CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Interconnecting Distributed Generation (DG) to an existing distribution system provides various benefits as DG provides an enhanced power quality, higher reliability of the distribution system and can peak shaves and fill valleys. However, the integration of DG into existing networks has associated several technical, economical and regulatory questions. Penetration of a DG into an existing distribution system has many impacts on the system, with the power system protection being one of the major issues. DG causes the system to lose its radial power flow, besides the increased fault level of the system caused by the interconnection of the DG.

In a smart grid, various kinds of Distributed Generation Sources (DGS) could be connected into the main power grid in order to enhance the reliability of power system. Increase in power generation capacity of electrical power systems has led to increase in the fault current level which can exceed the maximum designed short-circuit ratings of the switchgear. Superconducting Fault Current Limiter (SFCL) is optimal equipment which has the capability to reduce fault current level in power system. The application of SFCL for smart grid is reduction of abnormal fault current and the suitable location in the micro grids. In this work, a resistive type SFCL model was proposed using Simulink tool. The designed SFCL model could be easily utilized for determining an impedance level of SFCL according to the fault-current-limitation requirements of various kinds of the smart grid system.

Finally, implementation of SFCL technique in the conventional grid interconnected with wind farm has been carried out to find its optimal location in smart grid having DG.

CHAPTER 1

OPTIMAL LOCATION OF SUPERCONDUCTING FAULT CURRENT LIMITER (SFCL) - AN OVERVIEW

1.1 DISTRIBUTED GENERATION

Distributed energy or decentralized energy is generated or stored by a variety of small, grid-connected devices referred to as Distributed Energy Resources (DER) or distributed energy resource systems. The Conventional power stations, such as coal-fired, gas and nuclear powered plants, as well as hydroelectric dams and large-scale solar power stations, are centralized and often require electricity to be transmitted over long distances. By contrast, DER systems are decentralized, modular and more flexible technologies that are located close to the load. DER systems are small-scale power generation or storage technologies used to provide an alternative to or an enhancement of the traditional electric power system. Distributed Generation (DG), is clean and renewable energy. Distributed Generation contains wind power, solar power, hydraulic power and so on. This can be seen in Fig1.1. However, compared with the traditional way, capacity of DG is small and power output is not stable.

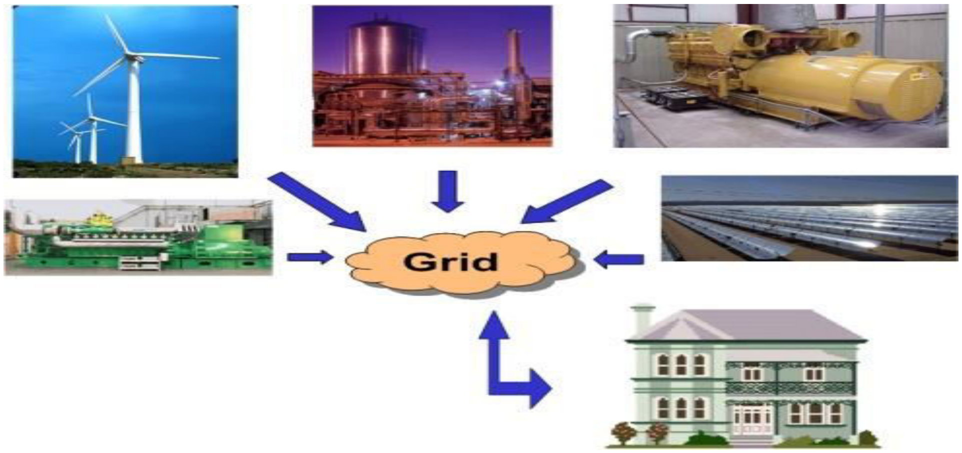

Fig.1.1 Distributed Generation with Main Grid

1.2 SMART GRID

Smart grid is an advancement of the existing electrical grid. The most important aspect of the future smart grid is decentralization of the existing electrical grid into number of smaller grids, which are also called as micro grids as shown in Fig 1.2.

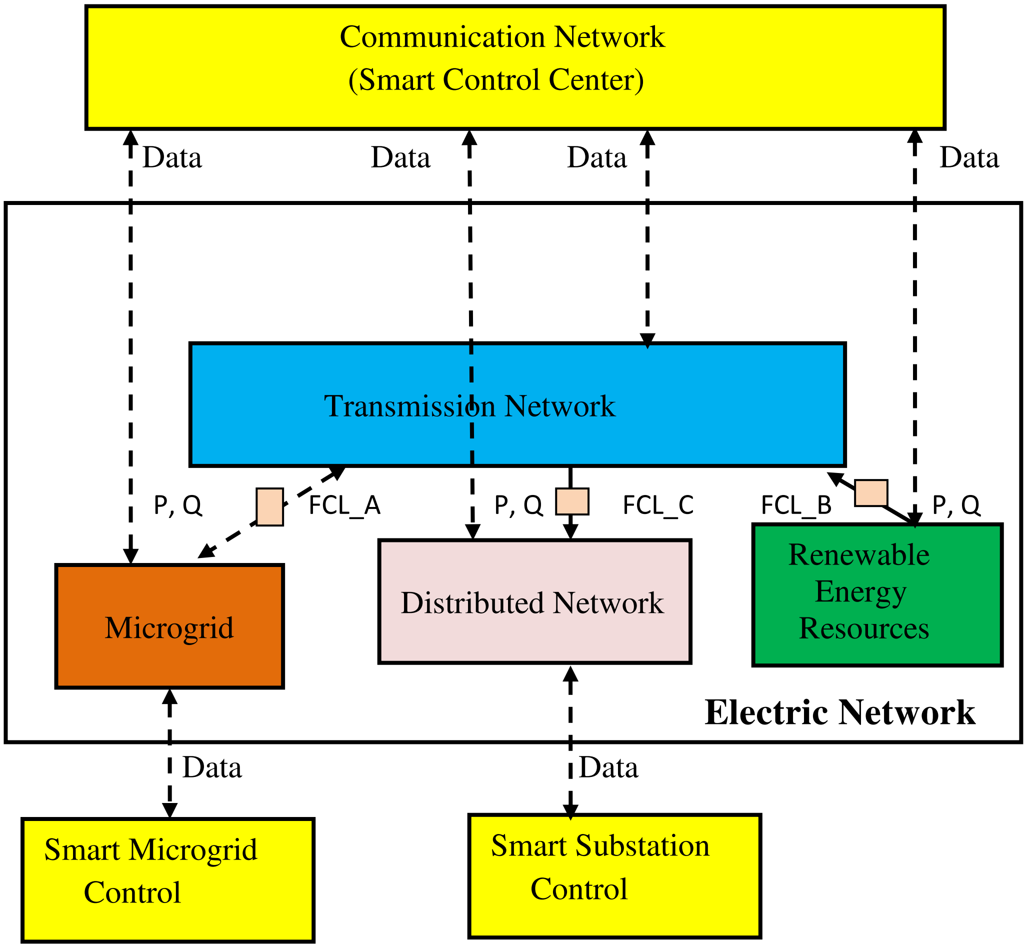

Fig.1.2 Smart Grid System

The key feature of the smart grid is the amalgamation of Distributed Energy Resources (DER) with the main grid. Smart Grid is the 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.

1.3 ADVANTAGES AND PROBLEMS AFTER INTERCONNECTING DISTRIBUTED GENERATION TO THE MAIN GRID

The advantages after interconnecting distributed generation to the main grid are given as:

- Increased power generation capacity of power system
- Reduces blackout and load shedding
- Reduces transmission and distribution losses
- Higher reliability of the distribution system
- Improves load factor

The following are the problems after interconnecting distributed generation to the main grid:

- Excessive increase in fault current
- Increases voltage sag
- Power quality problems
- Reduces transient stability

1.4 CONVENTIONAL METHODS OF FAULT CURRENT LIMITATION

The conventional methods for fault current limitation are given as:

1.4.1 UPGRADE SUBSTATION

Upgrade substation means construction of new substations. Fault current over-duty coupled along with other factors may result in a utility selecting this solution, which will correct immediate problems, as well as providing for future growth. However, this is the most expensive of all the conventional solutions.

1.4.2 BUS SPLITTING

This entails separation of sources that could possibly feed a fault by the opening of normally closed bus ties, or the splitting of existing busses as shown in Fig 1.3. This effectively reduces the number of sources that can feed a fault, but also reduces the number of sources that supply load current during normal or contingency operating conditions.

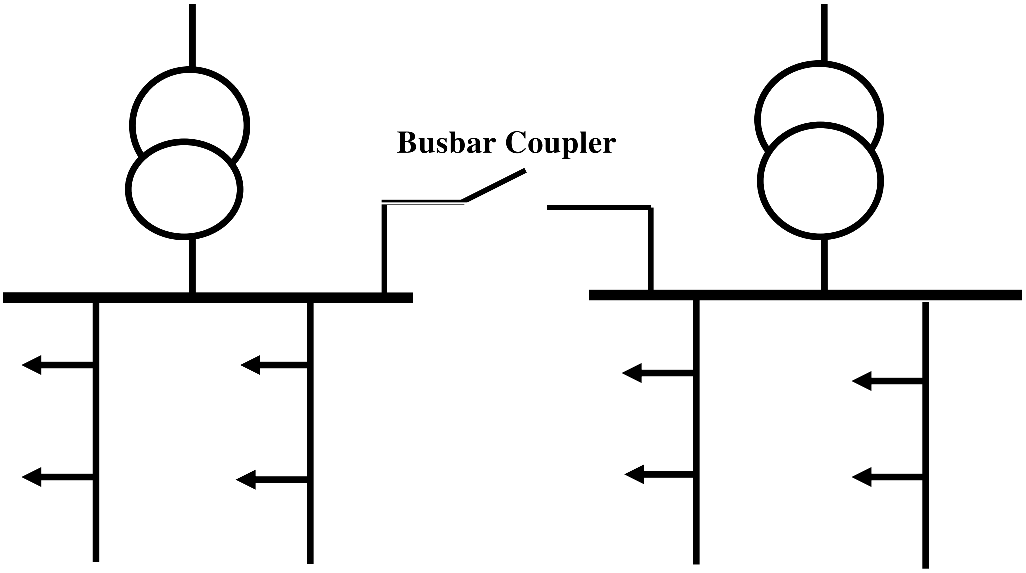

Fig.1.3 Splitting of Busbar

1.4.3 MULTIPLE CIRCUIT BREAKER UPGRADE

When a fault problem occurs, usually more than one breaker will be affected. Upgradation of these breakers has the disadvantage of not reducing available fault currents and their associated hazards, as well as the often prohibitive expense of replacing the switchgear within a substation.

1.4.4 CURRENT LIMITING REACTORS AND HIGH IMPEDANCE TRANSFORMERS

Fault current limiting reactors limit fault current due to the voltage drop across their terminals, which increase during the fault. However, current limiting reactors also have a voltage drop under normal loading conditions and present a constant source of losses. They can interact with other system components and cause instability.

1.4.5 SEQUENTIAL BREAKER TRIPPING

A sequential tripping scheme prevents circuit breakers from interrupting excessive fault currents. If a fault is detected, a breaker upstream to the source of fault current is tripped first. This reduces the fault current seen by the breaker within the zone of protection at the location of the fault. This breaker can then open safely. A disadvantage of the sequential tripping scheme is that it adds a delay of one breaker operation before final fault clearing. Also, opening the breaker upstream to the fault affects zones that were not originally impacted by the fault.

1.5 SUPERCONDUCTING FAULT CURRENT LIMITER (SFCL)

Superconductivity was first discovered by Kamerlingh Onnes in 1911, where mercury was found to have zero electrical resistance at temperatures below 4 K. There are several attractive applications of superconductivity in power systems, including transmission cables, transformers, magnetic energy storage, and electrical machines. Superconductivity is a phenomenon occurring in certain materials at low temperatures, characterized by the complete absence of electrical resistance and the damping of the interior magnetic field (the Meissner effect). The expulsion of magnetic lines of force from a superconducting specimen when it is cooled below the critical temperature is called Meissner effect. Silsbee rule is another important property of superconductor that is when critical strength of current I flowing in the superconductor exceeds this limit causes the disturbance of superconductivity. The first superconducting Fault Current Limiters (SFCL) was proposed in the 1970s, and significant research and development has been undertaken, particularly since the discovery of High-Temperature Superconductors (HTS) in 1986. HTS materials typically permit liquid nitrogen to be used for cooling the superconductor, rather than a more costly cryogen such as liquid hydrogen.

Superconducting Fault Current Limiter (SFCL) is innovative electric equipment which has the capability to reduce fault current level within the first cycle of fault current as shown in Fig 1.4. The first-cycle suppression of fault current by a SFCL results in an increased transient stability of the power system carrying higher power with greater stability.

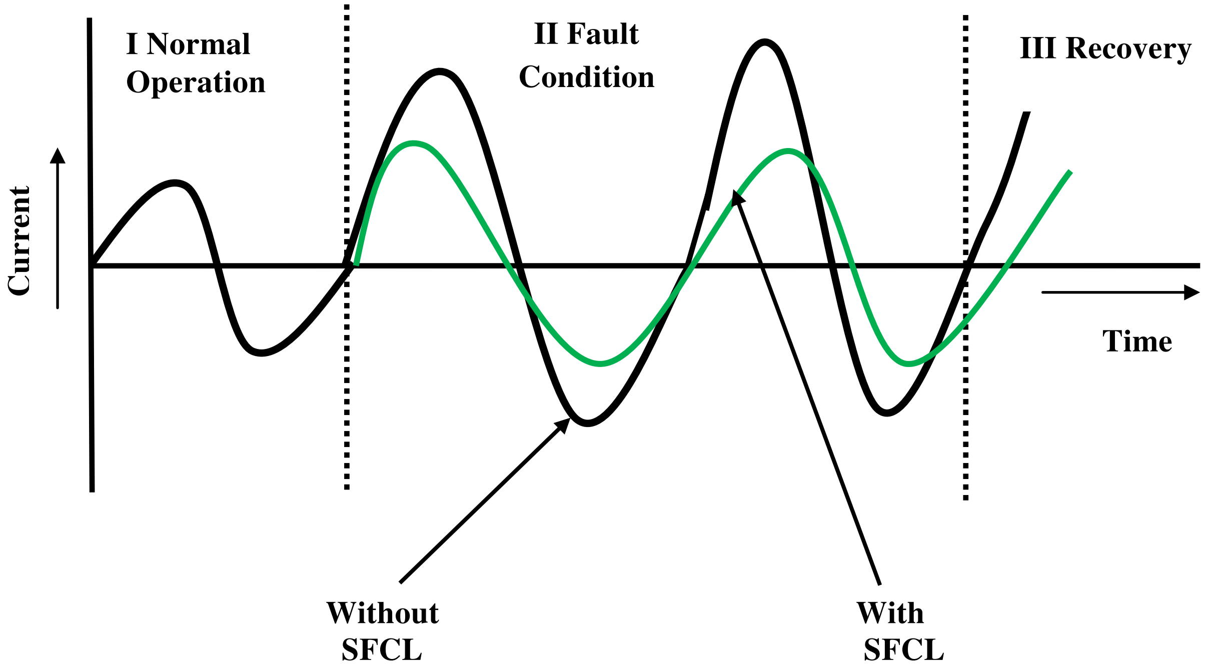

Fig.1.4 Waveform of Current during Normal and Faulty Condition with and without SFCL

Accordingly, the fault current magnitude in power systems is increasing. Because of such developments, and the rising need to counter this trend, current limiting technology has been getting much attention as it can efficiently limit the short-circuit faults and improve power system reliability. The introduction of new generating facilities by independent power producers and increasing load demand can result in fault current over duty on existing transmission system protective equipment. Conventional solutions to fault current over duty such as major substation upgrades, splitting existing substations buses or multiple circuit breakers upgrades could be very expensive and require undesirable extended outages and result in lower power system reliability.

Due to the difficulty in power network reinforcement and the interconnection of more distributed generations, fault current level has become a serious problem in transmission and distribution system operations. The utilization SFCL in power system provides an effective way to suppress fault currents. SFCL can be categorized into two types: passive and active. The commonly used SFCL are of passive type. In radial transmission and distribution systems, the placement of SFCL is not difficult, but in loop transmission or distribution system, SFCL placement becomes much more complex when more than one location has high fault current problems.

1.6 TYPES OF SFCL

A variety of FCL technologies that utilize unique and novel approaches for limiting the magnitude of fault currents are now in the prototype stage of development and, if successful, will soon be ready for grid deployment. The types of SFCL are given as:

- Resistive SFCL
- Inductive SFCL
- Shielded-Core SFCL
- Hybrid SFCL

1.6.1 RESISTIVE SFCL

Resistive SFCL are the simplest and most obvious form, because the superconductors are electrically in series with the phase conductors. Resistive SFCL operates on the principle that passing a current, which is greater than the superconductor, rated critical current (I), as shown in Fig 1.5, through a superconducting wire initiates quenching and results in a transition to a resistive state. Nevertheless, the superconductors may experience AC losses and there are power losses associated with the operation of the cryogenic system, mainly due to heat loss from the current leads which connect the external power system to the superconducting elements. Several superconductor materials have been used for resistive SFCL, including Bismuth Strontium Calcium Copper Oxide (BSCCO), Yttrium Barium Copper Oxide (YBCO), and Magnesium Diboride ($\mathrm{M_gB_2}$). BSCCO is considered a first generation (1G) HTS material, whereas 2G materials such as YBCO offer higher critical current values for a given wire radius, particularly under an external magnetic field, and provide better mechanical stability. In Fig 1.5, $\mathrm{Z_{SH}}$, is the shunt impedance connected in parallel with the SFCL resistance to reduce the non-uniform heating of the superconductor (hot spots).

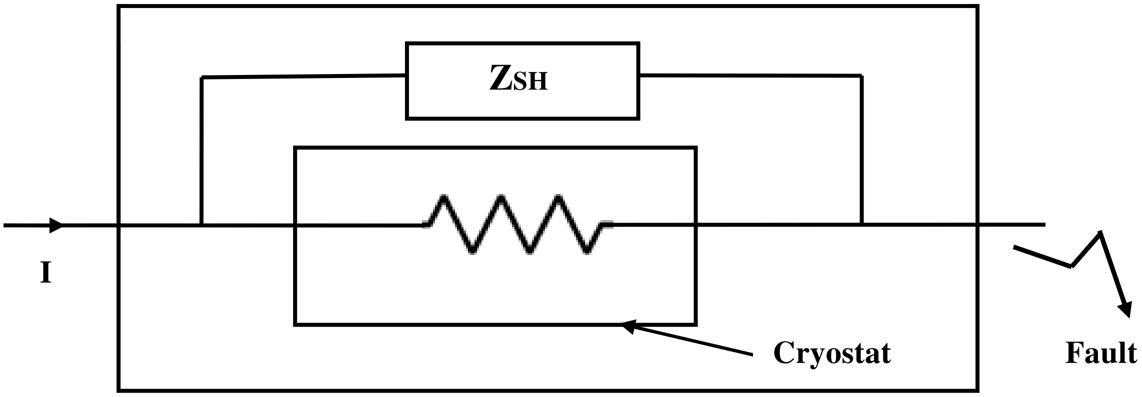

Fig.1.5 Resistive SFCL with Cooling System

The benefits of the Resistive SFCL are described as follows:

- SFCL can typically limit the first peak of fault current. An SFCL with suitably rated switchgear to interrupt fault current therefore acts much faster than a circuit breaker, without SFCL. No remedial action occurs until a circuit breaker opens. This offers significantly reduced damage at the point of fault, and reduced damage or heating to any equipment carrying fault current. Consequently, the presence of an SFCL can lead to improve overall reliability for other devices in distribution systems.
- There is an opportunity to use switchgear of a lower fault current breaking capability, which is less expensive, smaller, and lighter. Alternatively, the use of fault current limitation in existing systems could delay, or even avoid, the replacement of existing switchgear, should fault levels rise due to system changes or the connection of DG.
- There is an increased opportunity for network interconnection. This improves the security of supply, leads to lower network losses, and improves power quality due to the lower system impedance.
- Another advantage is reduced circuit breaker Transient Recovery Voltage (TRV). In general, resistive SFCLs will limit both the AC and DC components of fault current, and will dampen any transients (while in the resistive state). Inductive SFCL, by comparison, will only limit the varying components of fault current, i.e., the level of limitation depends upon di/dt.

1.6.2 INDUCTIVE SFCL

An inductive saturated iron-core SFCL is shown in Fig.1.6. It consists of two iron cores, which are driven by a DC bias supply (V_{dc}). Two iron cores are used so that the unit can limit the current in both directions. Among SFCL, the inductive type has some distinctive merits such as large design flexibility due to the turn ratio, isolation between a current-limiting device and a power transmission line, and low heat losses. These are considered technically feasible and economically viable alternative for the LSFCL in terms of compactness, efficient limitation, and lower alternating-current losses, which prove to be a construction cost-effective means of fault-current management.

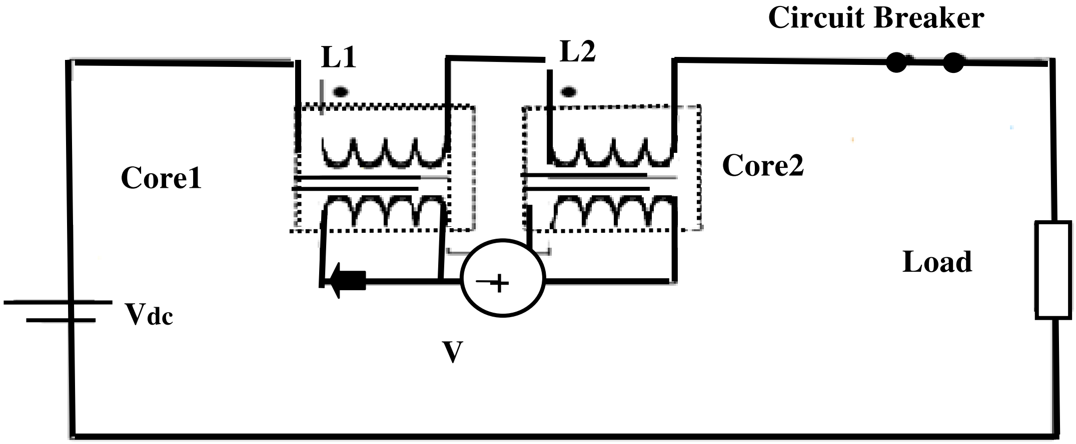

Fig.1.6 Circuit Diagram of Inductive SFCL with Circuit Breaker

An LSFCL generally consists of a primary copper coil L1 & L2 and a whole/partial superconducting secondary coil core1 or core2 as shown in Fig.1.6, wound around a magnetic iron core. The shielded core-type LSFCL, i.e., the superconducting element, is not connected physically into the power circuit but coupled into it by means of a series transformer. In particular, the secondary side of the coupling transformer is a single turn (cylinder) of High-Temperature Superconducting (HTS) material.

