactive power drawn from the grid to 1430Var from 6 Mvar at fault clearance. This would enhance the stability of the overall system.

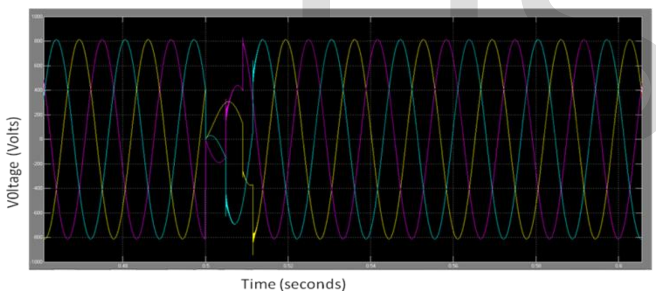

Fig. 12 Voltage waveform with SFCL Fault at 0.5 Sec

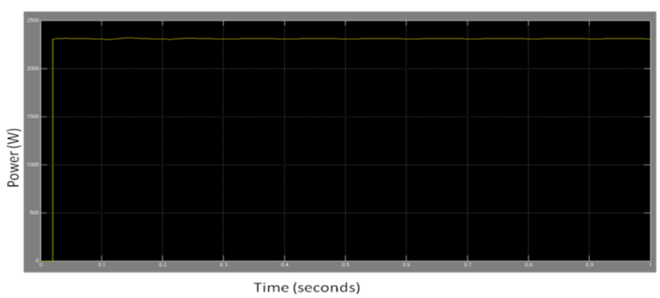

Fig. 13 Real Power waveform without Fault

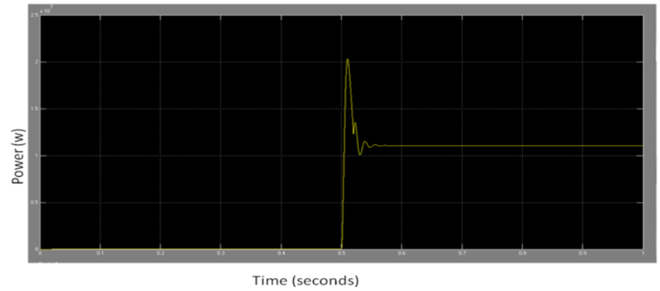

Fig. 14 Real Power waveform with Fault at 0.5 Sec

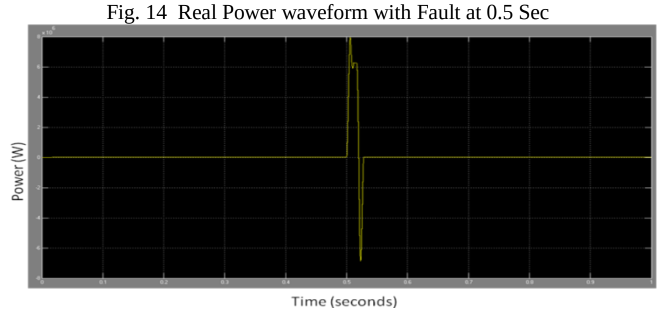

Fig. 15 Real Power waveform with SFCL Fault at 0.5 Sec

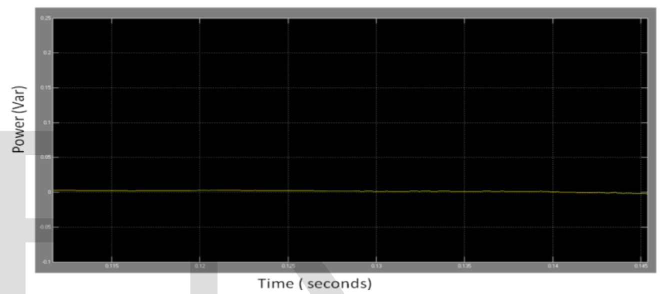

Fig. 16 Reactive Power waveform without Fault

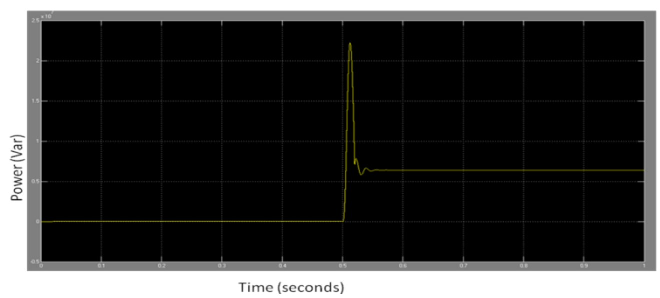

Fig. 17 Reactive Power waveform with Fault at 0.5 Sec

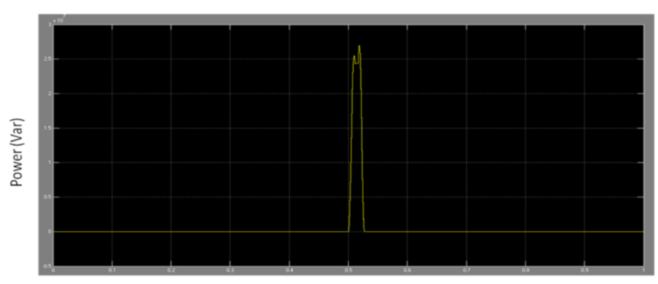

Fig. 18 Reactive Power waveform with SFCL Fault at 0.5 Sec

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5.4 Comparison of results with and without SFCL

Table 1. shows the comparative study of system voltage, current, real and reactive power values in the system, with and without incorporating the proposed SFCL in the system.

Table I. Magnitudes of Voltage, Current, Real and Reactive Power with and without SFCL Fault at 0.5 Seconds

S.No	Parameters	System Without Fault	System with Fault at 0.5 Seconds	
			Without SFCL	With SFCL
1	Voltage (v)	812.9V	140V	360V
2	Current(Amp)	2.56 A	109.95 KA	90 KA
3	Active power(W)	2310W	20.3MW	8MW
4	Reactive power(Var)	0	6MVar	1430 Var

These results show that the system performance is improved due to implementation of SFCL in the test system model.

6 CONCLUSION

In this paper, an effective solution to the problem of short circuit fault current in wind power system has been presented. The Superconducting fault current limiter is designed and implemented in DFIG fed wind power systems. Detailed analysis of the wind system has been done with and without the implementation of the proposed SFCL.The simulation results based on the responses of voltage, current, active and reactive power shows that the fault ride through capability has been increased and hence the wind system reliability is increased to a good extent.

7 APPENDIX

7.1 Component Specifications:

GENERATOR

Power : 1.5 MW
Voltage : 575 V
Frequency : 60 Hz

TRANSFORMER

Voltage : 575/120 KV
Connection Y/Y

GRID

Voltage : 120Kv
Frequency : 60 Hz
Wind Speed : 12 m/sec
SFCL (Resistance) : 200Ω

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