Feasible positioning of Super Conducting Fault Current Limiters for Wind Farm intermittency and Fault currentReduction in a Smart Power System

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Abstract: The promotion of recent power system fault current reduction research has been directed towards the super conducting fault current limiters. Many conventional protective devices installed for protection of excessive fault current in electric power systems especially at power stations are circuit breaker tripped by over current relay protection. They have a responds time delay that can pass initial two to three fault current cycles through it before getting activated. Super conducting fault current limiter (SFCL) is innovative electric equipment which has the capability to limit fault current within first cycle. The first cycle suppression of fault current by SFCL results in an increased transient stability of power system carrying higher power with greater stability. This paper presents a wind farm based smart power system with super conducting fault current limiter for wind farm fault current reduction. In this work, a resistive type SFCL model is implemented by integrating Simulink and Sim power system block in Matlab. In addition, typical smart grid model including generation, transmission and distribution network with dispersed energy resource (wind farm) is modeled to determine the performance of SFCL. Three phase fault have been simulated at different locations in smart grid and the fault current analysis is done with and without SFCL.

Key–Words: Fault current, Super Conducting Fault Current Limiter, Smart grid, wind farm,Super Conductor.

1 Introduction

Smart grid is the technology used to Enable decentralized power-generation, optimize usage, Explore alternate methods of storage, Reduce Distribution losses and Handle peak-demand better. The main aim of Smart grid is to manage demand and supply to meet creatively at all points of time, by using storage and high-cost instantaneous powersources at local level, neighborhood level, district level, state level and national level.The flow of electricity from utility to consumer becomes a two-way conversation, saving consumers money, energy, delivering more transparency in terms of end-user use, and reducing carbon emissions Modernization of the electricity delivery system so that it monitors, protects and automatically optimizes the operation of its interconnected elements from the central and distributed generator through the high-voltage network and distribution system, to industrial users and building automation systems, to energy storage installations and to end-use consumers and their thermostats, electric vehicles, appliances and other household devices.Micro grids are sub set of electric power system, having distributed generation sources (DG) connected with them. These micro grids may or may not be connected with conventional power grid according to their modes of operation, but the need to integrate various kinds of DGs and loads with safety should be satisfied. However, newly emerging problems due to these integrations are also of severe nature and needs to be taken care of. Two major challenges expected by direct connection of DGs with the power grid are the excessive increase in fault current and the islanding issue which is caused when, despite a fault in the power grid, DG keeps on providing power to fault-state network[1].