The main advantages of inductive type SFCL are:

- ❖ No current lead is required into the cryogenic environment, which reduces substantially the refrigeration requirements.

- ❖ With the additionally free parameter of the turn ratio between the line-side winding and the HTS-side single turn, the HTS material is better utilized as a high-current device, which reduces the hot-spot problem. In the transformer type, the secondary winding is a copper coil shorted via a superconducting component, which results to nearly zero impedance from the primary side. In the event of a fault, a superconducting-to-normal transition occurs in both types of LSFCLs reflecting limiting impedance on the primary side, thereby limiting the fault current.

1.6.3 SHIELDED-CORE SFCL

One of the first SFCL designs developed for grid deployment was the shielded-core design, a variation of the resistive type of limiter that allows the HTS cryogenic environment to remain mechanically isolated from the rest of the circuit. An electrical connection is made between the line and the HTS element through mutual coupling of AC coils via a magnetic field.

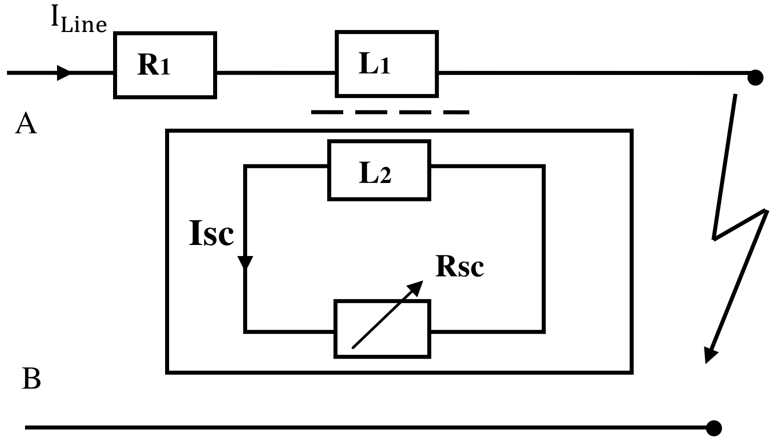

Fig.1.7 Circuit Diagram of Shielded-Core SFCL

Inductive SFCL is shown in Fig 1.7, where I_{Line} is the rated current in the primary winding, R_1, is the primary winding resistance and L_1, L_2 are the primary and secondary inductances respectively and I_{SC} is the current flowing in the secondary winding across SFCL resistance (R_{SC}). Basically, the device resembles a transformer with the secondary side shunted by an HTS element. During a fault, increased current on the secondary causes the HTS element to quench, resulting in a voltage increase across L1 that opposes the fault current.

Although the superconductor in the shielded-core design has to re-cool after a limiting action just like the resistive type, non-uniform heating of the superconductor (hot spots) is easier to avoid through optimization of the turns ratio. A major drawback of the shielded-core technology is that it is approximately four times the size and weight of purely resistive SFCL.

Although prototypes of shielded-core designs have worked well, their size and weight have limited grid deployment. The current limiting behavior of Electro Magnetic Fault Current Limiter (EMFCL) is caused by the variation of magnetic field. The saturated iron-core SFCL is also an EMFCL, wherein the superconducting windings just reduce the power loss during normal operation. The unique property of Dynamic Fault Current Limiter (DFCL) is that as the current increases, the permeability increases, which results in increase in current limiting reactance. DFCL have a power rating of 9.35 MVA (12 kV, 0.45 kA) and are operating at customer plants. Comparing to the saturated iron-core SFCL, DFCL has a relatively smaller power rating, but it operates in the unsaturated zone of the B-H curve of the core material and generates zero harmonics in normal state.

1.6.4 HYBRID SFCL

The SFCL is of hybrid type, in which the fault current is detected by a superconductor and bypassed by a high-speed switch to a reactor in a parallel circuit for current limitation. The impedance and short-time current rating of the reactor was 0.4 Ω and 12.5 kA, respectively. The impedance was selected considering the protection coordination of the grid. The SFCL limits the fault current after a half cycle.

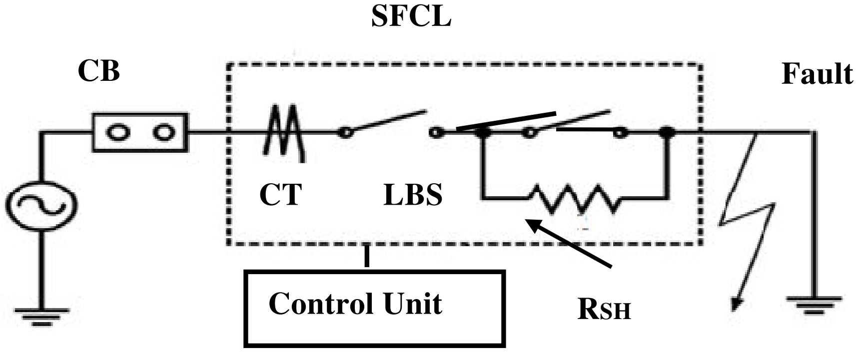

Fig.1.8 Circuit Diagram of Hybrid SFCL

Hybrid fault current limiters are the combined devices including superconductors, semiconductors, conventional fuse or circuit breaker and fast switches. Fig.1.8 shows Hybrid SFCL. This fault current limiter could reduce 12.5 kA fault current into 2 kA within 20ms. But vacuum arc commutation type fault current limiter was restricted in increasing current limiting capabilities and this could be obstacles to practical use in electric networks. Fig.1.8 shows the concept of hybrid fault current limiter proposed by ABB.

This hybrid limiter consisted of Circuit Breaker (CB) and parallel resistor (RSH). When fault occurs, electromagnetic repulsion plate moves upward very rapidly by condenser current injection. And fault current flows through the parallel resistor whose role is to limit fault current. Then the circuit breaker could interrupt reduced fault current easily.

This structure could be used in extra high voltage circuit breaker which had to face excessive fault current than its ratings. But the injection of high current to repulsion plate in a very short time and the fast arc elimination between repulsion plate contacts is to be solved for commercialization. Hybrid superconducting fault current limiters use superconductor as a fault current sensor and current commutation media, not for current limiting purpose. Consequently, superconductor usage was drastically reduced. Also the cryogenic system and cooling capacity could be reduced. These hybrid superconducting fault current limiters could be one of prominent candidate for practical and commercial solutions in the near future.

1.7 OPERATION OF RESISTIVE SFCL

As depicted in Fig 1.9 superconductors remain in the superconducting state whilst three conditions are met. They are:

- ❖ The temperature is below the critical temperature, T_C.
- ❖ The magnetic field, whether self-induced by current in the superconductor or externally applied, is below the critical magnetic field, H_C. This is due to the expulsion of flux from an externally applied field, a property of superconductors known as the Meissner effect, until the H_C threshold is reached.

- For Type-II superconductors, there are lower and upper values of, $\mathrm{H_C}$. The intermediate region between $\mathrm{H_{C1}}$ and $\mathrm{H_{C2}}$ is known as the flux-flow state where magnetic flux vertices begin to form, but the material is still considered to be superconducting in this state. The magnetic field greater than $\mathrm{H_{C2}}$ will cause breakdown of superconductivity.
- The current is below the critical current, $\mathrm{I_C}$.

These physical properties therefore allow superconductors to inherently limit fault currents in power systems. During non-fault conditions, the superconductors act as ideal conductors. During a short-circuit fault, the relatively high fault current causes the superconductor to change to the intermediate flux-flow state.

Typically, $\mathrm{I^2R}$ heating developed in the superconductor's flux-flow resistance causes $\mathrm{T_C}$ to be exceeded, resulting in a transition to the resistive state. This increases the electrical impedance in the path of fault current, thereby reducing the fault current.

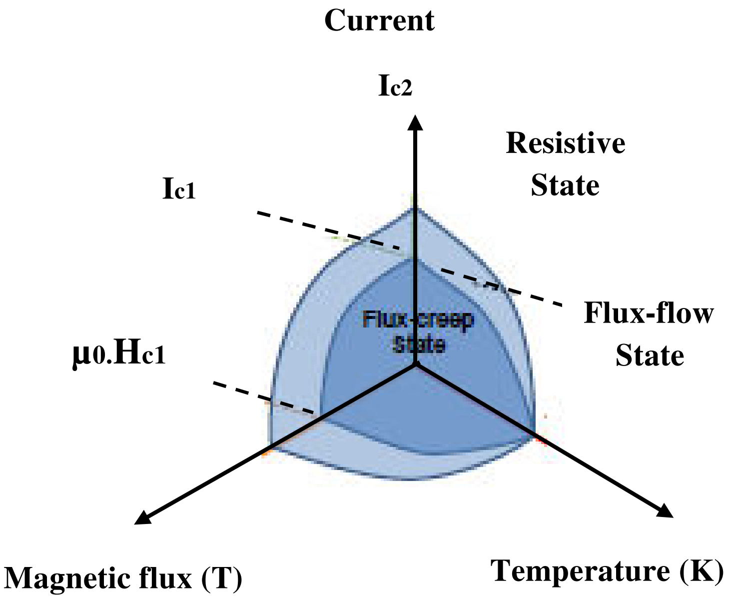

Fig.1.9 Different States of Operation of Resistive SFCL

1.8 APPLICATION OF SFCL

SFCL as versatile devices for fault current management can be applied at different positions within a typical grid. Applications of SFCL can be given as:

1.8.1 FEEDER APPLICATION

Depending on the protective function, the RSFCL can be used either in incoming feeders, e.g., as transformer feeder, or in the outgoing feeders as shown in Fig1.10. This inline application protects all elements downstream of the point of installation. Obviously, the rating of the device changes according to the chosen position.

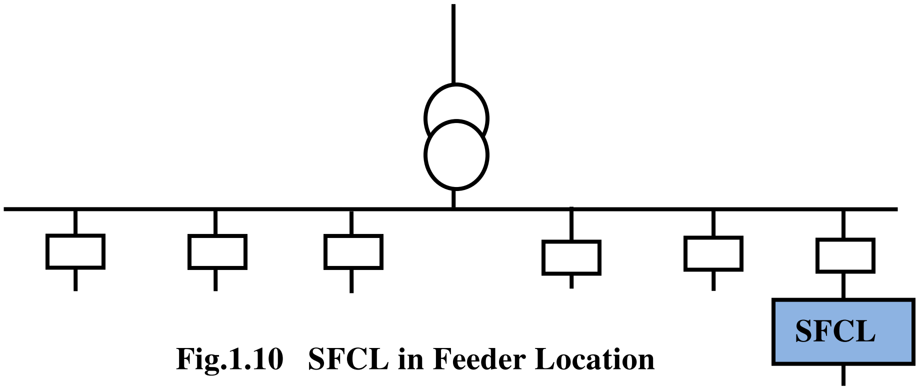

Fig.1.10 SFCL in Feeder Location

1.8.2 BUSBAR COUPLING

The RSFCL is especially advantageous for busbar couplings, as fully redundant feed-in is possible without a normally associated increase in short-circuit currents as shown in Fig.1.11. In case of a fault, the limiter ensures that the short-circuit contribution from the un-faulted bus is strongly reduced.

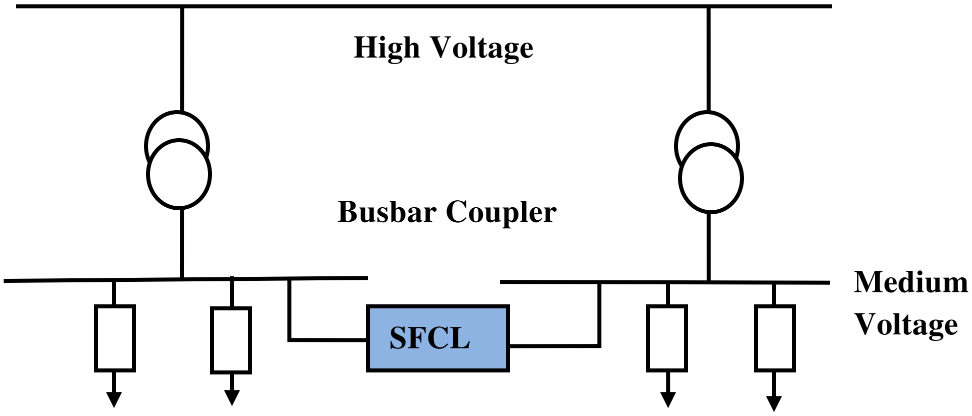

Fig.1.11 SFCL in Busbar Coupling Point

1.8.3 SFCL IN A TRANSFORMER FEEDER LOCATION

Placing a SFCL in a transformer feeder location offers great flexibility in reducing substation fault levels to accommodate switchgear ratings as shown in Fig 1.12. One or more SFCLs may be installed, depending on the fault reduction required, with minimal changes to existing protection settings.

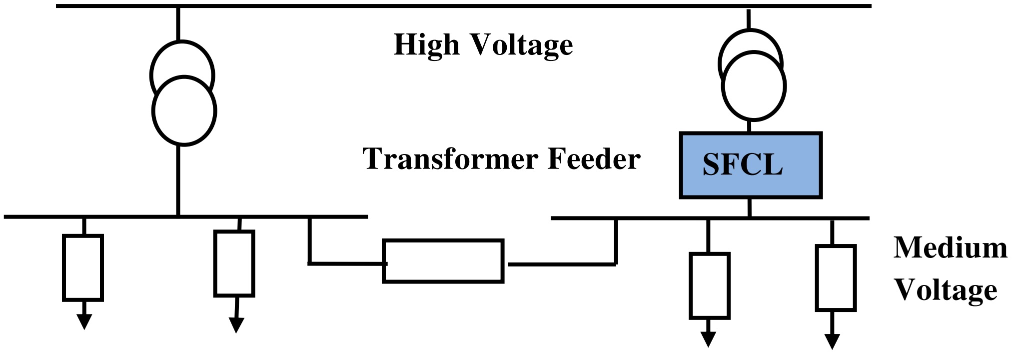

Fig.1.12 SFCL is placed in Transformer Feeder Point

1.8.4 SFCL IN BUS-TIE LOCATION

Placing a SFCL in a bus-tie location offers significant advantages in paralleling bus sections upon loss of one or more transformers in the substation as shown in Fig1.13.

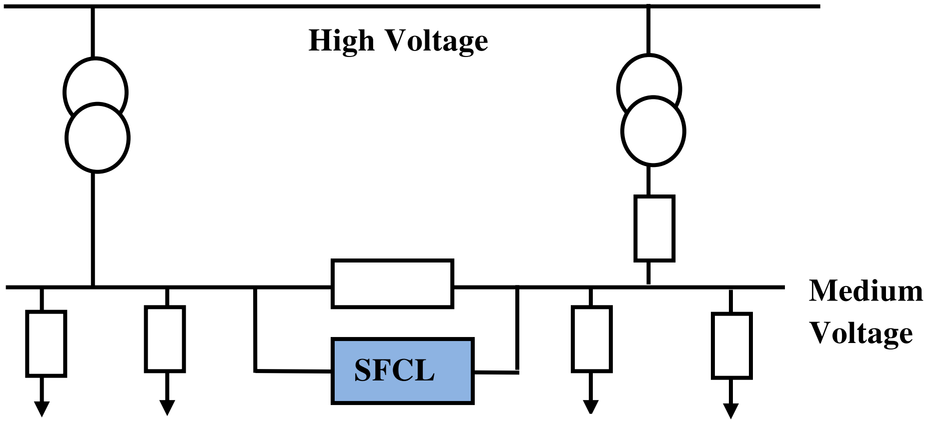

Fig.1.13 SFCL is placed in Bus-tie Location

One or more SFCL may be installed, depending on the bus-bar topology and fault reduction required, with minimal changes to existing protection settings. It also enables paralleling of bus sections in previously split substations, allowing interconnectivity, more flexible running arrangements and improved power quality.

This chapter describes the basic introduction of superconducting fault current limiter for limiting the magnitude of the fault current in faulty condition when distributed generation interconnected to the main grid. In addition to this, operation of SFCL and its application in power system is discussed. Literature review and inferences drawn out of literature review are discussed in the next chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

A power system consists of a large number of equipment such as generator, transformer, bus bar, transmission line etc. These equipments are protected by protective relaying system comprising of instrument transformers, circuit breaker and communication equipment. The fault clearance time is usually specified by the regulating bodies and network services provider. The clearance time is given for local and remote circuit breaker which depends on the voltage level and is determined primarily to meet stability requirement and also to minimize plant damage.

The maximum clearance time of the backup protection are also specified. Electrical power system operates at various voltage levels from 415 V to 400 kV or even more. Electrical apparatus used may be enclosed (e.g., motors) or placed in open (e.g., transmission lines). All such equipment undergoes an abnormal issue due to various reasons. Condition of under frequency or over frequency occurred in generator may result in mechanical damage to its turbine requiring tripping of an alternator.

A Microgrid (MG) can be considered as an entirely DG based grid that contains both generators and loads. It is usually connected to the utility grid through a single point: the Point of Common Coupling (PCC).

To the utility grid, the microgrid behaves as a fully controllable load which at peak hours can even supply power back to the utility grid. A microgrid can operate in either (utility) grid connected mode or islanded mode and can seamlessly change between these modes depending upon the requirements. In an islanded mode, the DGs connected to the microgrid supply its load, where a provision for load shedding exists if the load demand is higher than the total DG generation.

2.2 LITERATURE SURVEY

Several works in progress on Superconducting Fault Current Limiter (SFCL). Some of the important literatures which the investigator has gone through are discussed below.

Sung et al in [1] examined the optimal resistive value of SFCL for enhancing the transient stability of a power system more effectively. The optimal resistive value of the SFCL connected in series with a transmission line during a short-circuit fault is systematically determined by applying the equal-area criterion based on the power-angle curves. To verify the effectiveness of the optimal value of the proposed SFCL for reducing the value of fault current, several case studies are carried out by both simulation and experimental tests, particularly including the 220-V/300-A-scale laboratory and 13.2-kV/630-A-scale distribution system hardware tests.

Hong et al in [2] explained the design and performance test of a 10 kV, 200A resistive type SFCL prototype. A series of tests including short circuit test, recovery test, auto-reclosure test, and LN2 boiling test have been performed. This single phase SFCL is made from 15 current limiting modules. Several 1-m long Yttrium Barium Copper Oxide (YBCO) coated conductors prepared by Shanghai Jiaotong University are used to build the current limiting module. Each module has 2 tapes connected in parallel to carry 200 A rated current and 6 tapes connected in series to withstand 700V to 800V voltage drop.

Hwang in [3] estimated that the combinations of ac and dc distribution grids are also considered for the efficient connection of renewable power resources. In this case, one of the critical problems due to these integrations is the excessive increase in the fault current because of the presence of DG within the smart grid. In order to protect the smart grid from increasing fault current, a SFCL could be applied, which has negligible power loss and capability to limit initial fault currents effectively. Transient analyses were performed for the worst case faults with the different SFCL arrangements.

Kozak et al in [4] presented the design and development of coreless inductive SFCL for MV distribution systems. It is a very attractive design which reduces the weight of the device. The primary High Temperature Superconductor (HTS) and secondary HTS windings are magnetically coupled to one another. Copper primary winding connected parallel to the HTS primary winding is magnetically coupled to HTS windings to ensure that in case of lack of cooling or superconductor failure, the protected circuit will not be disrupted. In this paper coreless construction discussed which reduces the weight of the device and the size of the primary copper winding. The primary copper winding is connected parallel to HTS primary winding which gives better coupling with secondary HTS winding. This results in a reduction of the voltage drop on the limiter in nominal conditions when the HTS tape is in the superconducting state.

Lee et al in [5] discussed the current issues and commercialization problems of SFCL considering various aspects such as coordination with conventional relay, high voltage and high current issues, performance, cost, size, and life and maintenance issues. The viable method, hybrid superconducting fault current limiters in order to solve the practical problems of conventional superconducting fault current limiters was briefly introduced. Hybrid fault current limiters are the combined devices including superconductors, semiconductors, conventional fuse or circuit breaker and fast switches. The emerging solutions for fault current limiters are hybrid type fault current limiter which has several merits such as low cost, high performance, coordination with conventional systems.

Elsamahy et al in [6] carried out to explore the impact of SFCL installed in the transmission system in coordination with the generator distance phase backup protection and the generator capability curve. The function of phase backup protection is to disconnect the generator if a symmetrical or unsymmetrical phase fault outside of the generator zone of protection has not been cleared by other protective devices after a sufficient time delay has elapsed. The result of these investigations shows that both the resistive and inductive type SFCL have an adverse effect on this coordination. Such an impact varies according to the fault type, the fault location, and the generator loading. The dynamic simulations have been conducted by using the PSCAD/EMTDC software.

Noe et al in [7] showed feeder locations of power stations, of power station auxiliaries and of local generating unit's places of SFCL in an urban network up to a voltage of 110 kV, lists technical benefits and calculates the economical savings. Depending on the location, SFCL either limit the short-circuit capacity in case of a short circuit or result in a higher short-circuit capacity during normal conditions without increasing the short-circuit capacity during fault conditions. A high short-circuit capacity improves power quality and stability conditions. In this paper a method for the economical evaluation concentrates on the prospective savings by using SFCL.

Nagarathna et al in [8] discussed the various applications of SFCL in the power system like limit the fault current, secure interconnector to the network and reduces the voltage sag at distribution system. SFCL are anticipated as a solution for existing electric networks. The emerging solutions for fault current limiters are SFCL which has several merits such as low cost, high performance, coordination with conventional systems.

Kovalsky et al in [9] explained the various problems of conventional solution to fault current over-duty such as major substation upgrades, splitting existing substation busses or multiple circuit breaker upgrades could be very expensive and require undesirable extended outages and result in lower power system reliability. The performance of a particular type of limiter, the Matrix Fault Current Limiter (MFCL) is presented. The use of this device in a particular application in the American Electric Power (AEP) 138 kV transmission grid is also discussed. Here the MFCL is represented by an HTS element as variable resistance in parallel with a reactor. Under normal operating conditions, the peak of the AC current level of the power transmission network is always below the critical current level of the superconductor, therefore there is essentially not voltage drop across the device and there are no losses. The device is "invisible" to the grid. When the fault occurs, the fault current level exceeds the critical current level of the superconductor, creating a quench condition.

Baldan et a in [10] proposed an evaluation of a superconducting fault current limiter (SFCL) by modular superconducting device combined with a short-circuited transformer with a primary copper winding connected in series to the power line and the secondary side short-circuited by the superconducting device. The evaluation tests were performed with a prospective current up to 2 kA, with the short-circuited transformer of 2.5 kVA, 220 V/660 V connected to a test facility of 100 kVA power capacity. The resistive SFCL using a modular superconducting device was tested without degradation for a prospective fault current of 1.8 kA, achieving the limiting factor 2.78; the voltage achieved 282 V corresponding to an electric field of 11 V/m. The test performed with the combined SFCL (superconducting device + transformer) using series and toroidal transformers showed current limiting factor of 3.1 and 2 times, respectively.

Martini et al in [11] reported on the successive step, which is concerned with developing, testing and installation at the hosting utility of the final three-phase SFCL prototype. In this paper SFCL main characterizations are considered such as: Critical current (Ic) measurements at 65 K and 77 K for each winding of the three-phase device, AC losses measurement consists in injecting 50 Hz modulated-amplitude sinusoidal-AC currents in the HTS windings immersed in a liquid nitrogen bath at 77 K. During the measurement, voltage drop across winding terminals and injected current have been acquired with a sampling frequency of 100 kHz for a time-interval of ten periods (200 ms).

Kraemer et al [12] addressed the collaboration of American Superconductor, Siemens, Nexans and Southern California Edison one electrical phase of a resistive superconducting. The active part of the limiter consists of 63 bifilar coils made of 12 mm wide steel stabilized YBCO conductor and is housed in a cryostat operated at 5 bar and 74 K. fault current limiter for the 115 kV transmission voltage level has been designed and manufactured. The design, manufacture and test of a transmission voltage (115 kV) resistive FCL based on 2nd generation HTS wires studied in this paper. The partners and their responsibilities within the project are: American Superconductor (AMSC) for project lead, production of wire, cryostat design and system integration, Nexans for design and manufacturing of high voltage terminations and their connection to the limiter, Siemens for the design and manufacturing of the active part of the limiter and Southern California Edison as the partner for installation and on-site testing.

Bock et al in [13] discussed the Resistive SFCL as reliably reacting devices and excellent means to overcome issues of higher short circuit current levels resulting from added electricity generation and more interconnected networks. Several RSFCL systems based on different superconductor materials have been designed, built, tested, and commissioned by Nexans Superconductors at distribution grids of several DNO and also two times at a power plant. With a resistive SFCL in the line, the limiter minimizes the phase shift between current and voltage during a short circuit, an effect which strongly reduces the stress and requirements on the circuit breakers in line, because the current and voltage are zero almost simultaneously. All circuit breakers, busses and cables downstream of a limiter can have much lower ratings and significant equipment cost can be saved.

Wojtasiewicz et al in [14] discussed the Inrush current in superconducting transformers. Because of its high values and long time, it may lead to loss of superconductivity in transformers windings. In this paper inrush current measurements in two superconducting transformers of the same power but different winding geometries. The results were confronted with inrush current registered for a transformer with copper windings. The results suggest different parameters of inrush current for superconducting transformers as compared to transformers with copper windings. The experiment presented here showed that superconducting transformer of power 8.5 kVA has slightly greater values of inrush current than an 8.5 kVA transformer with copper windings.

Zhang et al in [15] presented the state of the art of Fault Current Limiters (FCL), focusing on devices in or near to field test status based on capabilities and characteristics of FCLs. Smart grid, assign the various types to the most appropriate nodes in a smart grid: solid-state FCLs can be installed at Microgrid and renewable energy resource feeders to replace circuit breaker and maintain protection coordination of the transmission network, resistive SFCL, saturated iron-core SFCL and dynamic FCL can be installed at distribution substations to maintain downstream over-current protection without current harmonics disturbance. With these placements, we can make full use of the advantages of smart grid's communication network and different characteristics of FCL devices in different categories to offer a more flexible and reliable protection for future power grid.

Naeckel et al in [16] discussed the design, set-up and short circuit testing of an air coil superconducting fault current limiter for 60 kVA, 400 V, z = 6% demonstrator. It consists of a primary winding made of copper, which is basically the equivalent of an air core reactor and a secondary superconducting winding made of BCO tapes, which are individually short-circuited. Both windings are inductively coupled and intended to work in liquid nitrogen. The measurements shows, that the AC-SFCL has an improved fault current limiting capability compared to the shunt reactor and is capable of maintaining its current limiting capability regardless of phase angle.

Kim et al in [17] presented the development and grid operation SFCL have been carried out in Korea Electric Power Corporation (KEPCO). Temperatures and level of liquid nitrogen that cools the superconducting element have been maintained constant. There was no need to add liquid nitrogen. A short-circuit test on the modified SFCL showed it started limiting the current within 2 ms. In parallel, a 154 kV SFCL has been also developed. The element is planned to be integrated into a single-phase 154 kV SFCL together with the cooling system and other components. The SFCL used is of hybrid type, in which the fault current is detected by a superconductor and bypassed by a high-speed switch to a reactor in a parallel circuit for current limitation. After successfully passing the tests, the cooling system of the SFCL was operated for more than 5 months under no-load and load conditions to optimize its operation condition. The SFCL was then energized and went into grid operation successfully.

Ye et al in [18] investigated the effectiveness of the resistive SFCL for fault level management in wind power system. In this paper, a comprehensive study has been performed in Electro Magnetic Transient Program (EMTP) software package to demonstrate efficient operation of the system integrated wind power system by use of the SFCL under fault conditions. The peak value of the fault current at fault point fed by main transformer reached 43 kA in the first half cycle without the SFCL after the fault occurred. With SFCL installed on the main road of the wind farm, the maximum fault current was limited to about 12.5 kA, and was further reduced to 9.8 kA in the second cycle. The short circuit current reduction ratio in the first half cycle was about 70%.

Shu et al in [19] carried out the theoretical analysis has been to apply a bridge type SFCL to a network 10 kV distribution side and a saturated iron core SFCL is applied to the network 220 kV transmission side. This paper presented the application considerations and prospects of SFCLs in Chinese power grids. A hybrid SFCL implanted a resistive SFCL and a saturated iron core SFCL in series, and it offers fast response to the faults and durable function for the steady state. For the 220 kV high-voltage rings, the total short-circuit current is very high because of the existing parallel and intersected branches. In this case, a number of SFCLs should be installed near the branched lines.

Blair et al in [20] discussed the use of multiple SFCL in a protection scheme to locate faulted circuits, using an approach which is radically different from typical proposed applications of fault current limitation. The technique, referred to as Current Division Discrimination (CDD), is based upon the intrinsic inverse current-time characteristics of resistive SFCL, which ensures that only the SFCLs closest to a fault operate. CDD is especially suited to meshed networks and particularly when the network topology may change over time. SFCLs are re-settable, unlike fuses; the use of SFCL avoids the cost and inconvenience of replacing fuses.

Lee et al in [21] analyzed the effects of a SFCL on commutation failure in a High Voltage Direct Current (HVDC) system. Most commutation failures are caused by voltage disturbances at the inverter side and cannot be avoided in HVDC systems using thyristors. The SFCL can limit the fault current on the ac side of the converter and thus quickly restore the HVDC system to normal status. A detailed simulation based on modeling of an actual system is carried out to verify that the SFCL can reduce commutation failure in a HVDC system.

Kozak et al in [22] discussed the comparison of inductive and resistive SFCL built with the same length of HTS tape. The resistive limiter is constructed as a non inductive bifilar winding. The analysis of the test results shows that the limiters are very fast and the first peak is almost equally limited by both types of limiters. The winding temperature of bifilar coil (resistive limiter) is lower than the primary winding temperature of the inductive limiter. The secondary current in the inductive limiter is lower than the primary current during a fault primary winding and secondary shorted winding. Both limiters are connected parallel to the additional Cu primary winding, which helps to reduce the power dissipated in the HTS windings during and after a fault.

Xin et al in [23] presented a 220 kV/300 MVA saturated iron-core SFCL has been successfully manufactured and installed at Shigezhuang substation in Tianjin, China. Two categories of tests were conducted at the factory before the SFCL was shipped to the installation site. One was to examine whether the device met the relevant industrial standards, such as lightning impulse, high voltage withstanding, partial discharging, and temperature rising, etc. The other was to determine the functional performance and key operational parameters, such as measuring steady impedance, magnetizing and demagnetizing the superconducting coil. The performance of this SFCL satisfies the design expectations and it satisfies the applicable Chinese national standards or codes for HV utility equipment. The 220 kV SFCL has been installed at the Shigezhuang substation of Tianjin, China and passed a series of acceptance tests. Now this SFCL is under trial operation.

Kim et al in [24] analyzed the bus voltage sags in a power distribution system with SFCL. The bus voltage sags, depend on the Current Limiting Reactor (CLR) magnitude in the SFCL and the fault period in the power distribution system. The effects of the voltage sags are analyzed when the reclosing function is adopted in the-trigger type SFCL, which consists of a Super Conducting Element (SCE), Mechanical Switch (MS), and Current Limiting Reactor (CLR). The introduction of the SFCL without reclosing the SW in the SFCL with high CLR impedance improves the voltage sag.

Choi et al in [25] analyzed the unsymmetrical fault characteristics of resistive SFCL based on YBCO thin films with the unbalanced faults such as a single line-to-ground fault, a double line-to-ground fault, and a line-to line fault in a three-phase system. The positive sequence current I_1 was the highest in a double line-to-ground fault, immediately after the fault onset, but that of a line-to-line fault was the highest after 50 ms. This means the current limiting effect was the worst in a line-to-line fault, due to the unbalanced quench between the SFCL units. The unsymmetrical rate of fault phases was the severest in case of a line-to-line fault among the unbalanced fault-types. That is, that of a line-to-line fault was relatively high after 50 ms because two SFCL units of fault phases did not quench simultaneously. The simultaneous quench between SFCL units was very desirable for reducing the line-to line fault currents.

X. Zhang et al in [26] investigated the superconducting fault current limiter is a promising device to limit the escalating fault levels caused by the expansion of power grid and integration of renewable. In order to unveil the impact of the superconducting material properties on the decision making for installing SFCL, two different models have been considered throughout the study. Firstly, the active operation of the SFCL has been modeled by means of a step resistance or Heaviside function which is initialized by a set of preallocated parameters. Secondly, a most realistic model for the operation of the SFCL taking into consideration the proper $E - J$ characteristics of the superconducting material with dynamic temperature evolution has been considered.

J. Zhu et al in [27] analysized due to the increased fault-level currents, superconducting fault current limiter is more likely to penetrate into a low voltage and medium voltage transmission network to improve their stability and lower the electric devices capacity. A multidisciplinary model of a bifilar resistive SFCL considering the electromagnetic properties of YBCO superconducting material is developed in the Matlab/Simulink environment. This SFCL model can show its internal electromagnetic behavior which is influenced by the variation of the operation condition. The current simulation results validate the multidisciplinary design of the SFCL and the application potential of SFCL in a power grid.

A. Morandi et al in [28] discussed the DC-operating resistive-type superconducting fault current limiter for AC applications (in short a DC Resistive SFCL) is based on the synergistic use of the resistive and the rectifier fault current limiter concepts, and allows the superconductor to operate in nearly DC current conditions. This regime of operation drastically reduces the AC losses and therefore opens up completely new perspectives with regard to the materials, the architecture of the cable, the layout of the windings and the cryogenics.

S. Nemdili et al in observed [29] to ease the design of SFCL and to allow experimentation with different materials and geometries, a computer simulation has been developed. The formula-based modeling of resistive type SFCL using MATLAB simulink software is presented. The characteristics of the quench and the current limit of SFCL are validated.

A. Golzarfara et al in [30] investigated the effect of number and SFCL location in order to have maximum reduction of short circuit current level in all buses in a real network. The faulty buses were identified in terms of short circuit current level by computing short circuits on the desired network. Then, while the fault current limit was modeled, its optimal location and amount for the greatest reduction in the fault current level of the whole critical buses was determined. Optimization computations have been done using the genetic algorithm and method of reducing the search space and all implementation stages of the proposed algorithm and reduction of search space has been conducted in DIGSILENT software using programming language DPL.

2.3 INFERENCES DRAWN OUT OF LITERATURE REVIEW

The investigator after going through number of literature has drawn out of the following inferences:

(i) Distributed generation is an emerging technology that has potential to offer improvements in power system efficiency, reliability and diversity and to help contribute to making renewable a greater percentage of the generation. While a great amount of knowledge has been gained through past experience, the practical implementation of distributed generation has proven to be more challenging than perhaps.

(ii) A number of solutions have been provided by the authors for the fault current limitation, stability and the reliability of the electrical power after interconnecting Distributed Generation (DG) to the existing Grid.

(iii) Conventional solutions to fault current over duty such as major substation upgrades, splitting existing substations buses or multiple circuit breakers upgrades could be very expensive and require undesirable extended outages and result in lower power system reliability.

(iv) The SFCL is innovative electric equipment which has the capability to reduce fault current level within the first cycle of fault current .The first-cycle suppression of fault current by a SFCL results in an increased transient stability of the power system carrying high power with greater stability.

(v) In radial transmission and distribution systems, the placement of SFCL is not difficult, but in loop transmission or distribution system, SFCL placement becomes much more complex when more than one location has high fault current problems.

(vi) The conventional protection devices used for protection of high voltage power system are circuit breakers tripped by over current relay, which require first two or three cycles to pass through, to get activated.

(vii) Several Resistive SFCL, based on different superconducting materials have been designed, built, tested by Nexans Superconductor. Materials used for SFCL are Bismuth Strontium Calcium Copper Oxide (BSCCO) and Yttrium Barium Copper Oxide (YBCO).

(viii) RSFCL can be either AC or DC. If it is AC then there will be steady power dissipation from AC losses, which must be removed by Cryogenic system. Maximum energy dissipation occurs across SFCL when the SFCL resistance approximately equals the magnitude of the source impedance.

(ix) SFCL could not only reduce the fault currents but also suppress the inrush currents, when wind farm has adopted in the case of the system interconnection. SFCL reduces the voltage sag at distribution system and provide secure interconnection to the network.

(x) Analysis of the fault characteristics of RSFCL with the unbalanced faults such as a single line-to-ground fault, a double line-to-ground fault, and a line-to line fault in a three-phase system. The unsymmetrical rate of fault phases was the severest in case of a line-to-line fault among the unbalanced fault-types.

2.4 SCOPE OF INVESTIGATION

The following features comprise the scope of the present work:

(i) Implementation of SFCL and find its optimum location in Smart Grid.

(ii) Implementation of Current Division Discrimination (CDD) in Modern power system. CDD offers a number of advantages such as: Automatic isolation of the minimal faulted circuit, or \zone without communications, automatic backup if an SFCL is out of service and the scheme remains applicable if the electrical network topology changes.

(iii) Another method which can be utilized to find out the optimum location is the Sensitivity Factor Calculation with the help of Genetic Algorithm.

(iv) Implementation of Hybrid SFCL and find its optimum location in Micro Grid.

(v) In AC type SFCL, AC losses take place across SFCL impedance in fault condition this results non-uniform heating of the superconductor (hot spots), it can be reduce by implement DC SFCL in place of AC SFCL.

(vi) Wind farms must have the capabilities of frequency and voltage control by continuous modulation of active power and reactive power supplied to the transmission system, as well as ride through fault capability of remaining transiently stable in case of a three-phase fault on the transmission system.

(vii) The underlying design method of SFCL must be improved to take into account the variation of the temperature of the superconducting tapes during quench. If this problem is resolved and AC losses can be determined correctly, the design method can be used to scale up to higher voltages.

(viii) The Resistive SFCL, saturated iron-core SFCL and DFCL can be installed at distribution substations to maintain downstream overcurrent protection without current harmonics disturbance.

2.5 OBJECTIVE

The aim of the work is to reduce fault current level in power system by using SFCL and finds its optimal location. The main objectives are:

1. To develop a resistive type SFCL model, Wind Farm and Conventional Grid using Simulink tool.
2. To implement the SFCL model in the conventional grid interconnected with wind farm, and find its optimum location in the smart grid.

2.6 PROBLEM FORMULATION

Proposed work will focus on the following problems:

i. The main aim is to reduce fault current in the condition of fault when DG interconnected to the conventional plant.

ii. In this work first model of Resistive type SFCL will develop in Matlab/Simulink.

iii. To Implement this Resistive model of SFCL in the three phase system, consisting of three phase source, load and measurement blocks, to analyze the behaviour of SFCL in different operating condition like in steady state, fault without SFCL, fault with SFCL, etc.

iv. To Implement Resistive model of SFCL in the conventional grid interconnected with wind farm, to analyze the behaviour of SFCL in different operating condition and find its optimal location.

In this chapter, the problem has been formulated given by above points. The block diagram and methodology related to the work is discussed in next chapter.

CHAPTER-3

SOFTWARE DEVELOPMENT

3.1 SIMULATION AND ANALYSIS IN DIFFERENT POWER SYSTEMS

In this thesis, Matlab/Simulink/Simpower system was selected to design and implement the SFCL model. A complete smart grid power network including SFCL model, generation, transmission, and distribution with an integrated wind farm model was also implemented in it. Simulink/Simpower 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. Control systems designed in Simulink can be directly integrated with SimPowerSystem models.

3.2 SIMULINK MODEL OF RESISTIVE SFCL

The Matlab/Simulink used to design and implement the model of Resistive SFCL. There are various parameters out of which four fundamental parameters are used to design Resistive SFCL. These parameters are as follows:

- Transition/Response time
- Minimum and Maximum Impedance
- Triggering Current
- Recovery time

The SFCL parameters with their values are shown in Table.3.1. The SFCL working voltage is 33kV. The maximum impedance value can be varied from 20Ω to 27Ω. The single phase resistive type SFCL model developed in Simulink/SimPower System is shown in Fig.3.1. SFCL model calculates the RMS value of the flowing current and then compares it with the triggering or critical current which is defined in the Matlab function program. If a passing current is larger than the critical current level and temperature below critical temperature of

Table 3.1 Fundamental Parameters of AC SFCL

S. No	SFCL Parameters	Values
1.	Transition/Response time	2ms
2.	Minimum Impedance	0.01Ω
3.	Maximum Impedance	20Ω
4.	Recovery Time	10ms
5.	Triggering current	550A

Yttrium Barium Copper Oxide (YBCO) superconducting material, then SFCL resistance increases to maximum impedance level in a pre-defined response time otherwise it adds minimum resistance in the circuit. In the Fig. 3.1, I is the rms value of the flowing current, T is the temperature of YBCO superconducting material and R is the maximum or minimum resistance depending on the Matlab function program. The critical temperature of YBCO is 93K or -183ºC.

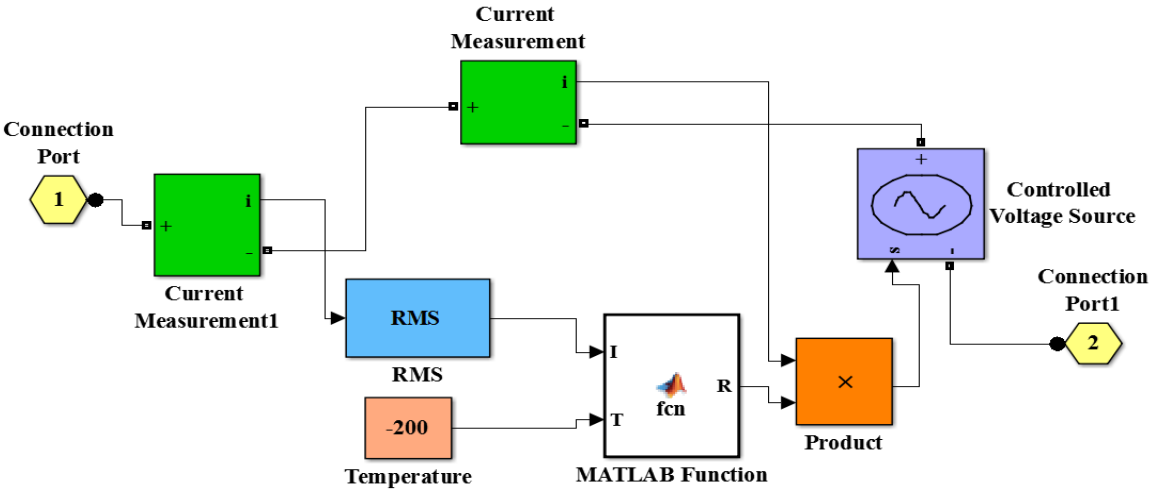

Fig. 3.1 Model of a Single Phase Resistive SFCL in Matlab/ Simulink

In fault condition, voltage get reduced, controlled voltage source is used to compensate the voltage sag problem. The product of flowing current and impedance is applied as an input to the controlled voltage source. Finally when the flowing current level falls below the critical current level the system waits until the recovery time and then goes into steady state. Fig.3.2 shows the three phase resistive type model of SFCL which is a combination of the single phase SFCL. The subsystem of three phase model of SFCL which has been used later in the subsequent models is shown in Fig.3.3.