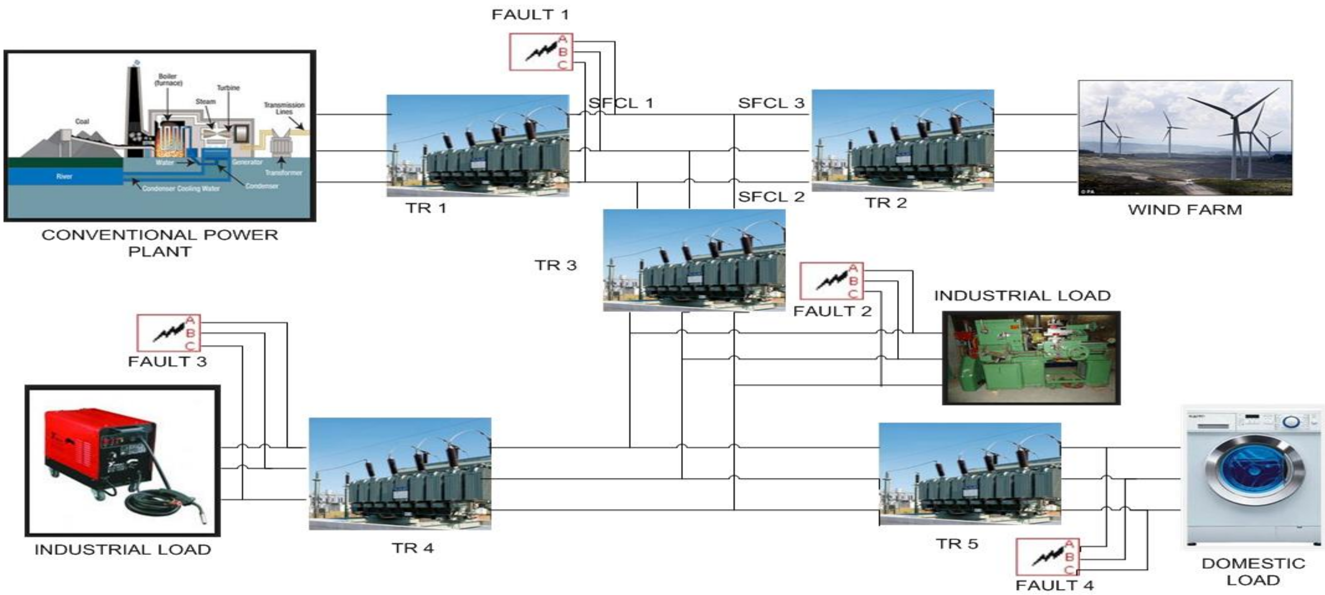

Figure 1: Single line diagram of Power system model designed in Simulink/Sim Power System with SFCL at different locations

For a complex smart power system consists of the interconnection of large number of wind farm to the existing distribution network leads to the increasing fault current beyond the capacity of the conventional protection devices and fails to operate. The fault current having high energy will damage the equipment connected to the system. Generally, the conventional protection overcurrent relay operates only after three to six cycle when a fault occurs. However, circuit breakers sometimes cannot be able to handle the high fault current, so they fail to operate. Traditionally to withstand this fault current requires replacement of costly substation equipments or changing the power system configuration by splitting power system. The splitting of power system may cause the decrease in operational flexibility and lowering reliability.so to reduce the fault current to a lower acceptable level ,an alternate way to use fault current limiters[2].

The super conducting material exhibit zero resistance at super conducting state and high resistance at normal conducting state is an ideal element to make fault current limiter. The movement from super conducting to normal conducting state is very rapid. A super conductor operates in super conducting state until a fault current is detected. This property of super conductor used here to develop super conducting fault current limiter. Fault current limiter utilizing super conducting materials can provide instantaneous fault current reduction is called super conducting fault current limiter. Super conducting fault current limiter is a lengthy super conductor wire inserted in series with transmission line or distribution feeder to limit fault current by abruptly increasing resistance [3,4]. In particular, a superconducting fault current limiter (SFCL) will be operating in a superconducting state and is basically invisible to the power grid because no major energy loss and voltage drop will be developed across the device during normal operation. During fault operation SFCL produce a certain amount of resistance with in few milliseconds due to the loss of super conducting property, and insert in to the power system network, thus reducing the fault currents to levels that circuit breakers can handle.

Up to now, there were some research activities discussing the fault current issues of smart grid [5,6]. But the applicability of a SFCL into micro grid for wind farm intermittency reduction was not found yet. Hence, solving the problem of increasing fault current in micro grids by using SFCL technology is the main concern of this work. In this paper, performance of SFCL and its effects on fault current with and without SFCL was investigated considering typical smart grid model including generation, transmission and distribution with wind farm as dispersed energy resource.

This paper is further organized as follows: section 2 defines modeling of wind farm.section 3 explains the modeling of resistive SFCL .Section 4 presents the power system model developed in Matlab simulink. Section 5 describes the case study and the result and discussion after the successful implementation of resistive SFCL at different locations. Section 6 concludes that SFCL can reduce the wind farm fault current.

2 Modeling of wind Farm

Doubly fed induction generator (DFIG) is widely used wind turbine in wind farm which can supply power at constant voltage and constant frequency while the rotor speed varies [7]. An equivalent DFIG model has been represented by combining the powers of identical individual wind turbines[8]. The proposed DFIG wind farm model for the generation system consist modules of wind speed, turbine, drive train and generation system.