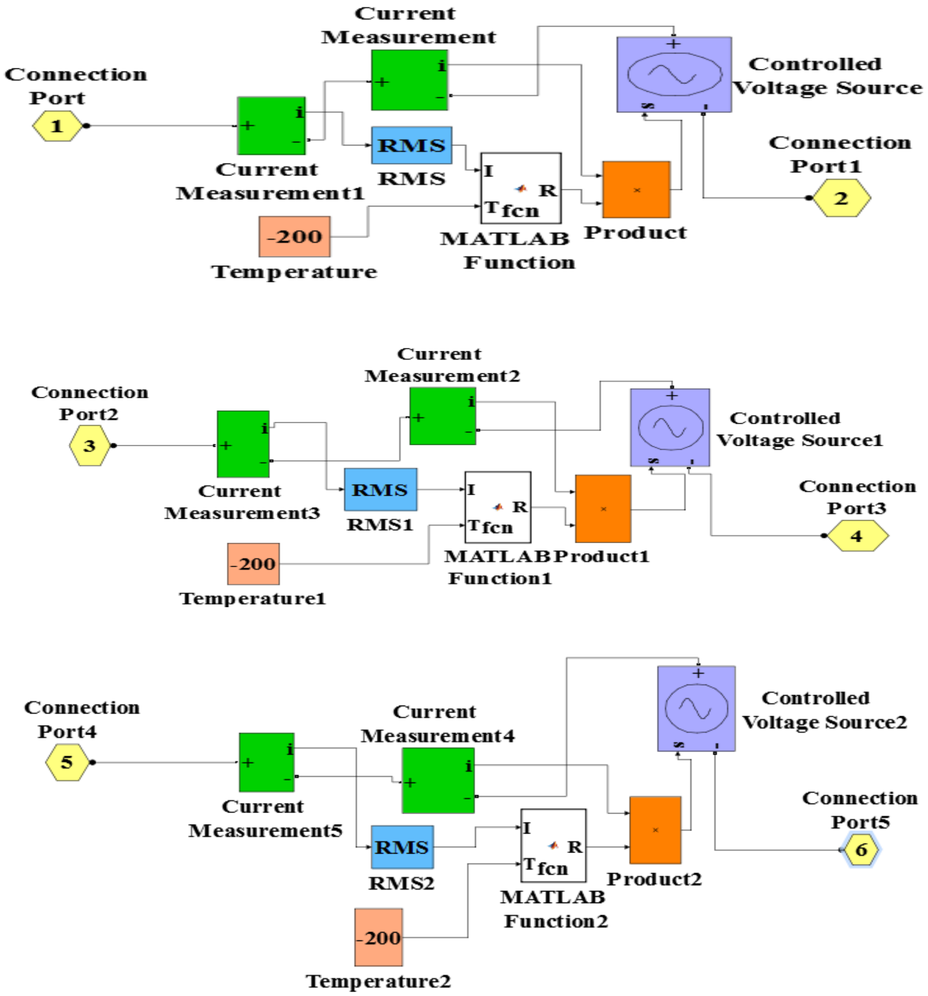

Fig.3.2 Model of a Three Phase Resistive type SFCL

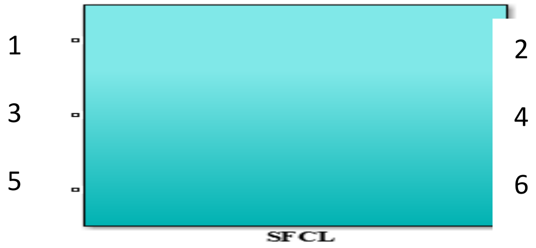

Fig.3.3 Subsystem of a Three Phase SFCL

3.3 SIMULINK MODEL OF THREE PHASE SYSTEM

An SFCL model is integrated into a practical power system to simulate its performance in a grid. Here a simple three phase system is designed in Matlab/Simulink which consist of three phase source, three phase load and three phase V-I measurement blocks as shown in Fig.3.4. The three phase system shown in Fig.3.4 is in steady state condition or normal condition. The current and voltage Simulink waveforms will be measured and analyzed in next chapter.

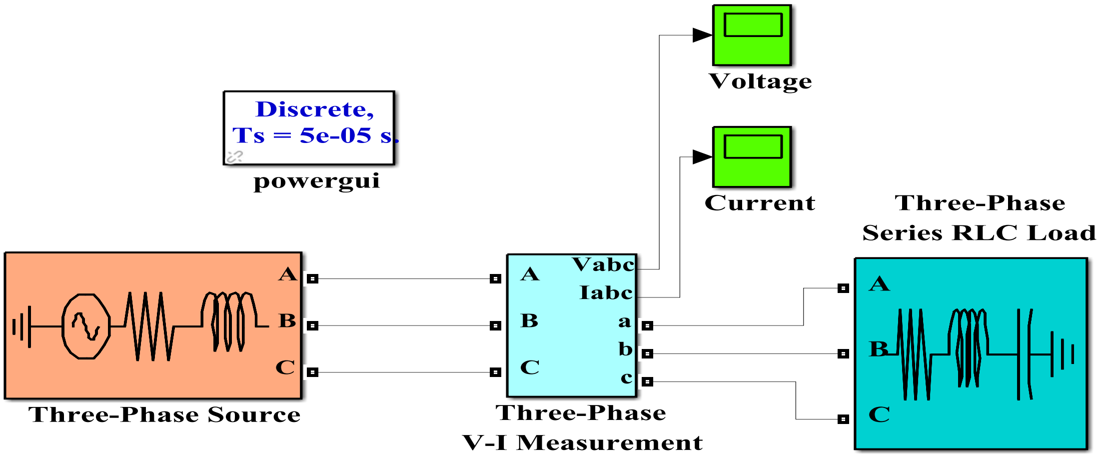

Fig.3.4 Three Phase System at Steady State Condition

3.4 SIMULINK MODELLING OF WIND FARM

In near future, many Independent Power Producers (IPP) will participate in power generations according to their own strategic contracts by deregulation. This has brought in its wake, the problem of increased fault levels often exceeding the withstand capability of existing circuit breakers. One possible option to combat this circumstance is to adapt new technologies as high-temperature superconducting equipment. Among them, Superconducting Fault Current Limiters (SFCL) are attractive because they bring benefits such as fast limiting of very high short-circuit current without sensors, no effects to the system during normal power system operation, etc. Since short circuit current is strongly related to the cost of apparatus and the efficient use of power transmissions, the reduction of high short-circuit current may bring to considerable reduction of investment cost for high capacity circuit breakers and construction of new transmission lines. Due to the rapid development of renewable energy generation in recent years, the number of wind farms connected to power grids has been significantly increased. Thus the SFCL in such a renewable generation system would provide a valuable role for its current limiting characteristics when connected to a power grid.

The wind turbine generation system has been simulated in Matlab/Simulink. The 10 MVA wind farm composes of three fixed-speed induction-type wind turbines having ratings of 5MVA, 3MVA and 2MVA.

Wind turbines use squirrel-cage Induction Generators (IG). The stator winding is connected directly to the 50 Hz grid and the rotor is driven by a variable-pitch wind turbine. The pitch angle is controlled in order to limit the generator output power at its nominal value for winds exceeding the nominal speed (10 m/s). In order to generate power, the speed of IG must be slightly above the synchronous speed. Speed varies approximately between 1 pu at no load and 1.005 pu at full load. Each wind turbine has a protection system monitoring voltage, current and machine speed.
The subsystem of 5MVA wind turbine is shown in Fig.3.5 and that of 2MVA wind turbine is shown in Fig.3.6. Fig.3.7 shows the subsystem of 3MVA wind turbine.

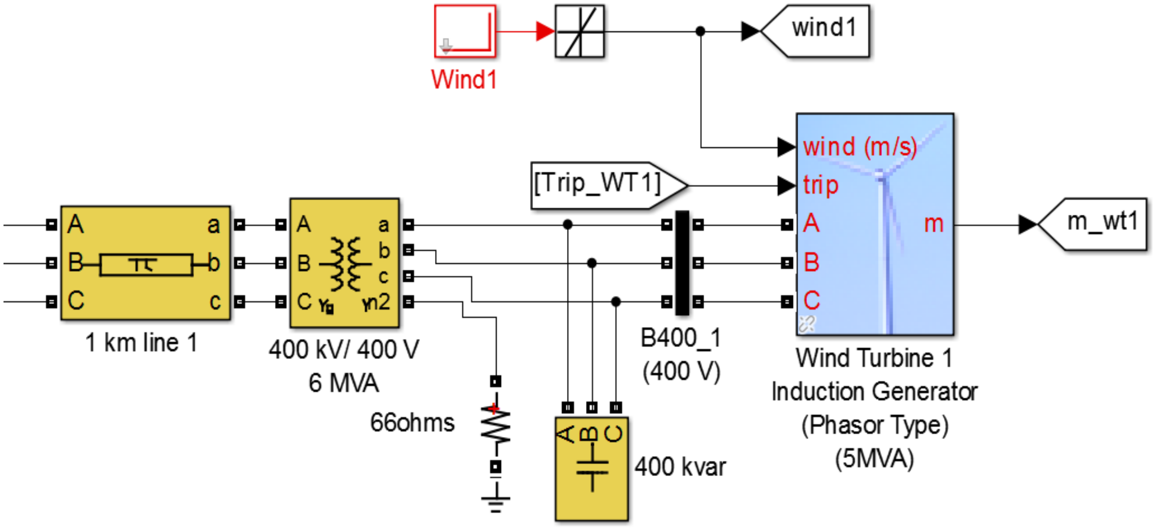

Fig.3.5 Subsystem of 5MVA Wind Turbine

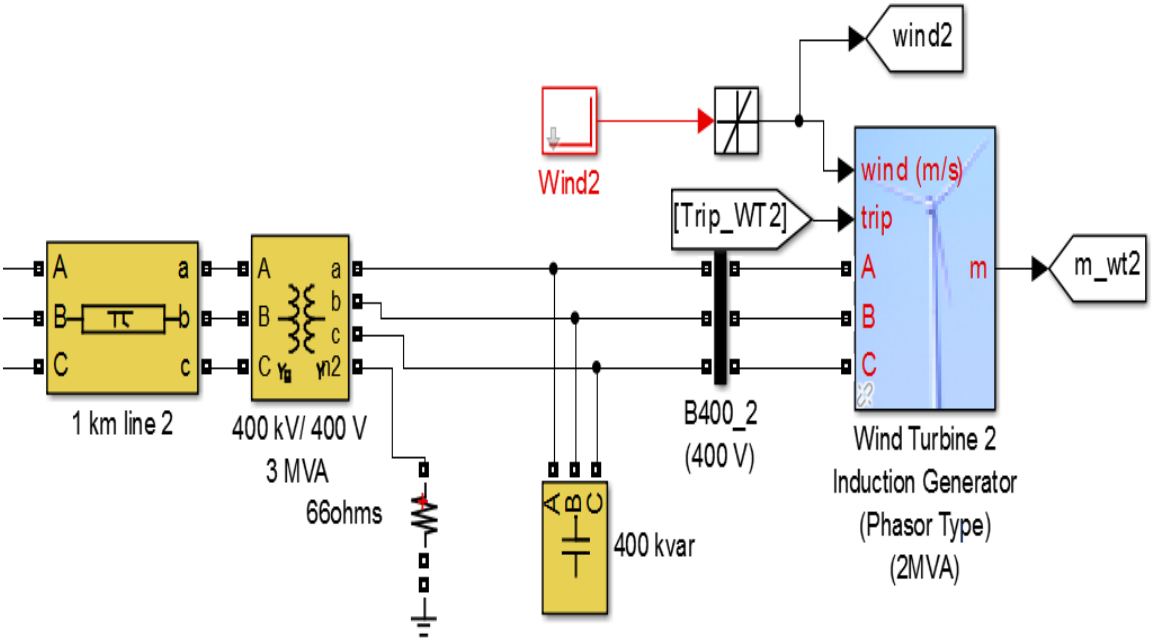

Fig.3.6 Subsystem of 2MVA Wind Turbine

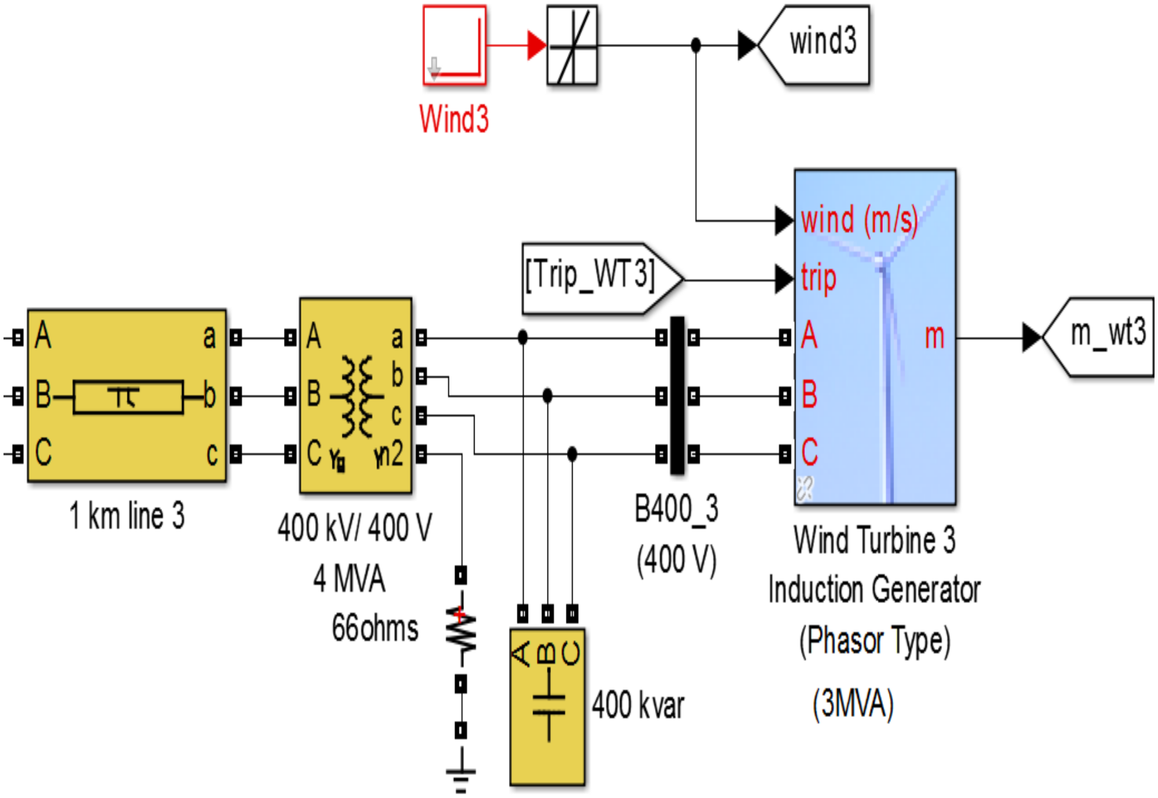

Fig.3.7 Subsystem of 3MVA Wind Turbine

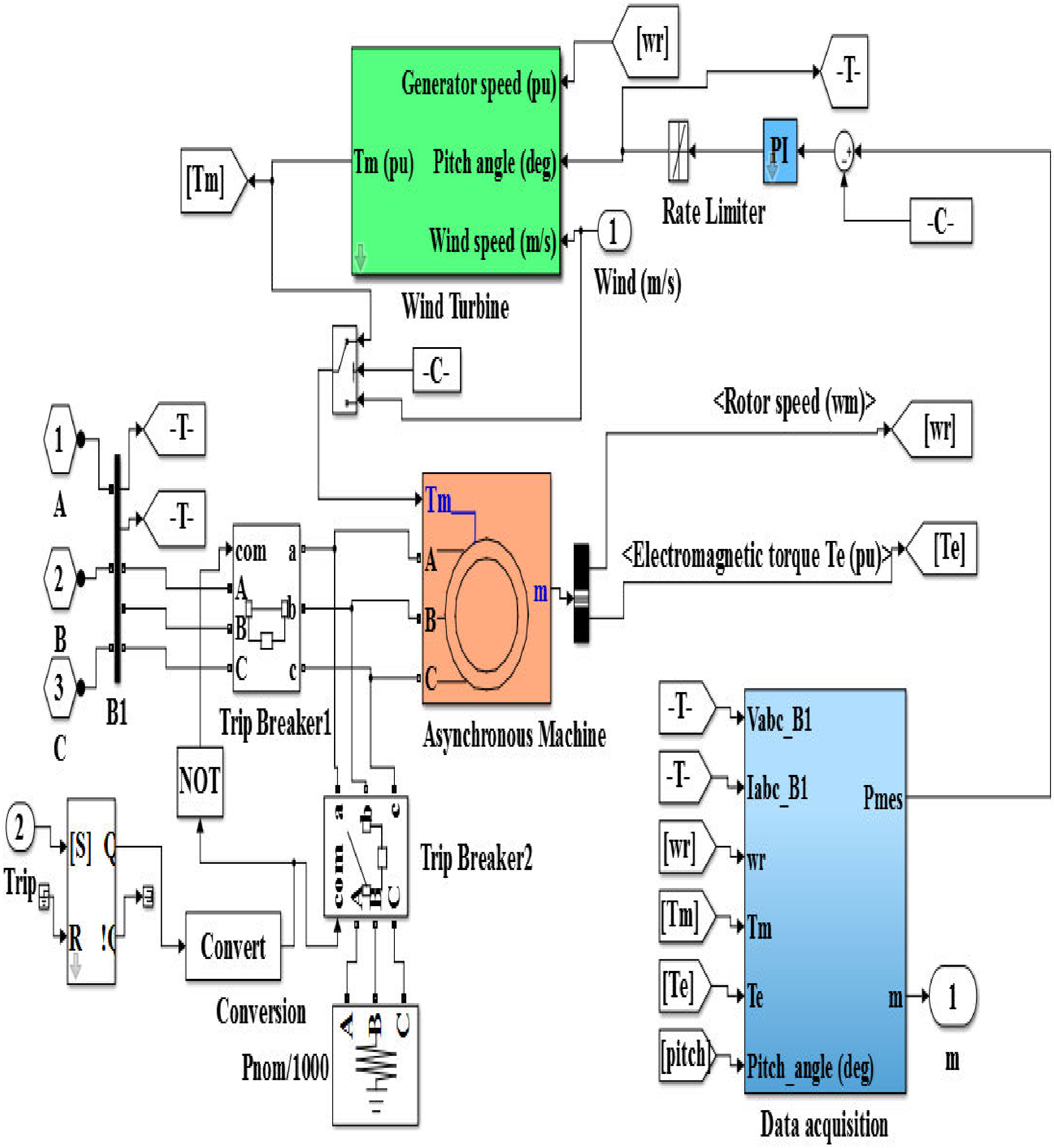

Fig.3.8 Detailed Simulink Model of Wind Turbine

The detailed Simulink model of Wind Turbine block included in these subsystems is shown in Fig.3.8, with the protection system represented as Data Acquisition for the monitoring of voltage, current and machine speed. The three subsystems of Fig.3.5, Fig.3.6 and Fig.3.7 is combined together to model a wind farm as shown in Fig.3.9. This model is then used as a subsystem in further modeling.

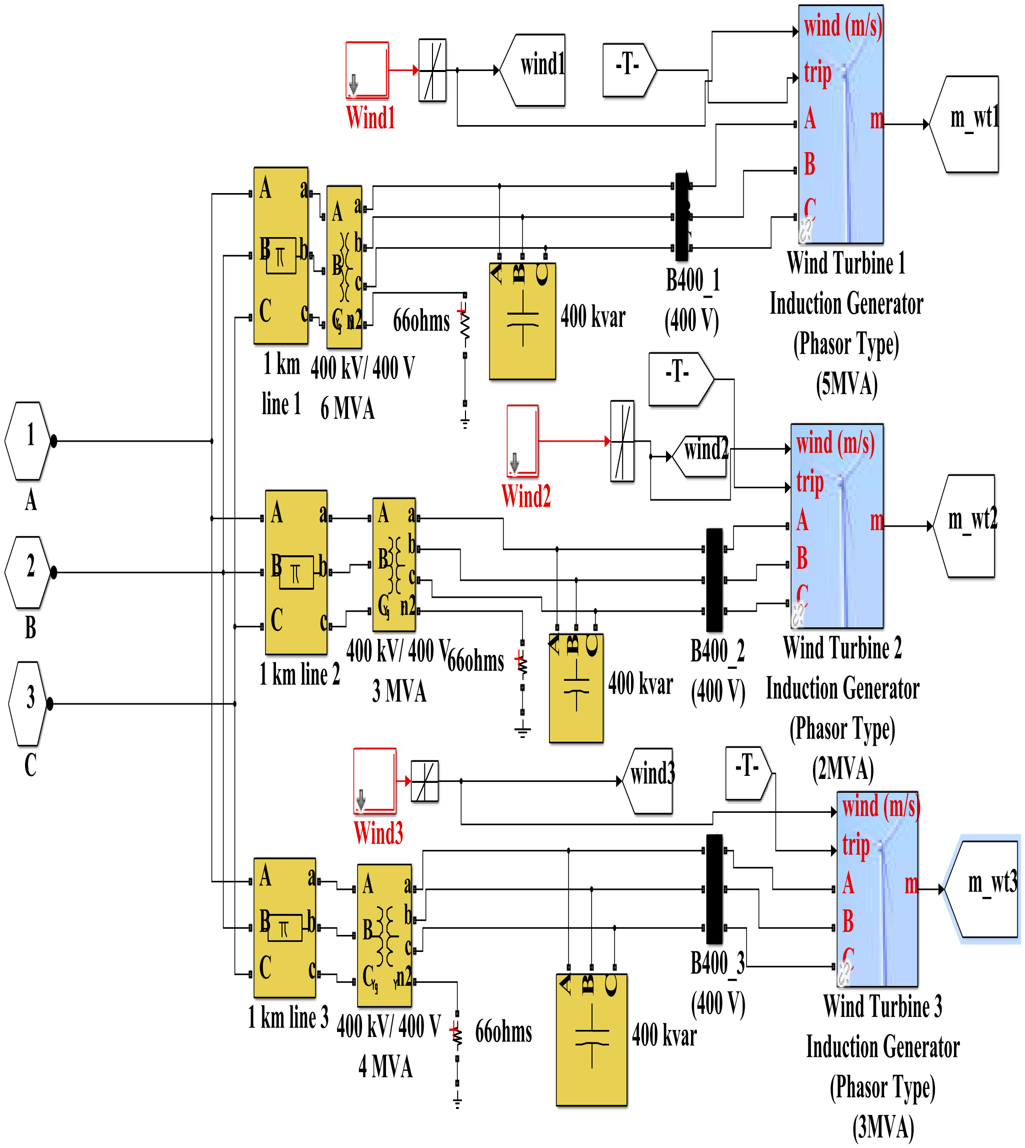

Fig.3.9 Simulink Model of 10 MVA Wind Farm

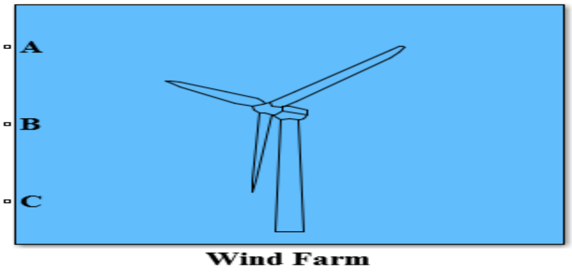

Fig.3.10 Subsystem of Wind Farm

The 10 MVA wind farm is connected to 400-kV distribution system to export power to a 100-kV grid through a 210-km 33kV feeder. The Subsystem of Wind Farm shown in Fig.3.10, has the terminals A, B and C which are used when wind farm is interconnected with conventional grid.