2.1 Wind Speed Model

The wind speed is modeled by combining base wind speed(V_b),gust wind speed(V_g),ramp wind speed(V_r),and noise wind speed(V_n)[9]. The wind speed model for a single wind turbine is given by

$$V_w = V_b + V_g + V_r + V_n \tag{1}$$

The equivalent wind speed model of the wind farm is the sum wind speeds of individual wind turbines i.e.

$$V_{wt} = V_{w1} + V_{w2} + V_{w3} + ... + V_{wn} \tag{2}$$

For n individual wind turbines.

2.2 Wind Turbine Model

For an area of the rotor disk(A), air density (ρ), wind speed (V_m) and power coefficient (C_p).The mechanical power extracted from the wind is expressed by the equation[10].

$$p_w = \frac{1}{2}\rho V_w^3 C_p \tag{3}$$

The function of both tip speed ratio and the pitch angle of the rotor blades give the characteristics of rotor aerodynamics. The ratio between the blade tip speed and the wind speed is called tip speed ratio.

2.3 Drive Train System

For the mechanical torque (T_{wt}) from the wind turbine rotor shaft, mechanical torque(T_{mech})from the generator shaft, generator electrical torque(T_e), stiffness(K_{mech}), damping of mechanical coupling(D_{mech})[11]. The drive train model of the DFIG wind turbine is represented by.

$$T_w - T_{mech} = 2H_r \frac{\mathrm{d}\omega_r}{\mathrm{d}t} \tag{4}$$

$$T_{mech} = D_{mech}\left(\omega_r - \omega_g\right) + K_{mech}\int\left(\omega_r - \omega_g\right)dt \tag{5}$$

$$T_{mech} - T_e = 2H_g \frac{\mathrm{d}\omega_g}{\mathrm{d}t} \tag{6}$$

2.4 Generation and Control System

The generation system is composed of the induction generator and the power converter. The wound rotor induction generation has been modeled by the three-order model [12]. The model is expressed in a direct and quadrature reference frame rotating at synchronous speed with the position of the direct axis aligned with the maximum of the stator flux. The bidirectional power converter connected to the rotor winding is composed of two converters linked by a dc bus. This converter enables the decoupled control of active and reactive powers.

The rotor side converter drives the wind turbine to achieve the optimum power efficiency in winds below rated, to limit the output power to the rated value in winds above rated, or to adjust both the active and reactive powers to the power references when power regulation is demanded. The supply side converter for voltage control maintains the exchange power from the rotor circuit to the grid and commonly operates with the unity power factor. In this case, DFIG wind turbine only delivers active power to the grid through the stator winding. This converter has been modeled as a controlled current source, where the direct and quadrature components of current source are calculated by the exchange power from the converter to the grid[13].

3 Modeling of Resistive SFCL

Critical temperature (T_c),critical magnetic field (H_c) and critical current density (J_c) are the three important factors which defines the superconducting state. These parameters are dependent on each other and material .To maintain super conducting state critical temperature,critical temperature,critical magnetic field as well as critical current density should be below its critical value. When a fault occurs at least one of the three critical parameter immediately reaches to its critical value and superconducting property get vanishes and current get reduced[14].

A resistive SFCL has a simple structure without any iron core. Resistive SFCL is a lengthy super conductor wire inserted in series with transmission line or distribution feeder to limit fault current instantly by the abruptly increasing resistance and also can recover to its normal state after fault suppression without any external assistance. Thus, the limitation performance is a multisided interaction between the fault current, temperature, current depended resistance, variable resistance of HTS substrate and other specification in the external power system.