3.5 CONVENTIONAL GRID INTERCONNECTED WITH WIND FARM

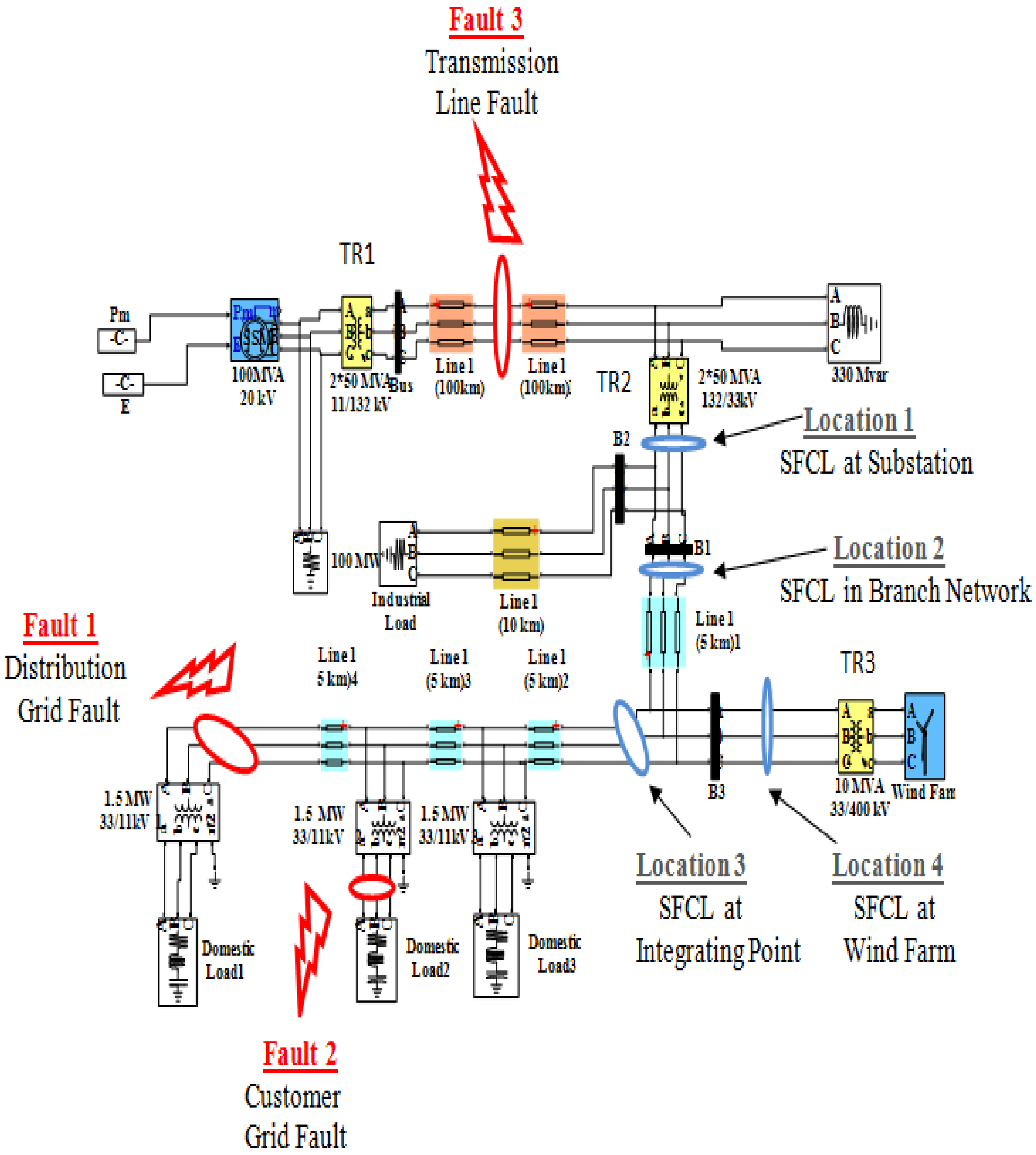

Fig.3.11 Power System Model designed in Simulink/SimPowerSystem with Fault and SFCL Locations

A complete smart grid power network including generation, transmission, and distribution with an integrated wind farm model was also implemented in Matlab/Simulink/SimPowerSystem. The power system model with fault and SFCL locations is shown in Fig.3.11. The power system is composed of a 100 MVA conventional power plant, of 3-phase synchronous machine, connected with 200 km long 154 kV distributed-parameters transmission line through a step-up transformer TR1. At the substation (TR2), voltage is stepped down to 33 kV from 154 kV. High power industrial load (6 MW) and low power domestic loads (1 MW each) are being supplied by separate distribution branch networks as shown in Fig.3.11.

The wind farm is directly connected with the branch network (B1) through transformer TR3 and is providing power to the domestic loads. The 10 MVA wind farm is composed of three fixed-speed induction-type wind turbines having a rating of 5MVA, 3MVA and 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.3.11 fault locations and locations of SFCL are indicated.

Three kinds of fault points are marked as Fault1, Fault 2 and Fault 3, which represent three-phase-to-ground faults in distribution grid, customer grid and transmission line respectively. Four prospective locations for SFCL installation are marked as Location 1 (Substation), Location 2 (Branch Network), Locations 3 (Wind farm integration point with the grid) and Location 4 (Wind Farm). The output current of wind farm (the output of TR3 in Fig.3.11) for various SFCL locations are measured and analyzed in next chapter for determining the optimum location of SFCL in a micro grid.

In this chapter the Simulink model of resistive type SFCL, the implementation of SFCL in three phase system and in conventional grid interconnected with wind farm and various loads have been design in Matlab/Simulink. The analysis of this system will discuss in next chapter.

CHAPTER-4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

After design and implementing the model of resistive type SFCL in simple three phase system and also in wind farm interconnected with conventional grid in Matlab/Simulink the results are obtained. The current and voltage waveforms are compared with and without SFCL in different operating conditions like steady state, fault etc. In the conventional grid interconnected with wind farm and various loads, the current waveforms of all the buses in steady state, fault without SFCL and fault with SFCL in different locations are analyzed and compared.

4.2 THE IMPLEMENTATION OF SFCL IN THREE PHASE SYSTEM

Due to the increased fault-level currents, SFCL is more likely to penetrate into a low voltage and medium voltage transmission network to improve their stability and lower the electric devices capacity. Therefore it is important to model a SFCL in power system to analyze its performance and study its characteristics. A SFCL model is integrated into a three system to simulate its performance in a grid.

4.2.1 THREE PHASE SYSTEM IN STEADY STATE CONDITION

The three phase system shown in Fig.3.4 is in steady state condition or normal condition that means there is no fault in this condition. A three-phase system has been triggered at time 0.1 s and lasts till the end of the simulation. The magnitude of current and voltage is 200A and 20 kV as shown in Fig.4.1 and Fig.4.2 respectively.

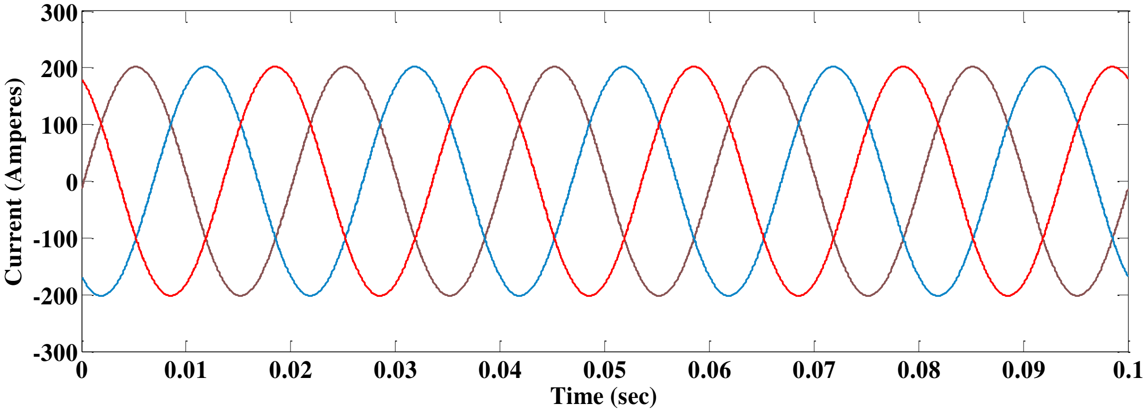

Fig.4.1 Three Phase Current Waveform at Steady State Condition

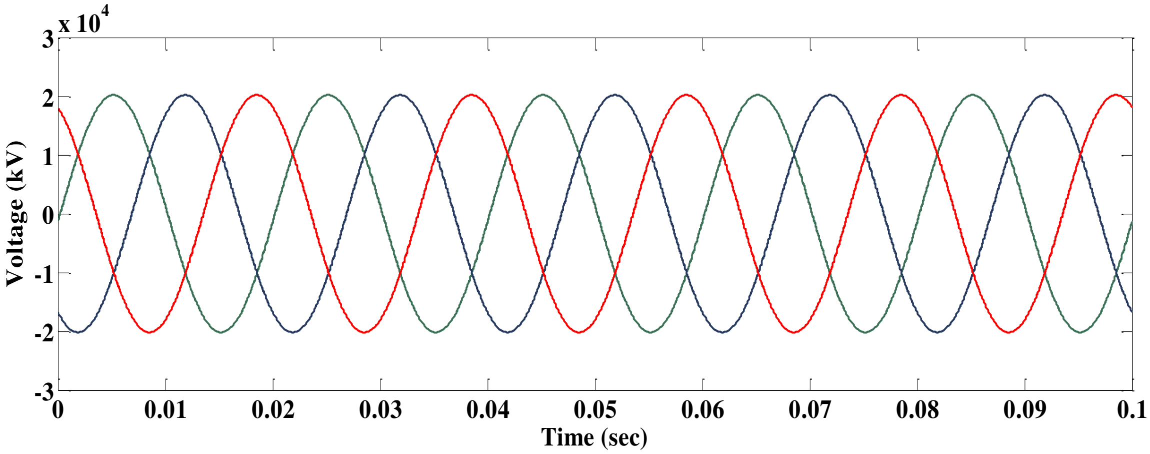

Fig.4.2 Three Phase Voltage Waveform at Steady State Condition

4.2.2 THREE PHASE SYSTEM IN FAULT CONDITION WITHOUT SFCL

As shown in Fig.4.3, the simulation power system includes a power source, and a load. A three-phase to ground fault has been triggered at time 0.0s and lasts till the end of the simulation. From Fig.4.4, it could be noted that when there is no SFCL applied in the system, the peak value of the three-phase fault current could be as high as about 3kA. Fig.4.5. shows that voltage drop to zero in faulty condition.

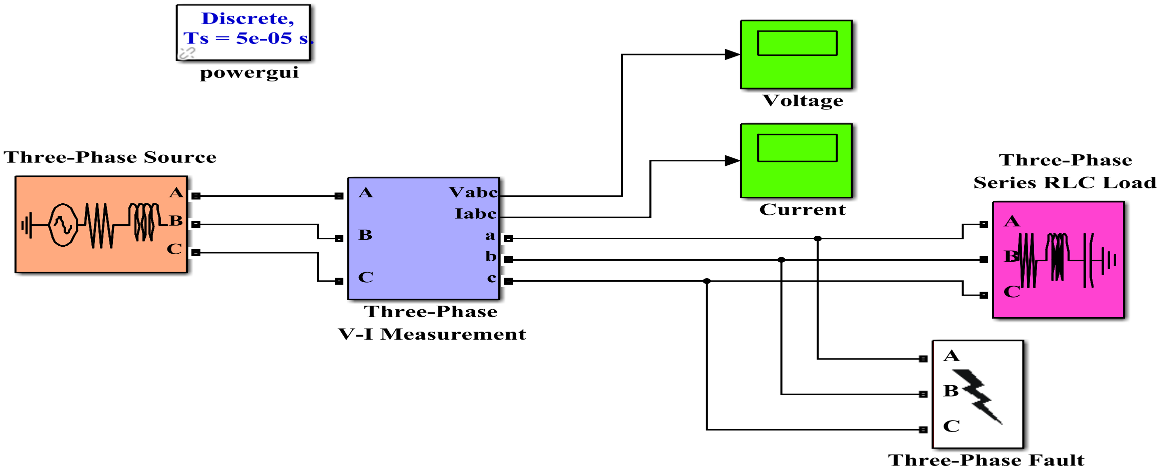

Fig. 4.3 Three Phase System in Fault Condition without SFCL

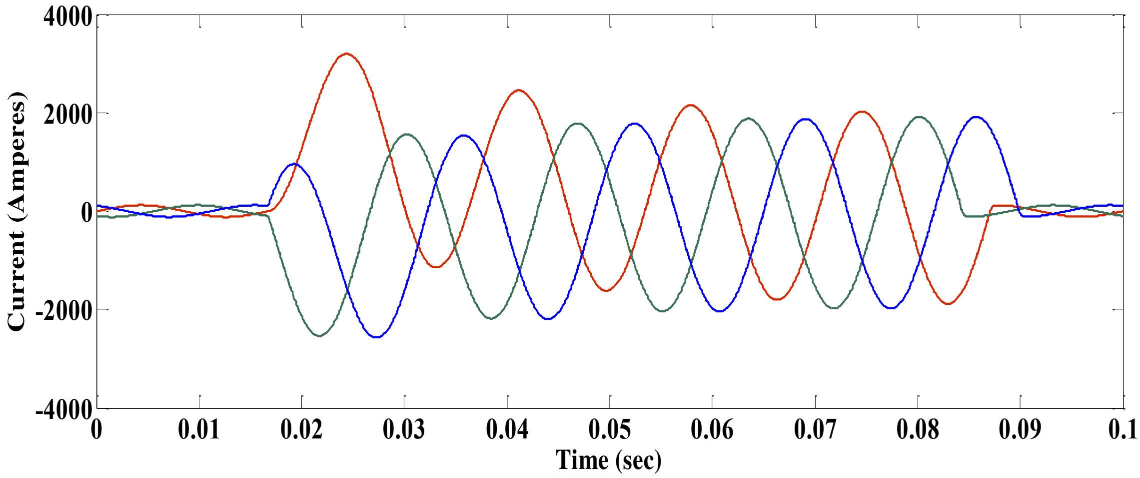

Fig.4.4

Three Phase Current Waveform during Fault Condition without SFCL

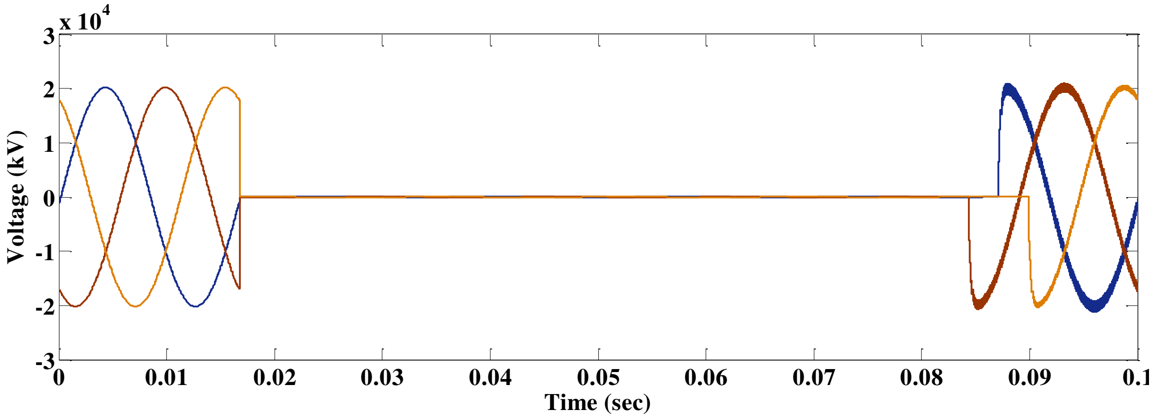

Fig.4.5 Three Phase Voltage Waveform during Fault Condition without SFCL

4.2.3 THREE PHASE SYSTEM IN FAULT CONDITION WITH SFCL

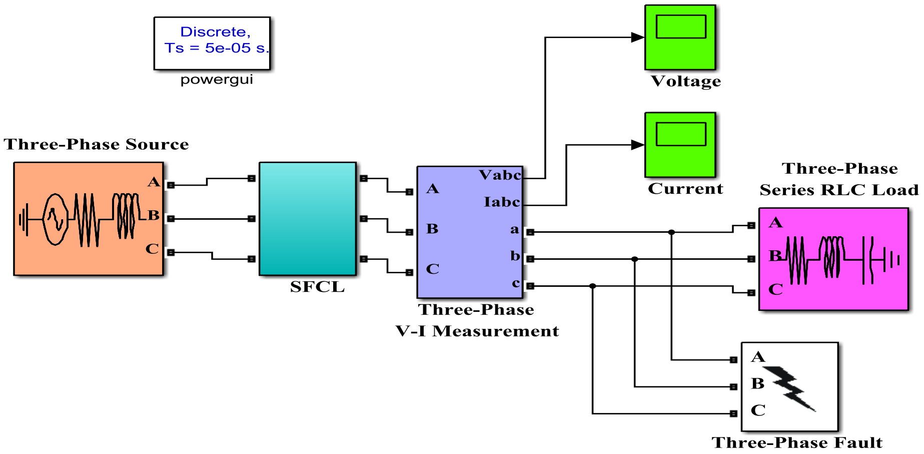

Fig.4.6 Three Phase System in Fault Condition with SFCL

In faulty condition the magnitude of fault current could be high as about 3 kA. This high magnitude of fault current has to be reduced within the rating of protective equipments. This can be achieved by implementing the SFCL in three phase system as shown in Fig.4.6. The presence of SFCL in the system reduces the peak value of three phase fault current to 400A as shown in Fig.4.7 and also builds up the voltage to 20kV as shown in Fig.4.8. When flowing current is greater than critical current and temperature is greater than critical temperature of superconducting material then there is transition from superconducting state to normal state, in normal state it adds higher resistance (20ohm). The product of this resistance and flowing current is applied to the input of controlled voltage source. This controlled voltage source builds up voltage in fault condition, thus reduces the current automatically. The critical current and critical temperature has been taken as 550A and -193°C respectively.

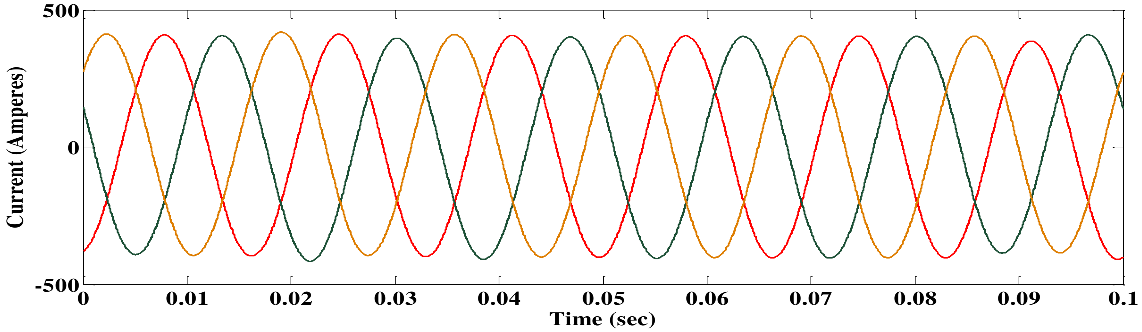

Fig.4.7 Three Phase Current Waveform during Fault Condition with SFCL

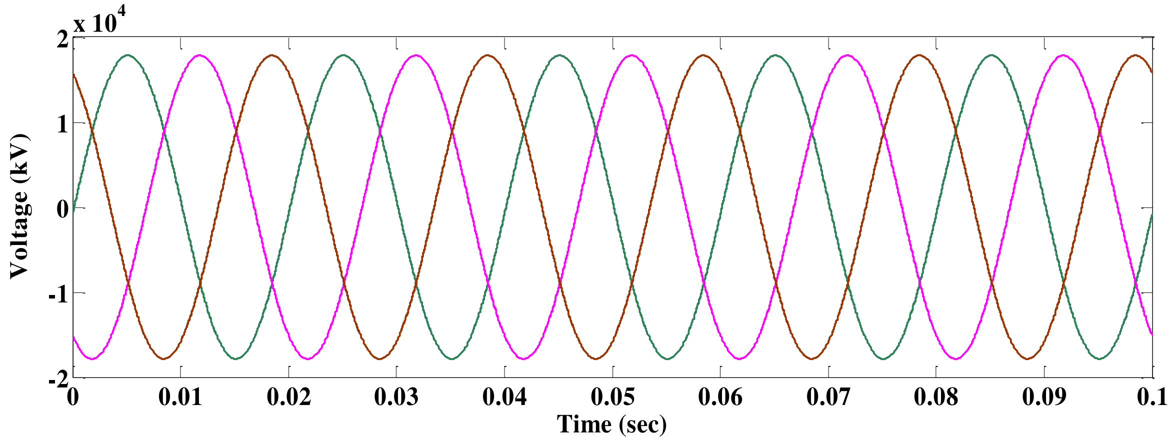

Fig.4.8 Three Phase Voltage Waveform during Fault Condition with SFCL

4.2.4 THREE PHASE SYSTEM IN STEADY STATE CONDITION WITH SFCL

The most common ways of handling this fault current are by using air core reactor, fuses and circuit breakers. Air core reactor although commonly used but are undesirable because it causes continuous voltage drop and power loss during normal system operation. However these undesirable effects can be reduced by implementing SFCL in the system, the advantage of implementing SFCL in the system is that in normal or steady state condition it offers zero resistance thus there is no voltage drop and power loss. As shown in Fig.4.9 the three phase system is in steady state condition with SFCL.

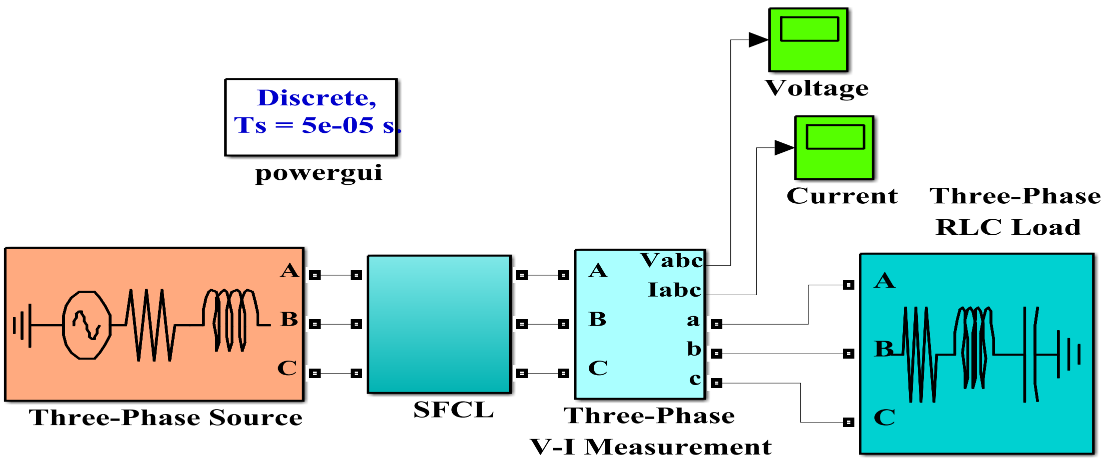

Fig.4.9

Three Phase System at Steady State Condition with SFCL

The magnitude of current and voltage waveforms obtained in this case is same as in the waveforms obtained in three phase system at steady state condition. When flowing current is less than critical current and temperature is less than critical temperature of superconducting material, that means system is in normal condition and superconductivity also achieves, thus it adds minimum resistance (0.01ohm) in normal condition due to this negligible resistance, power loss and voltage drop also negligible as shown in Fig.4.10 and Fig.4.11 respectively.