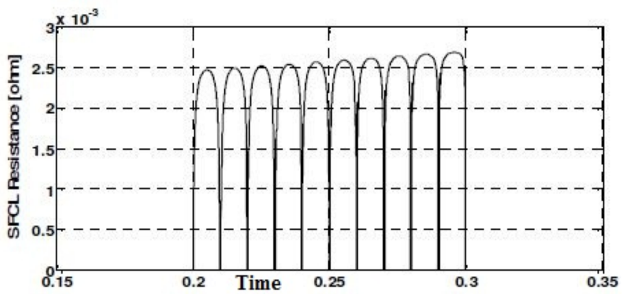

Figure 2: Variation of SFCL resistance in flux flow state

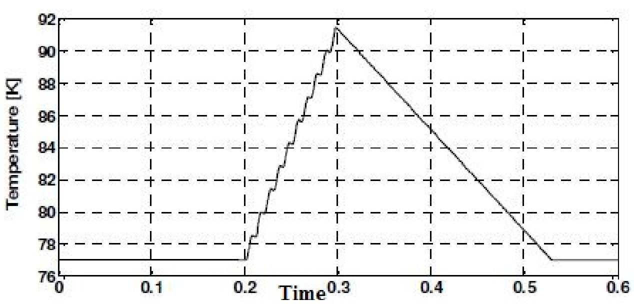

Figure 3: Variation of SFCL temperature in flux flow state .

By approximating 3 states are considered here

a) Superconducting state at temperature and current bellow critical value.

b) Flux state at current above critical value.

c) Normal conducting state at temperature above critical value. In flux state flux resistance depends on the HTS temperature (T) and instantaneous value of current density (J)[15]. The fig.2 and fig.3 respectively shows variation of SFCL resistance and temperature in flux flow state.

We can represent resistive SFCL (Rsfcl) as function

$$\begin{cases} 0 & \text{if } i_{sc} < I_c \text{ ,} T < T_c \\ \left\{ \frac{J_{c0}}{|J|} \left[\left(\frac{T-T_b}{T_c-T_b} - 1 \right) \right] + 1 \right\} * \\ \left(\frac{\rho_f J_{c0}^2 V_{sc}}{I_{ini^2}} \right) & \text{if } i_{sc} > I_c \text{ ,} T < T_c \\ \rho_n \left(\frac{T}{T_c} \right) \left(\frac{V_{sc}}{A_{sc}^2} \right) & \text{if } T > T_c \end{cases} \tag{7}$$

Table 1: characteristic table of SFCL

Symbol	Quantity	Value
T_c	Critical temperature for YBCO	107 K
T_0	Temperature of LN2	77 K
I_{c0}	Critical current in T=Tc	200 A
R_{sh}	Shunt resistance to HTS	50
C_p	Specific heat of HTS	2 MJm-3K-1
P	Cooling power	1000 kW
V_{SC}	Volume of HTS (flux flow)	8e-3m3
A_{SC}	Cross section of HTS (flux flow)	3e-5m2
ρ_f	flux flow resistivity	1e-10ohm-m

4 Simulation Set-up

Matlab/Simulink/SimPowerSystem is selected to design and implement the SFCL model. A complete smart grid power network including generation, transmission and distribution with wind farm as dispersed energy resource is also implemented in it. Simulink/Sim Power System has number of advantages over its contemporary simulation software (like EMTP, PSPICE) due to its open architecture, a powerful graphical user interface and versatile analysis and graphics tools. The resistive SFCL designed in Simulink can be directly integrated with SimPowerSystem models[16].

4.1 Power System Model

Fig.1 shows the power system model designed in Simulink/SimPowerSystem. In this TR1 to TR5 respectively represent the different transformers of the smart power system. The power system is composed of a 100 MVA conventional power plant, composed of 3-phase synchronous machine, connected with 200 km long 120 kV distributed-parameters transmission line through a step-up transformer TR1. At the substation (TR3), voltage is stepped down to 22.9 kV from 120 kV .The transformer TR5 step down the distribution level voltage to customer supply voltage. High power industrial loads (6 MW) and low power domestic loads (1 MW each) are being supplied by separate distribution branch networks. The wind farm is connected to the system through TR2. The 10 MVA wind farm is composed of five fixed-speed induction-type wind turbines each having a rating of 2MVA. At the time of fault, the domestic load is being provided with 3 MVA out of which 2.7 MVA is being provided by the wind farm.