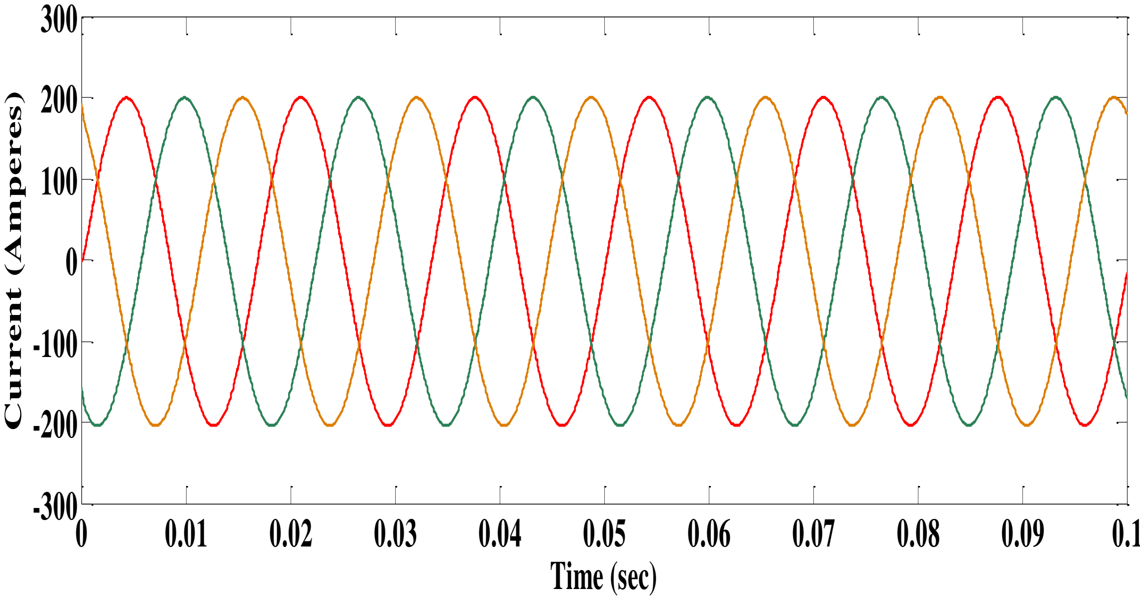

Fig.4.10 Three Phase Current Waveform at Steady State Condition with SFCL

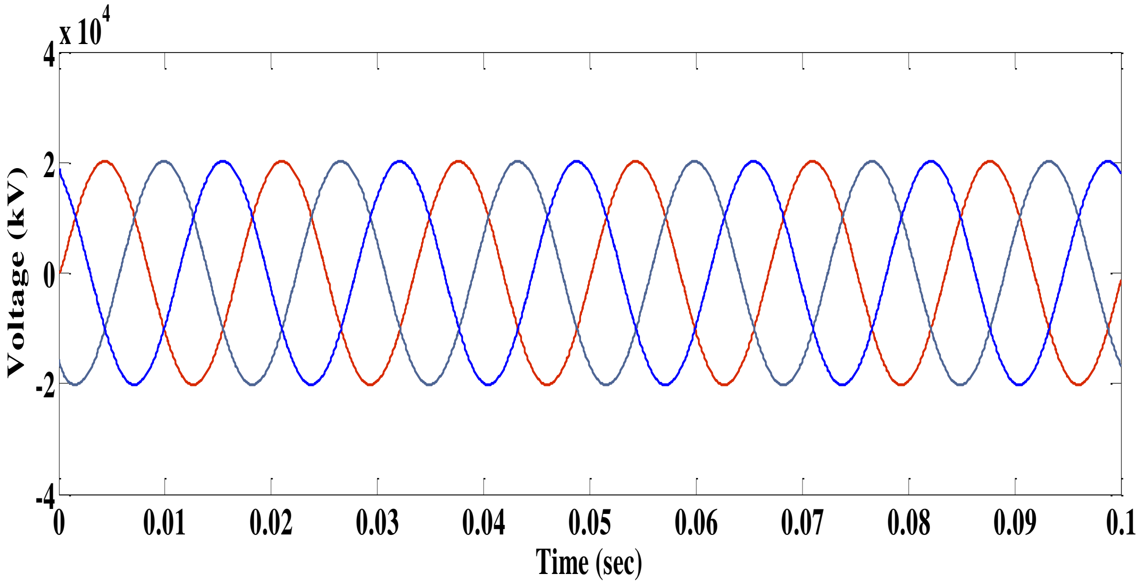

Fig.4.11 Three Phase Voltage Waveform at Steady State Condition with SFCL

When flowing current is less than critical current and temperature is greater than critical temperature of superconducting material then there is transition from superconducting state to normal state because its superconductivity destroys, in normal state it works as normal conductor thus it adds higher resistance (20ohm). And due to this resistance there is power loss and voltage drop as shown in Fig4.12 and Fig.4.13 respectively.

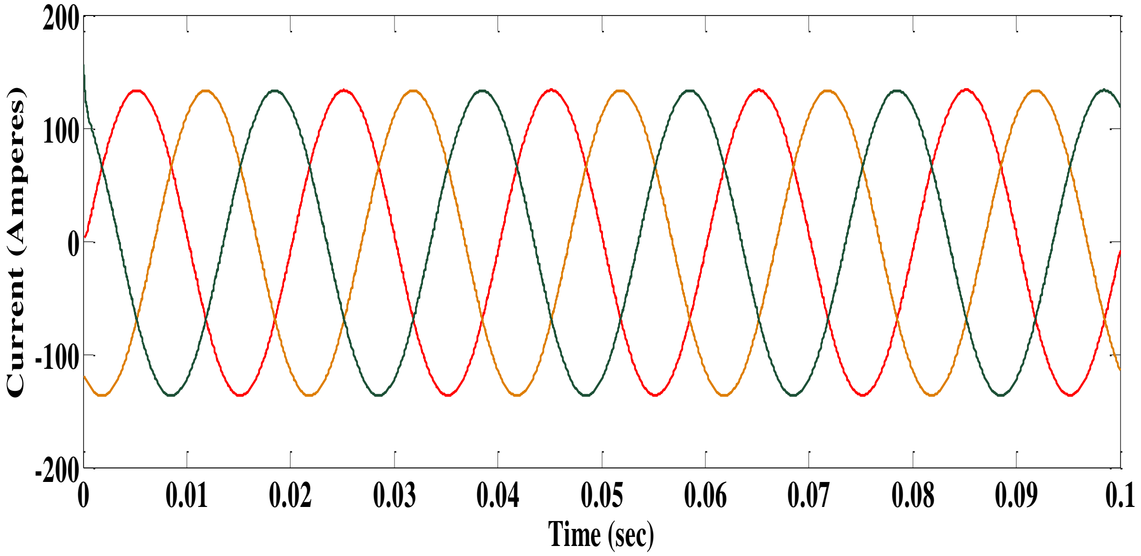

Fig.4.12 Three Phase Current Waveform when Superconductivity Destroys

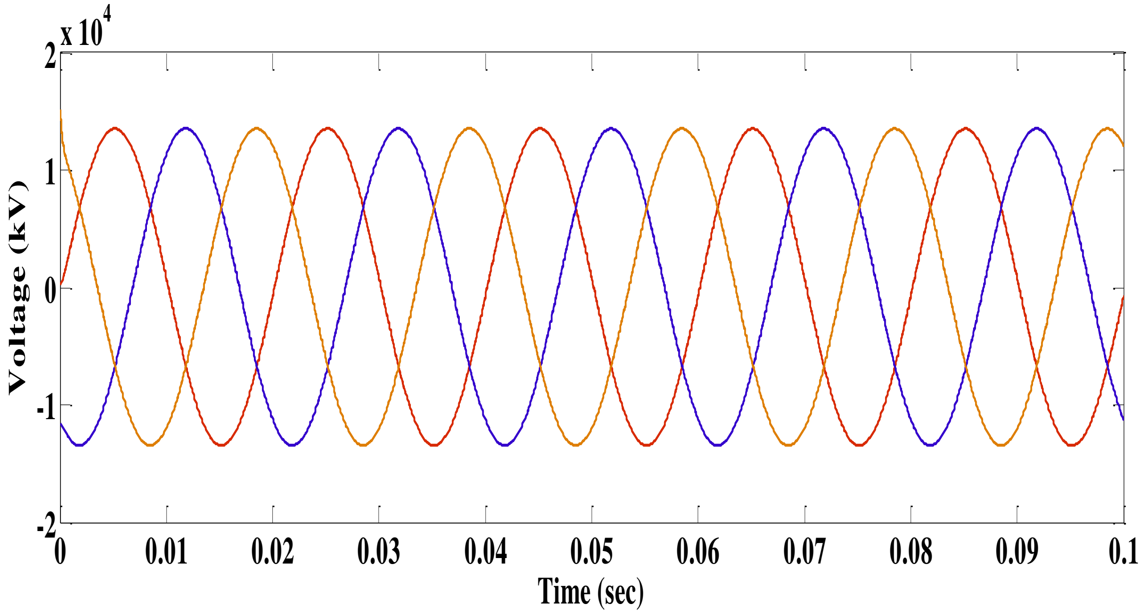

Fig.4.13 Three Phase Voltage Waveform when Superconductivity Destroys

4.2.5 THREE PHASE SYSTEM IN STEADY STATE CONDITION WITH INDUCTOR

The most common ways of handling this fault current are by using air core reactor, fuses and circuit breakers. Air core reactor although commonly used but are undesirable because it causes continuous voltage drop and power loss during normal system operation. This has been analyzed by the investigator by introducing an inductor in the place of SFCL in the three phase system as shown in Fig.4.14. The voltage drop due to this inductor is shown in Fig.4.15.When SFCL has been placed in the three phase system voltage was 20 kV. But when inductor has been placed the voltage drop is 300V. This gives 98.5% reduced voltage due to inductor.

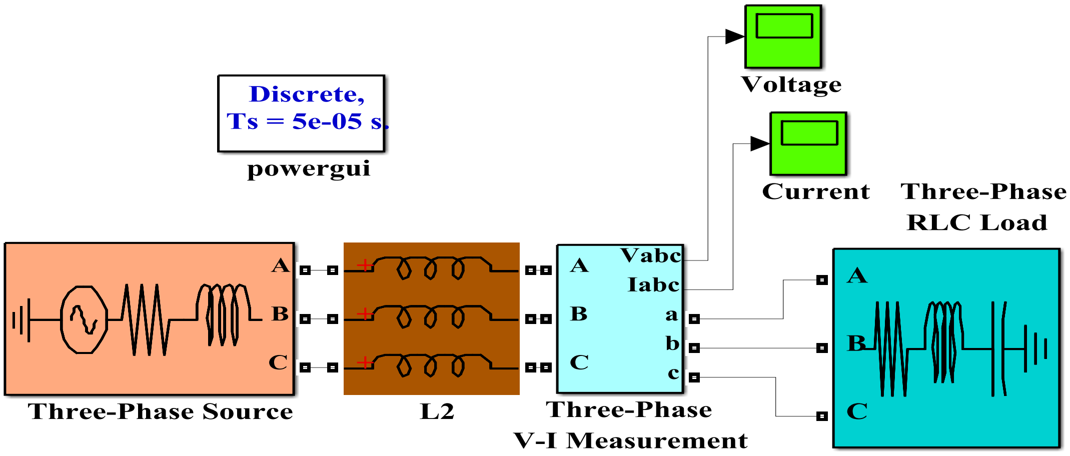

Fig.4.14 Three Phase System with Inductor

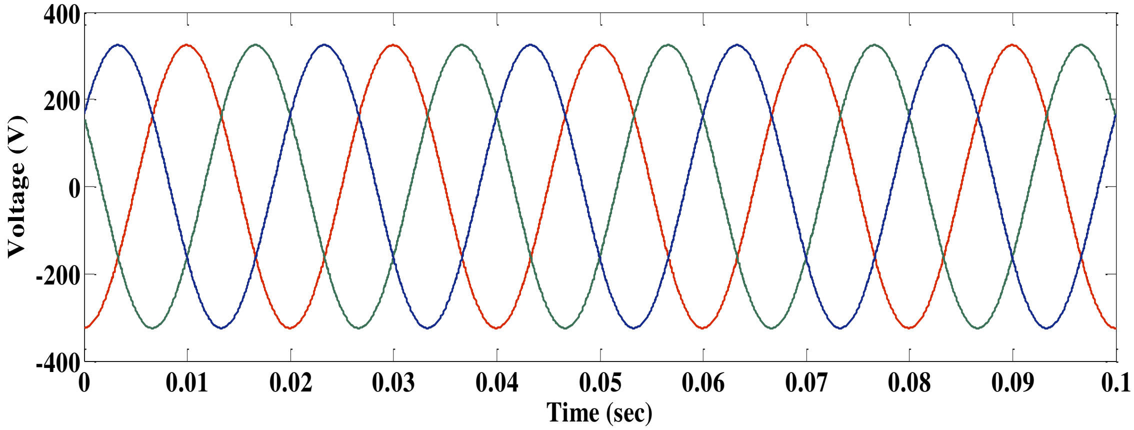

Fig.4.15 Three Phase Voltage Drop due to Inductor

The comparison of current in three phase system under steady state condition, fault condition without SFCL and fault with SFCL is shown in Fig.4.16. The comparison shows that after implementing SFCL in the three phase system, the fault current is reduced from 3kA to 400A.

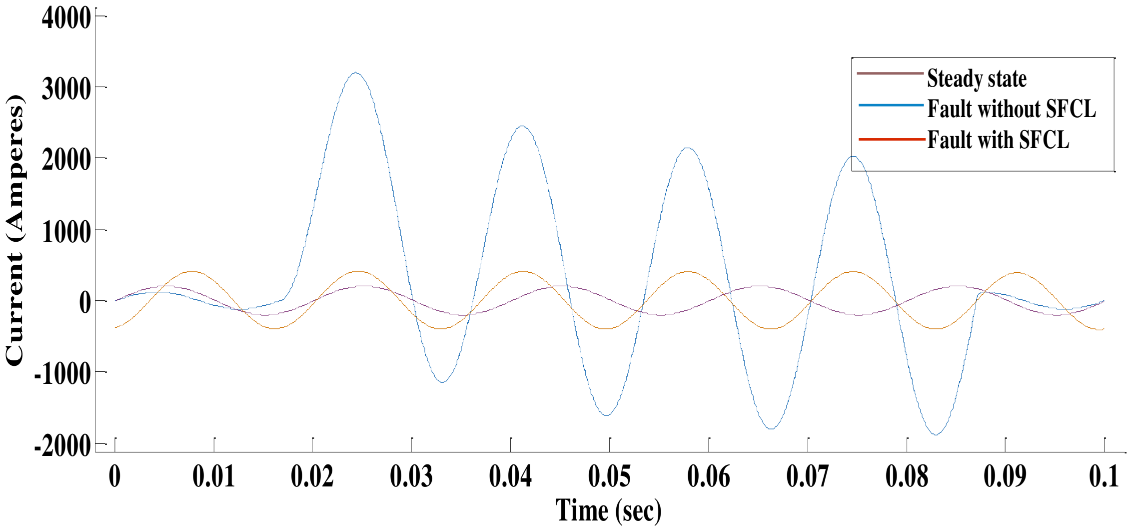

Fig.4.16 Comparison of Currents in Three Phase System under Different Conditions

Table 4.1 shows the current limitation rate during steady state condition, fault condition without SFCL and fault with SFCL condition. In steady state condition peak value of current is 200A with and without SFCL, but when fault occurs peak value of current increase upto 3kA. The presence of SFCL reduces the peak value upto 400A.This gives 50% reduction in fault current.

Table 4.1 Current Limitation Rate in a Three Phase Simulation System

S.No	Item	Current Peak value under Normal Operation	Current Peak value during Fault	Rate of Limitation
1.	without SFCL	200A	3kA	0%
2.	with SFCL	200A	400A	50%

4.3 CONVENTIONAL GRID INTERCONNECTED WITH WIND FARM

The power system is composed of a 100 MVA conventional power plant, 10MVA wind farm and different types of loads as shown in Fig.3.11. Three phase to ground faults have been simulated to occur at different locations in the power system such as (i) Distribution Grid (Fault 1), (ii) Customer grid (Fault 2) and (iii) Transmission Line (Fault 3). The investigator analyzed the performance of the power system at the occurrence of each of the faults and also the effect of the SFCL implementation in the system. Performance of the system with SFCL installed at four different locations such as (i) at Substation (Location 1) (ii) at Branch Network (Location 2) (iii) at the Wind Farm integration point with grid (Location 3) (iv) at Wind Farm (Location 4).

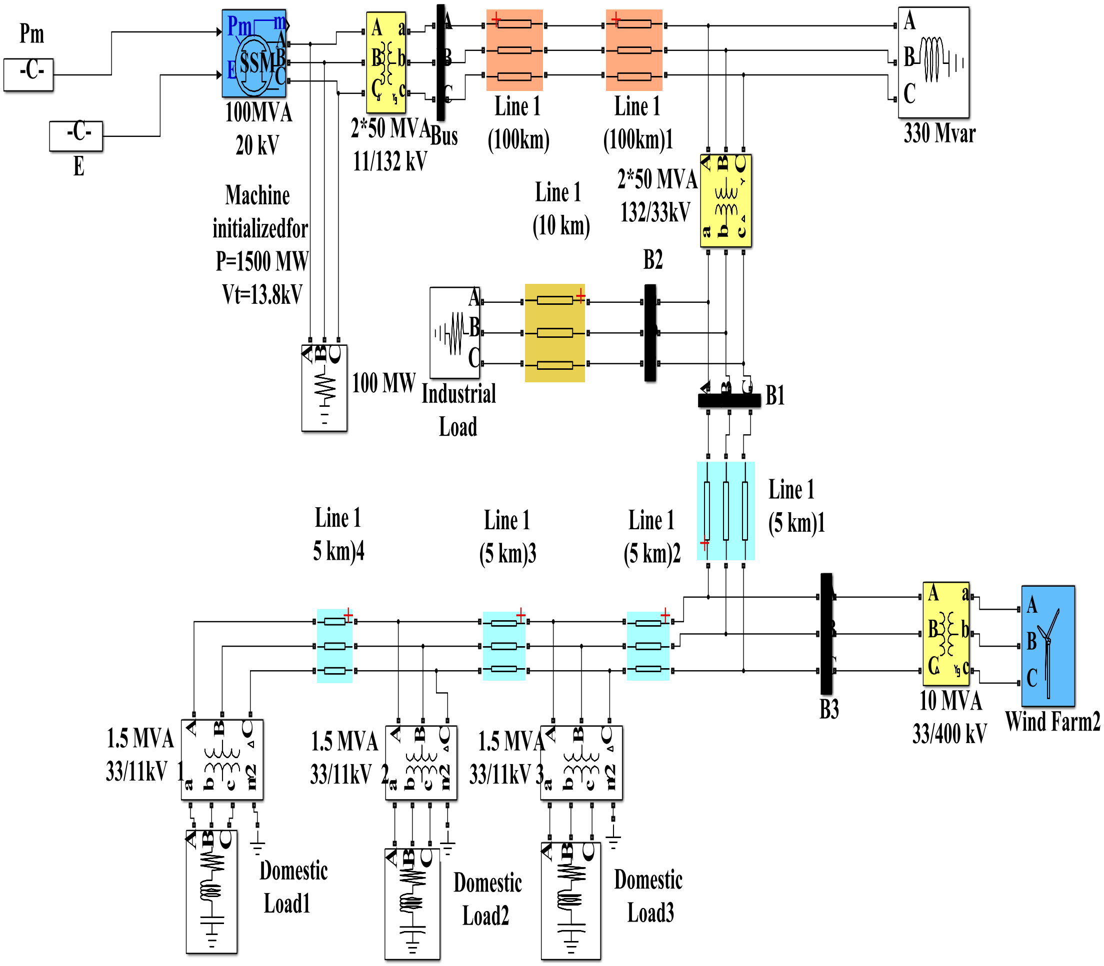

Fig.4.17 Power System Model, with no Fault and no SFCL

4.3.1 ANALYSIS IN STEADY STATE CONDITION WITHOUT SFCL

The conventional grid interconnected with wind farm is in steady state condition when there no fault occurs in this system and thus no SFCL has been placed as shown in Fig.4.17. The current waveforms obtained from all the buses (B, B1, B2 and B3) through scope were analyzed. The comparison of all the currents from different buses is shown in Fig.4.18.The magnitudes of current in different buses are shown in Table 4.2.

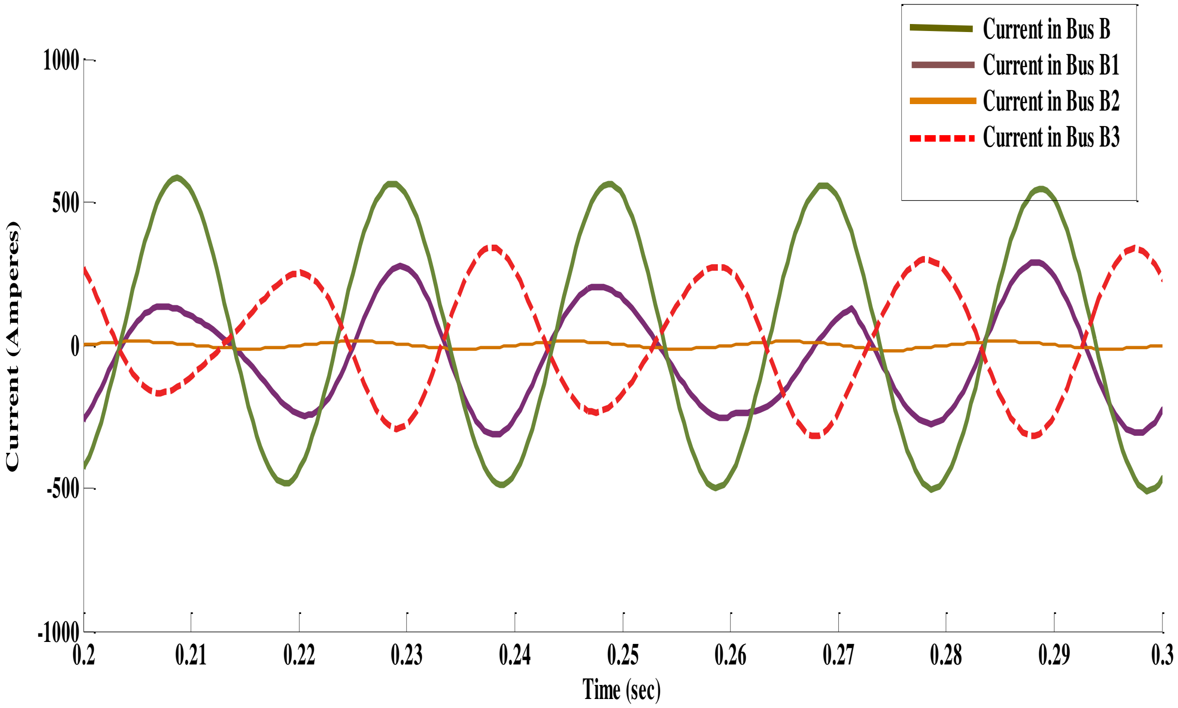

Fig.4.18 Comparison of Current at the Different Buses (B-B3) in Steady State Condition

Table 4.2 Current Magnitude in Steady State Condition

S. No	Different Buses	Current (A)
1.	B	500
2.	B1	200
3.	B2	50
4.	B3	250

4.3.2 ANALYSIS IN FAULT CONDITION WITHOUT SFCL

In this case fault has been applied first in the distribution grid, then in customer grid, and then in transmission line. Magnitude of fault current is different in all case as shown in Fig.4.19, Fig.4.20 and Fig.4.21.