In Fig.1 artificial fault and locations of super conducting fault current limiter (SFCL) are indicated in the diagram. Four kinds of fault points are marked as Fault 1, Fault 2 and Fault 3 and Fault 4 which represent three-phase-to-ground faults in distribution grid, customer grid and transmission line at different locations.

Three prospective locations for SFCL installation are marked as Location 1, Location 2, Locations 3 (Wind farm integration point with the grid). Generally, conventional fault Current protection devices are located in Location 1 and Location 2. The output current of wind farm (the output of TR3 in Fig.1) for various super conducting fault current limiter (SFCL) locations have been measured and analyzed in Section V for determining the optimum location of SFCL in a micro grid.

5 Result and Discussion

Three scenarios of SFCL's possible locations were analyzed for three different fault occurring points in the power system depicted in Fig. 1. First, we assumed that single SFCL is located at Location 1. Second, single SFCL is located at Location 2. Third, single SFCL is located at Location 3.The feasibility analysis has been done by considering four faults at different locations i.e. Fault 1, Fault 2, Fault 3 and Fault 4 as shown in Fig.1.Three phase fault has been simulated for a period of 0.35 seconds to 0.40 seconds that is fault occurred at 0.35 second and it cleared at 0.40 second.

5.1 Fault 1 and SFCL at different locations

Fig.4, Fig.5, Fig.6 and Fig.7 shows the fault current from wind farm (measured at output of TR2 in Fig.1) without and with SFCL at different locations respectively in case of fault 1 as shown in Fig.1.When a fault occurs in power system the fault current always flows towards fault point.Fig.5 shows the successful reduction in fault current with SFCL located at location 1 because during fault, the fault current from wind farm due to fault 1 flows through the SFCL towards the fault point. But in Fig.6 there is no reduction in fault current because in this case the SFCL is located at location 2 as in Fig.1, so no fault current will flow through the SFCL .Fig.3 is also showing the reduction in fault current because in this case also fault current is flowing towards fault point through SFCL.

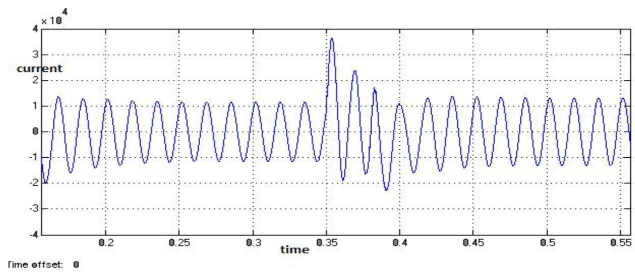

Figure 4: Fault current from wind farm without SFCL in case of fault 1.

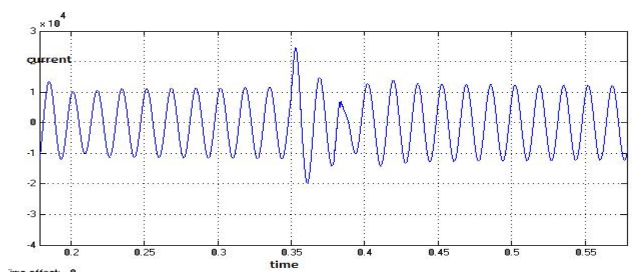

Figure 5: Fault current from wind farm with SFCL at location 1in case of fault 1.

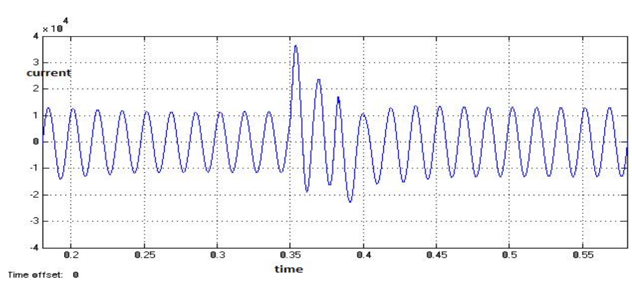

Figure 6: Fault current from wind farm with SFCL at location 2 In case of fault 1.

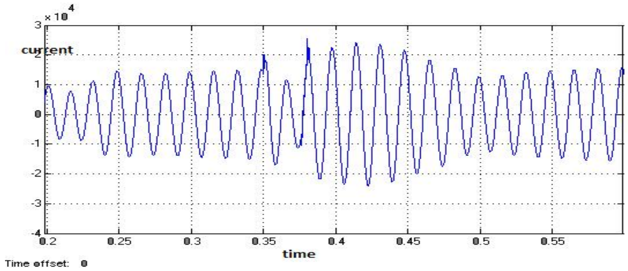

Figure 7: Fault current from wind farm with SFCL at location 3 in case of fault 1.

5.2 Fault 2 and SFCL at different locations

Fig.8, Fig.9, Fig.10 and Fig.11 shows the fault current from wind farm (measured at output of TR2 in Fig.1) without and with SFCL at different locations respectively in case of fault 2 as shown in Fig.1.When a fault occurs in power system the fault current always flows towards fault point. In Fig.9 there is no reduction in fault current because SFCL is located at the location 1 so fault current from the wind farm due to fault 2 bypasses through TR 3 to the fault point. Hence in this case no reduction in fault current was observed. In Fig.10 and Fig.11 successful reduction in fault current is observed because SFCL at location 2 and location 3(as in Fig.1) are the direct path of the fault current from wind farm so fault current should flows through SFCL and hence the reduction in fault current occurred.

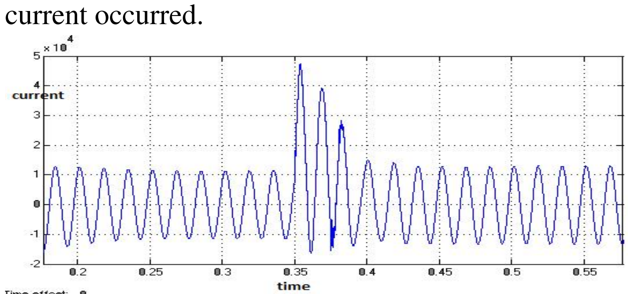

Figure 8: Fault current from wind farm without SFCL in case of fault 2.

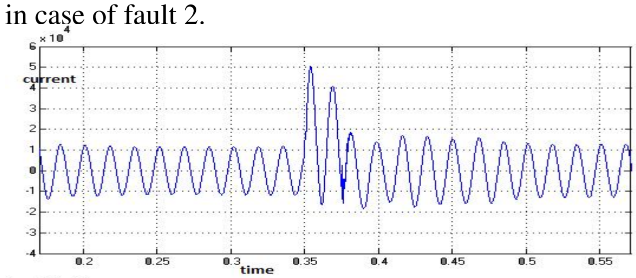

Figure 9: Fault current from wind farm with SFCL at location 1 in case of fault 2.

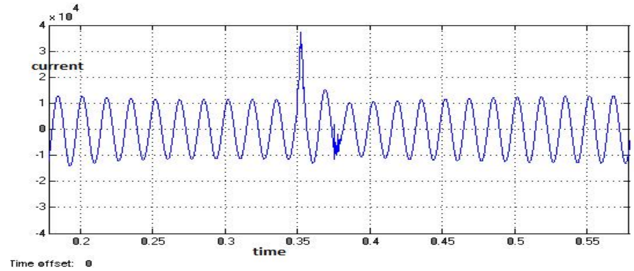

Figure 10: Fault current from wind farm with SFCL at location 2 in case of fault 2.

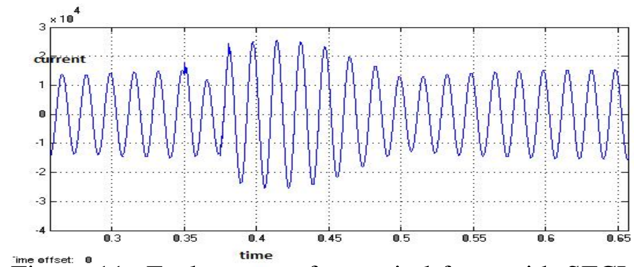

Figure 11: Fault current from wind farm with SFCL at location 3 in case of fault 2.