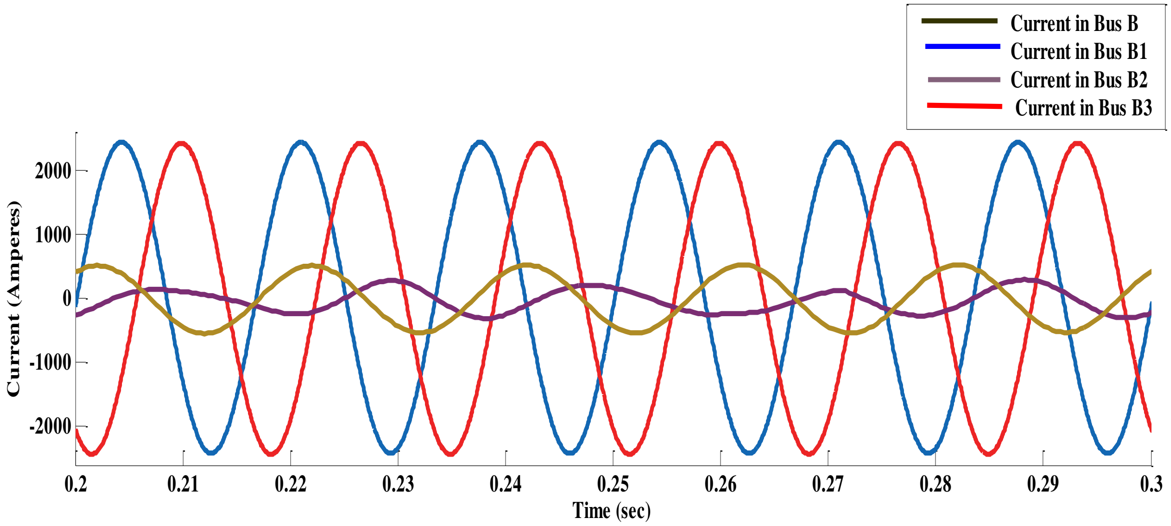

Fig.4.19 Comparison of Current of Buses (B-B3) when Fault in Distribution Grid (Fault 1) without SFCL

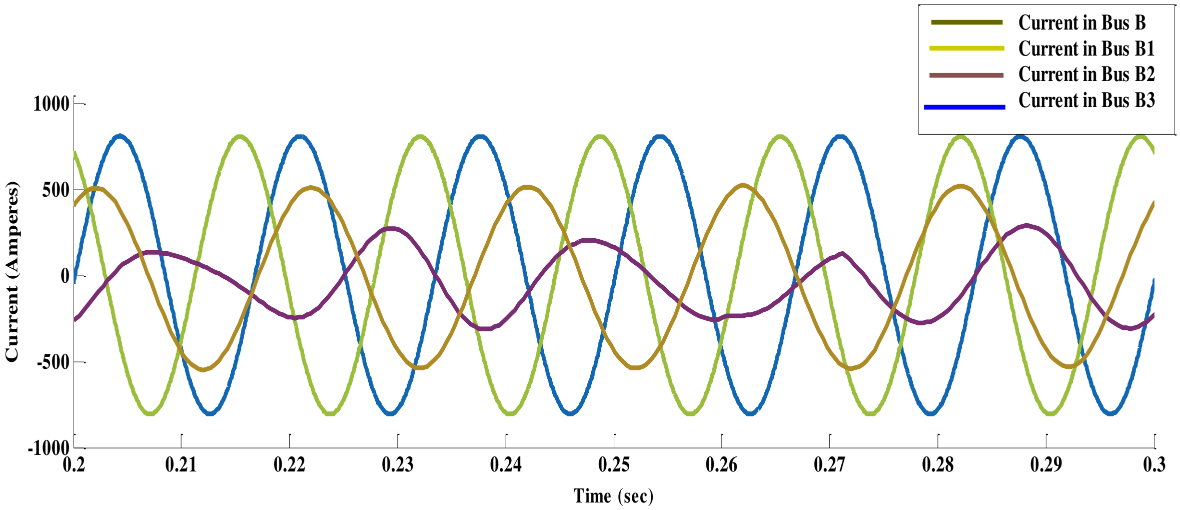

Fig.4.20 Comparison of Current of Buses (B-B3) when Fault in Customer Grid (Fault 2) without SFCL

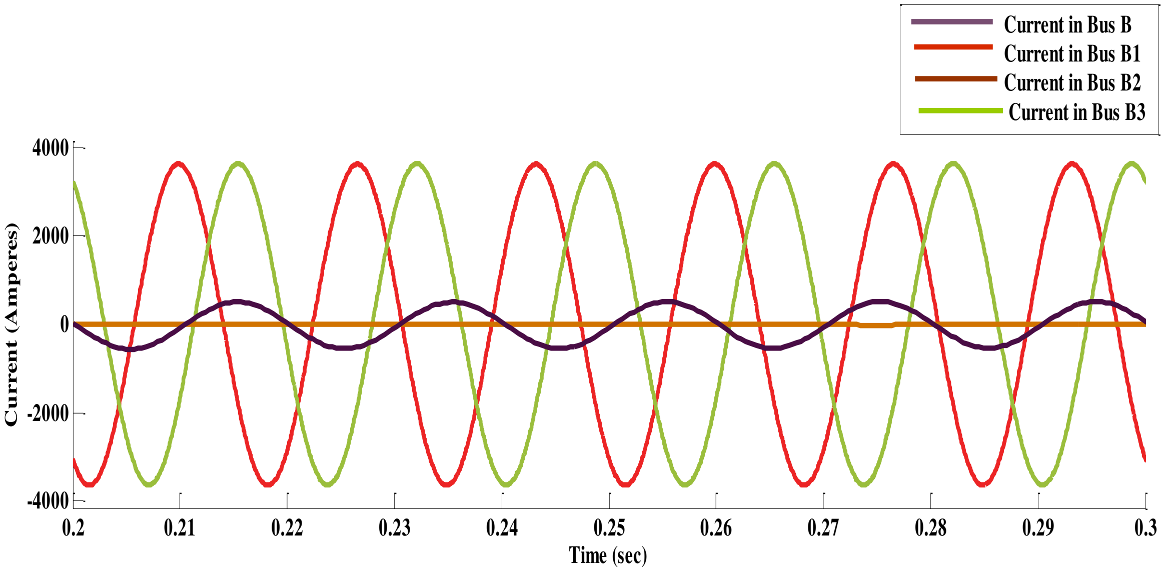

Fig.4.21 Comparison of Current of Buses (B-B3) when Fault in Transmission Line (Fault 3) without SFCL

Table 4.3 Current Magnitude when Fault in Distribution Grid without SFCL

S. No	Different Buses	Current(A)
1.	B	700
2.	B1	2500
3.	B2	600
4.	B3	2500

Table 4.4 Current Magnitude when Fault in Customer Grid without SFCL

S. No	Different Buses	Current(A)
1.	B	400
2.	B1	800
3.	B2	300
4.	B3	800

Table 4.5 Current Magnitude when Fault in Transmission Line without SFCL

S. No	Different Buses	Current(A)
1.	B	700
2.	B1	3500
3.	B2	600
4.	B3	3500

Magnitude of fault current when fault in distribution grid, customer grid and in transmission line is shown in Table 4.3, Table 4.4 and Table 4.5.

4.3.3 FAULT IN THE DISTRIBUTION GRID (FAULT 1) WITH SFCL AT DIFFERENT LOCATIONS

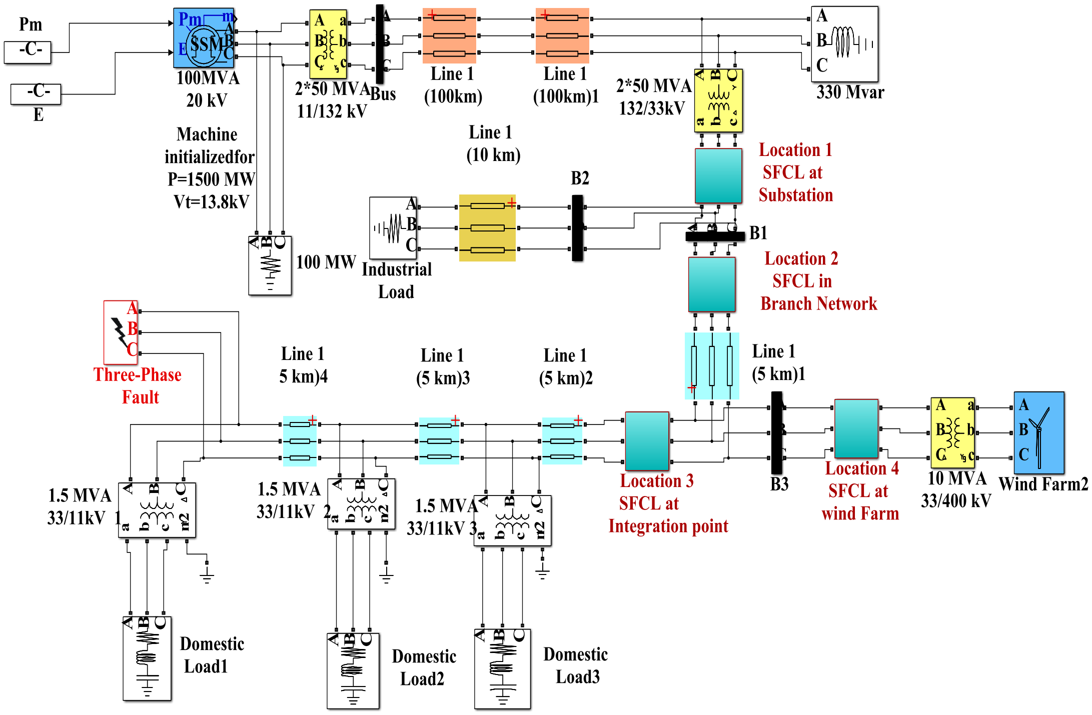

Fig. 4.22 Power System with Fault in the Distribution Grid and SFCL at Different Locations

Fig.4.22 shows the power system with fault in the distribution grid (Fault 1). The current magnitude has been measured at different buses B, B1, B2 and B3 when SFCL is placed at different locations. Fig.4.23 shows that current waveform of different buses with fault in distribution grid and SFCL at substation (Location 1). The fault current contribution from the wind farm (current in Bus B3) is found to be increased and the magnitude of fault current at B3 is higher than 'No SFCL' situation.

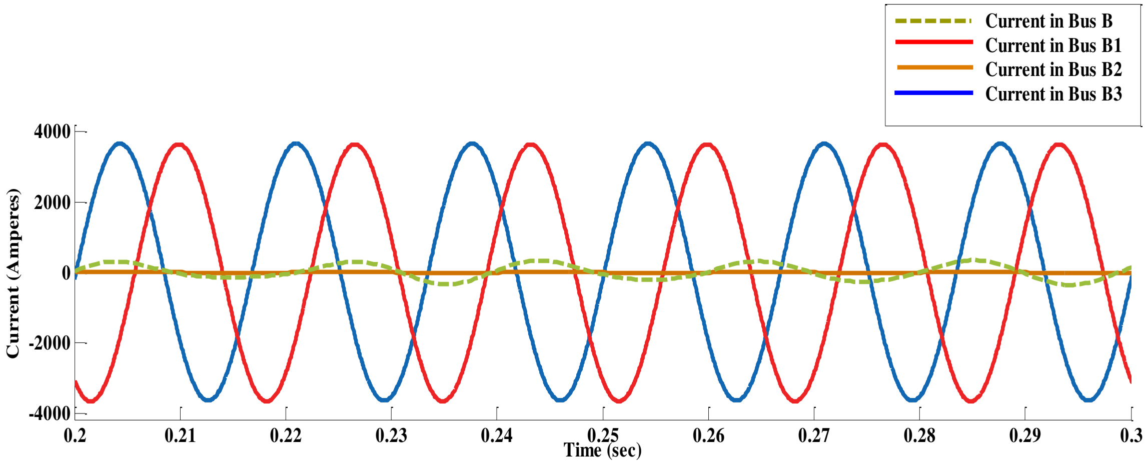

Fig.4.23 Comparison of Current when SFCL at Substation (Location 1) and Fault in Distribution Grid (Fault 1)

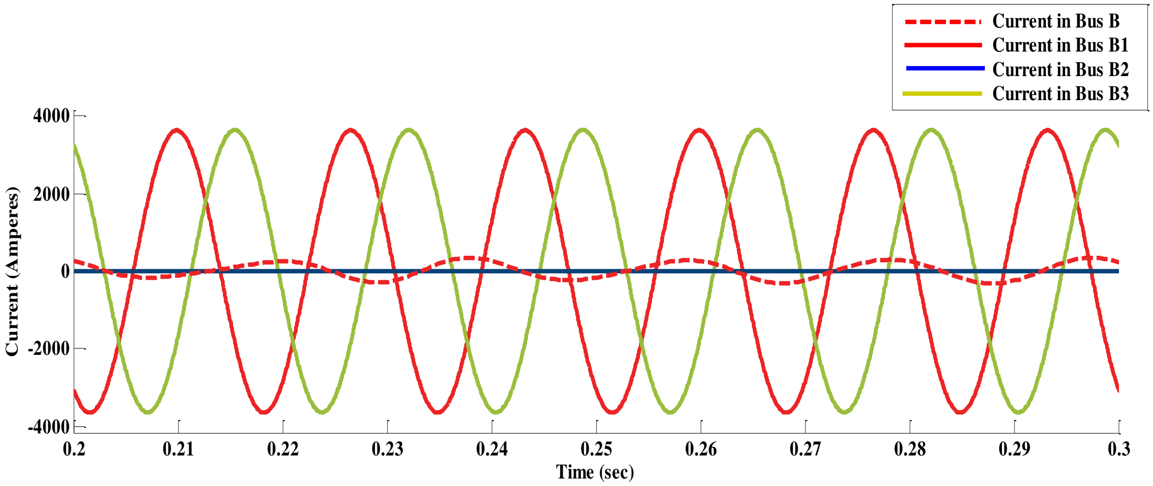

Fig.4.24 Comparison of Current when SFCL in Branch Network (Location 2) and Fault in Distribution Grid (Fault 1)

These critical observations imply that the installation of SFCL in Location1 and Location 2, instead of reducing, has increased the DG fault current. This sudden increase of fault current from the wind farm is caused by the abrupt change of power system impedance.

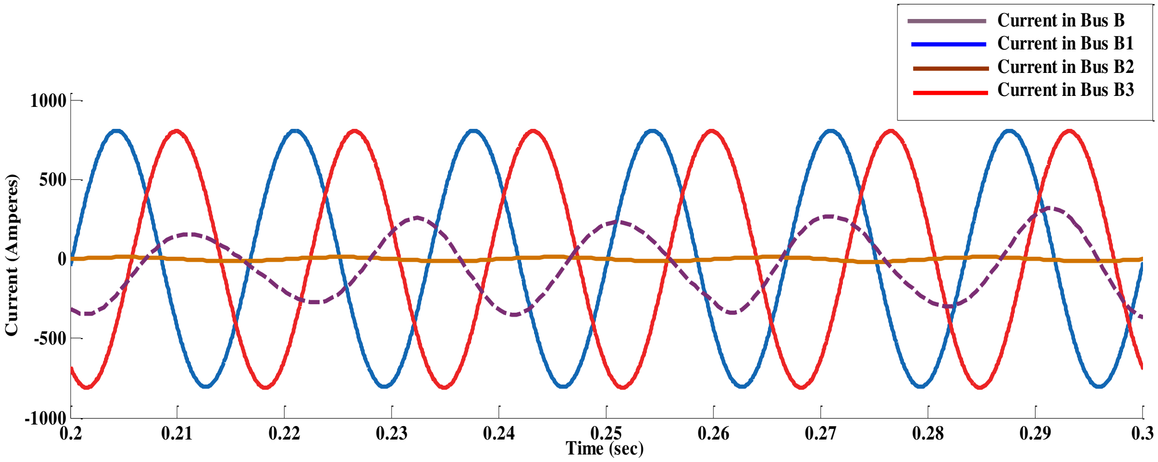

Fig.4.25 Comparison of Current when SFCL at Integration Point (Location 3) and Fault in Distribution Grid (Fault 1)

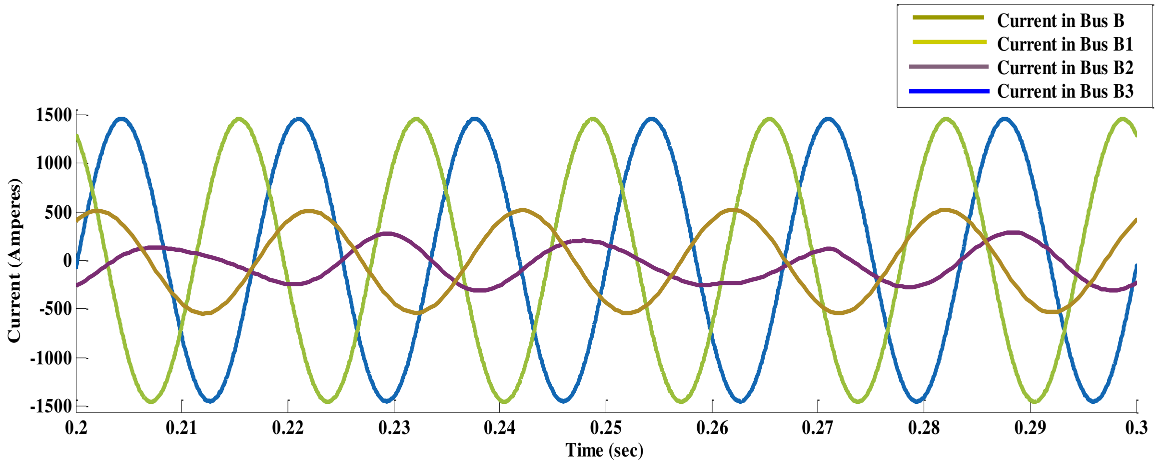

Fig.4.26 Comparison of Current when SFCL in Location 1 and Location 4 and Fault in Distribution Grid (Fault 1)

The fault current contribution from the wind farm (current in Bus B3) has been reduced and the magnitude of fault current is lower than 'No SFCL' situation as shown in Fig.4.25. Installation of two SFCLs in substation (Location 1) and SFCL at wind farm (Location 4) has also been combined and the fault current contribution from the wind farm is analyzed and shown in Fig.4.26.

The fault current from the wind farm (measured at output of TR3) at bus B3 for different SFCL locations when a three-phase-to-ground fault was initiated in the distribution grid (Fault 1) is found to be varying abruptly and is plotted as shown in Fig.4.27. When SFCL is installed at the integration point of wind farm with the grid, (Location 3) the wind farm fault current has been successfully reduced. The SFCL gives 68% reduction of fault current from wind farm and also reduce the fault current coming from conventional power plant because SFCL is located in the direct path of any fault current flowing towards Fault 1.

With dual SFCL installed at Location 1 and Location 4, 40% reduction in fault current is also observed. But installation of two SFCLs (Location 1 and Location 4) is economically and technically not feasible.

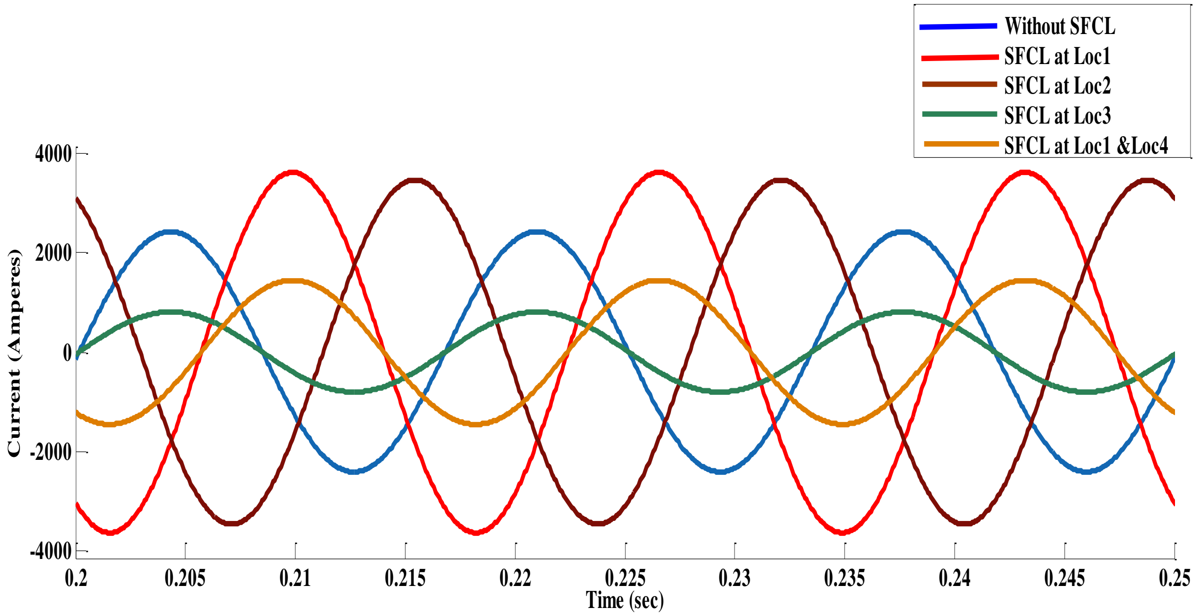

Fig.4.27 Comparison of the Wind Farm Fault Current for SFCL Locations in Case of Fault in Distribution Grid (Fault 1)

Table4.6 shows the magnitudes of fault current from the wind farm (measured at output of TR3) without and with SFCL at different locations and fault in the distribution grid. From Table4.6, it is concluded that optimal location for SFCL installation is this case is location 3.