5.3 Fault 3 and SFCL at different locations

Fig.12, Fig.13, Fig.14 and Fig.15 shows the fault current from wind farm (measured at output of TR2 in Fig.1) without and with SFCL at different locations respectively in case of fault 3 as shown in Fig.1.When a fault occurs in power system the fault current always flows towards fault point. In Fig.13 there is no reduction in fault current because SFCL is located at the location 1 so fault current from the wind farm due to fault 3 bypasses through TR 3 and TR 4 to the fault point. Hence in this case no reduction in fault current was observed. In Fig.14 and Fig.15 successful reduction in fault current is observed because SFCL at location 2 and location 3(as in Fig.1) are the direct path of the fault current from wind farm so fault current should flows through SFCL and hence the reduction in fault current occurred.

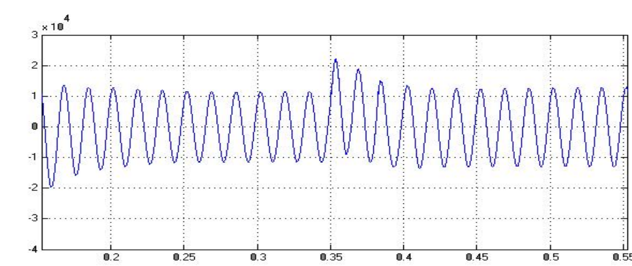

Figure 12: Fault current from wind farm without SFCL in case of fault 3.

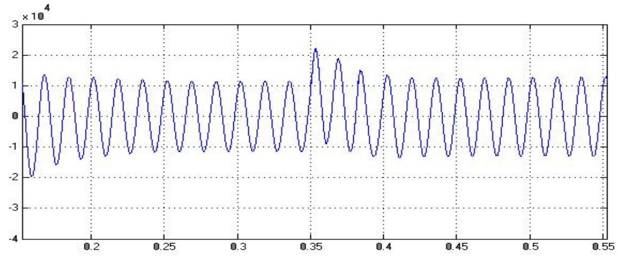

Figure 13: Fault current from wind farm with SFCL at location 1 in case of fault 3.

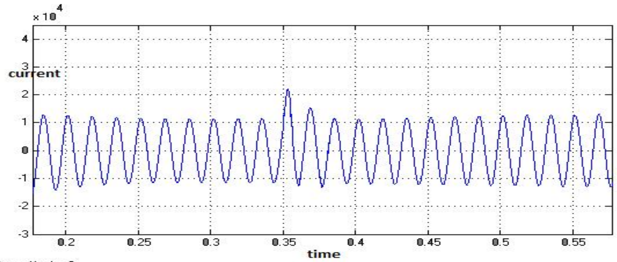

Figure 14: Fault current from wind farm with SFCL at location 2 in case of fault 3.

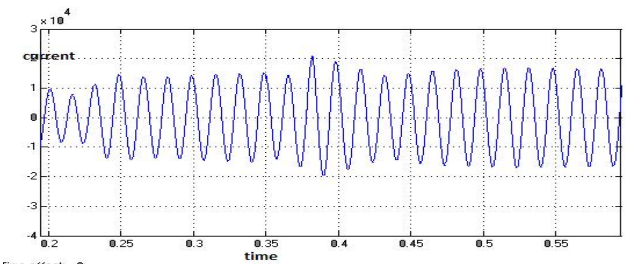

Figure 15: Fault current from wind farm with SFCL at location 3 in case of fault 3.

5.4 Fault 4 and SFCL at different locations

Fig.16, Fig.17, Fig.18 and Fig.19 shows the fault current from wind farm (measured at output of TR2 in Fig.1) without and with SFCL at different locations respectively in case of fault 2 as shown in Fig.1. When a fault occurs in power system the fault current always flows towards fault point. In Fig.17 there is no reduction in fault current because SFCL is located at the location 1 so fault current from the wind farm due to fault 4 bypasses through TR 3and TR 5 to the fault point. Hence in this case no reduction in fault current was observed. In Fig.18 and Fig.19 successful reduction in fault current is observed because SFCL at location 2 and location 3(as in Fig. 1) are the direct path of the fault current from wind farm so fault current should flows through SFCL and hence the reduction in fault current occurred.

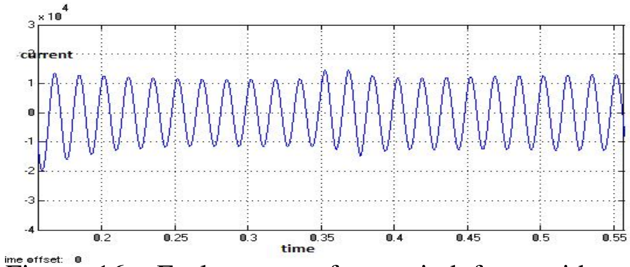

Figure 16: Fault current from wind farm without SFCL in case of fault 4.

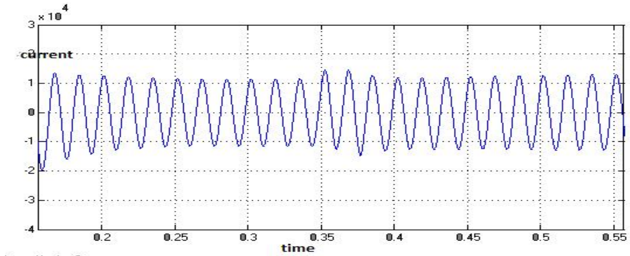

Figure 17: Fault current from wind farm with SFCL at location 1 in case of fault 4.

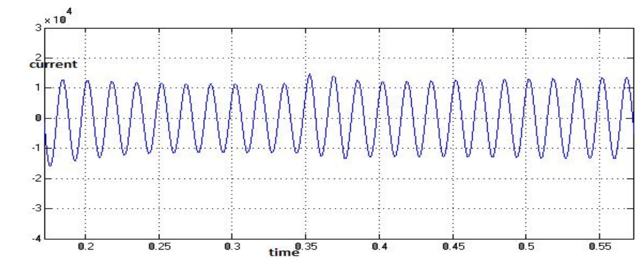

Figure 18: Fault current from wind farm with SFCL at location 2 in case of fault 4.

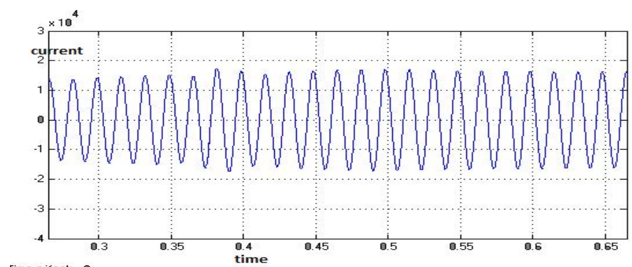

Figure 19: Fault current from wind farm with SFCL at location 3 in case of fault 4.

Table 2: percentage reduction in Fault Current due to SFCL location

Different Faults	Location 1	Location 2	Location 3
Fault 1	34	0	42
Fault 2	0	25	48
Fault 3	0	18	23
Fault 4	0	16	20

6 Conclusion

This paper presented a complete analysis of positioning of the SFCL in rapidly changing modern smart power system for wind farms. A complete power system with generation, transmission and distribution (having a wind farm connected with the grid) has been modeled and transient analysis for three-phase-to-ground faults at different locations of the grid were performed with SFCL installed at key locations of the grid. It has been observed that the optimum location of SFCL for the reduction in wind farm fault current for all types of fault is at location 3(from table II) and also location 3 is the grid integration point.so from here it is clear that SFCL can use for the large scale integration of wind farm to grid for reducing not only fault current but also intermittency of wind farm output.

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