Table 4.6 Wind Farm Fault Current Magnitude in case of Fault in Distribution Grid (Fault1), for Different SFCL Locations

S. No	With and without SFCL	Current (A)
1.	Without SFCL	2500
2.	SFCL in location 1	3500
3.	SFCL in location 2	3400
4.	SFCL in location 3	800
5.	SFCL in location 1 and location 4	1500

4.3.4 FAULT IN CUSTOMER GRID (FAULT 2) WITH SFCL AT DIFFERENT LOCATIONS

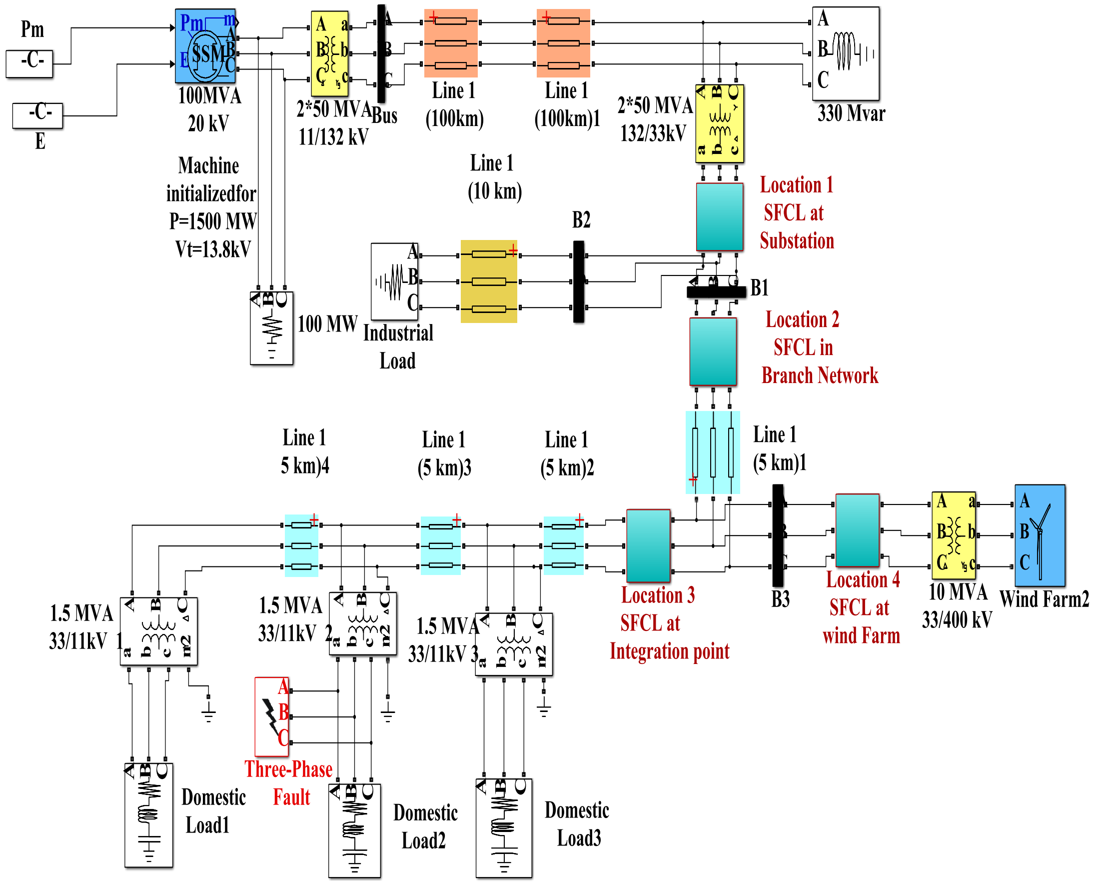

Fig. 4.28 Power System with Fault in Customer Grid and SFCL at Different Location

Fig.4.28 shows the power system with fault in the customer grid (Fault 2). Fault2 is comparatively a small fault as it occurred in low voltage customer side distribution network. The current magnitude has been measured at different buses B, B1, B2 and B3 when SFCL is placed at different locations. Fig.4.29 shows the current waveform of different buses with fault in customer grid and SFCL at Substation (Location 1). The fault current contribution from the wind farm (current in Bus B3) is found to be increased and the magnitude of fault current at B3 is higher than 'No SFCL' situation.

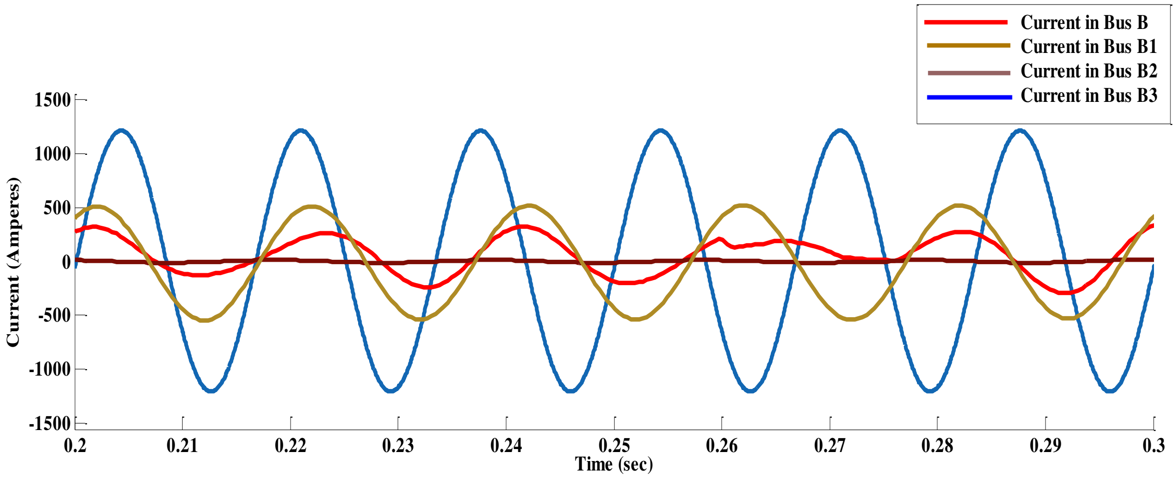

Fig.4.29 Comparison of Current when SFCL at Substation (Location 1) and Fault in Customer Grid (Fault 2)

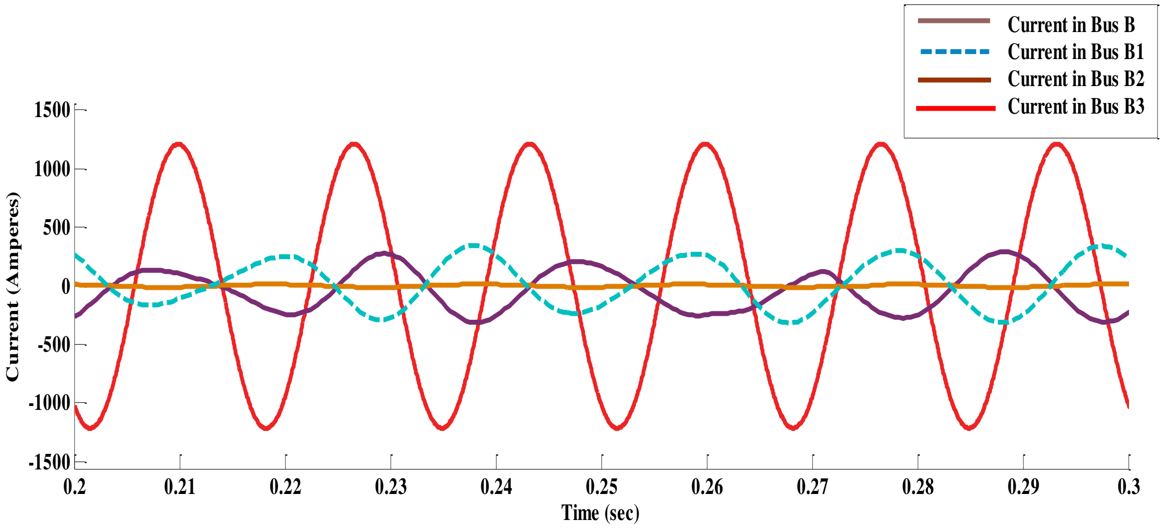

Fig.4.30 Comparison of Current when SFCL in Branch Network (Location 2) and Fault in Customer Grid (Fault 2)

The SFCL located in Location 3(intregating point), in this case the comparison of all buses current shown in Fig.4.31. The fault current contribution from the wind farm (current in Bus B3) has been reduced and the magnitude of fault current is lower than 'No SFCL' situation as shown in Fig.4.31. Installation of two SFCLs at substation (Location 1) and SFCL at wind farm (Location 4) has also been considered and the fault current contribution from the wind farm is analyzed and shown in Fig.4.32.

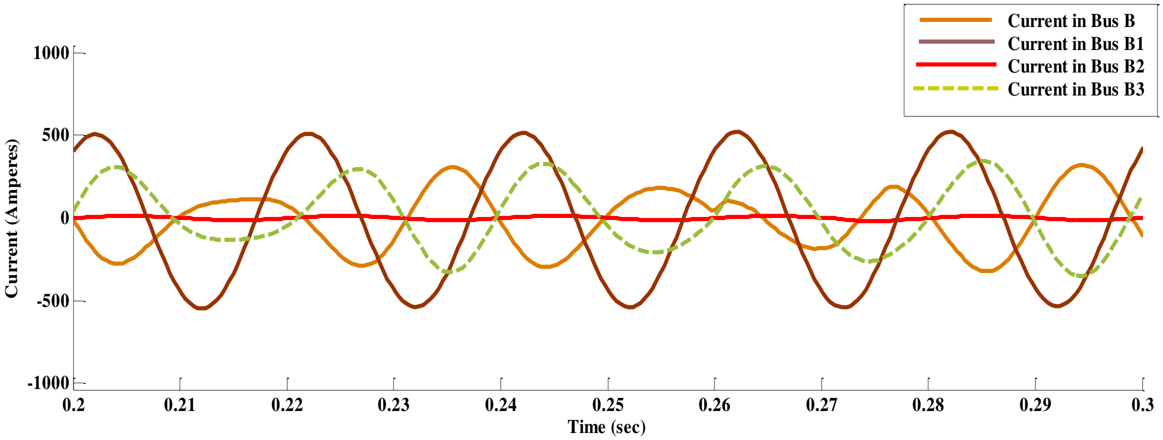

Fig. 4.31 Comparison of Current when SFCL at Integration Point (Location 3) and Fault in Customer Grid (Fault 2)

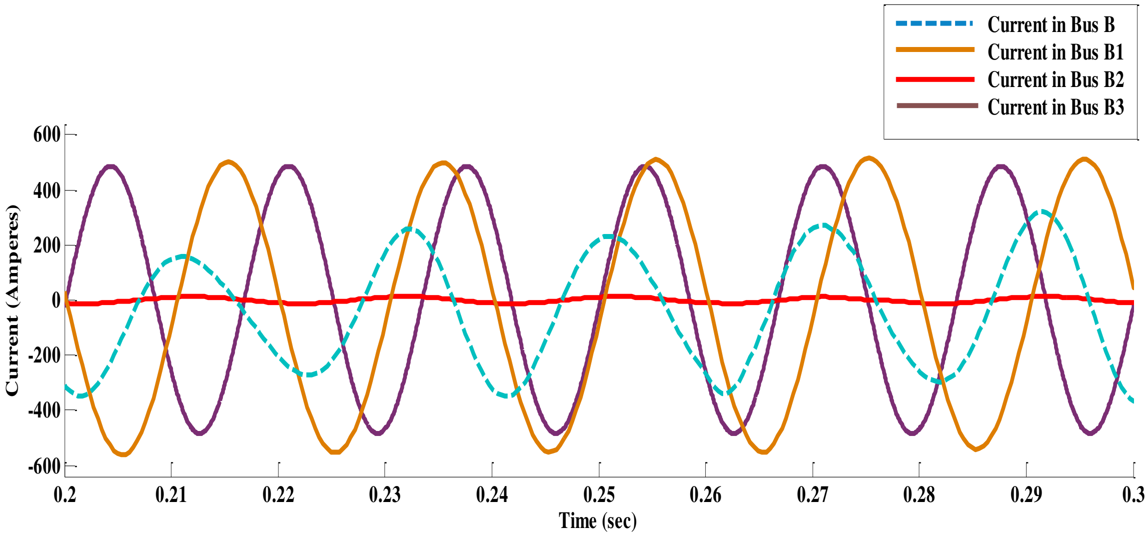

Fig.4.32 Comparison of Current when SFCL in Location1 and Location4 and Fault in Customer Grid (Fault 2)

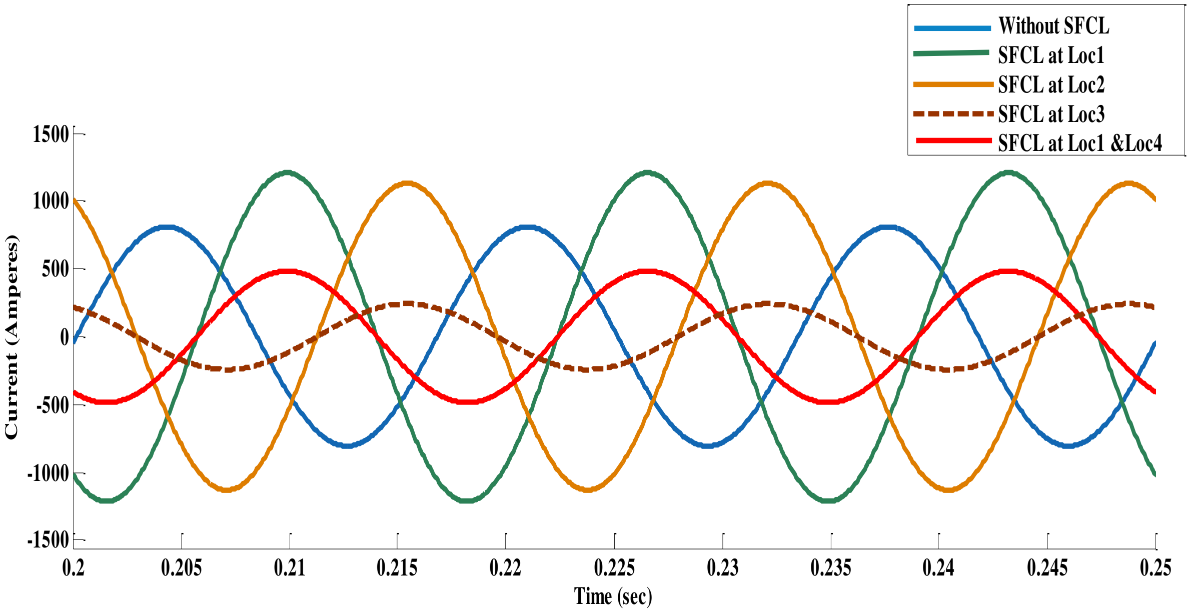

Fig. 4.33 Comparison of the Wind Farm Fault Current SFCL Locations in Case of Fault in Customer Grid (Fault2)

The fault current from the wind farm (measured at output of TR3) at bus B3 for different SFCL locations when a three-phase-to-ground fault was initiated in the customer grid (Fault 2). The results obtained are similar to what were observed in the case of distribution grid (Fault 1). Once again the best results are obtained when a single SFCL is located at Location 3, which is the integration point of the wind farm with the distribution grid.

Table 4.7 Wind Farm Fault Current Magnitude in case of Fault in Customer Grid (Fault 2), for Different SFCL Locations

S. No	With and without SFCL	Current(A)
1.	Without SFCL	800
2.	SFCL in location 1	1200
3.	SFCL in location 2	1100
4.	SFCL in location 3	250
5.	SFCL in location 1 and location 4	500

Table4.7 shows the magnitudes of fault current from the wind farm (measured at output of TR3) without and with SFCL at different locations and fault in the customer grid. From Table4.7, it is concluded that optimal location for SFCL installation is this case is location 3.

4.3.5 FAULT IN TRANSMISSION LINE (FAULT3) WITH SFCL AT DIFFERENT LOCATIONS

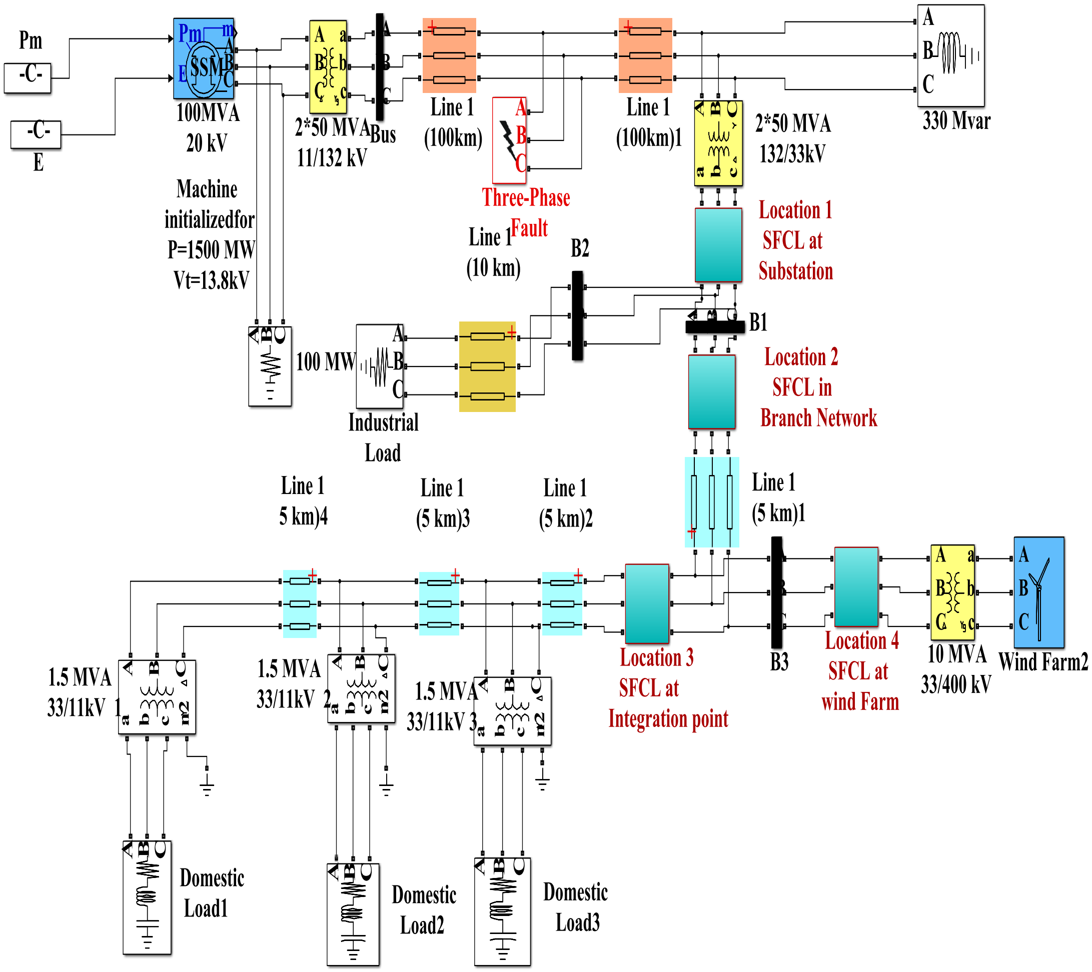

Fig.4.34 Power System with Fault in Transmission Line and SFCL at Different Locations

When a fault in transmission line occurs, fault current from the conventional power plant as well as the wind farm would flow towards fault point. Fig.4.34 shows the power system with fault in the transmission line (Fault3). Fault3 is the rarely occurring transmission line fault which results in very large fault currents. In case of wind farm, fault current would flow in reverse direction through the substation and into the transmission line to fault point. The current magnitude has been measured at different buses B, B1, B2 and B3 when SFCL is placed at different locations. Fig.4.35 shows the current waveform of different buses with fault in transmission line and SFCL at Substation (Location 1). Thus, on the contrary to the previous results obtained from fault 1 and fault 2.

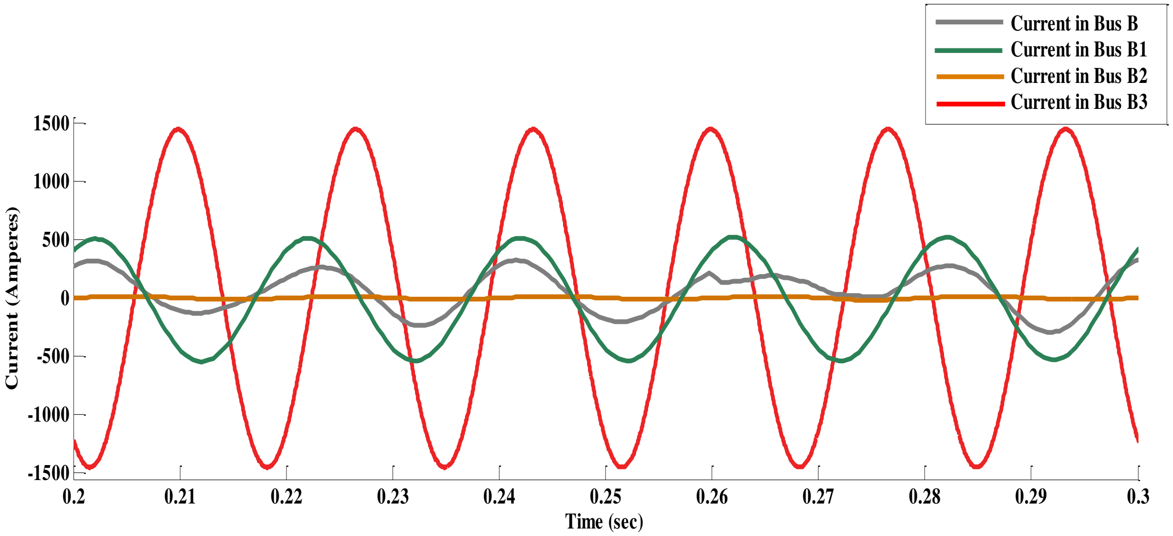

Fig.4.35 Comparison of Current when SFCL at Substation (Location1) and Fault in Transmission Line (Fault 3)

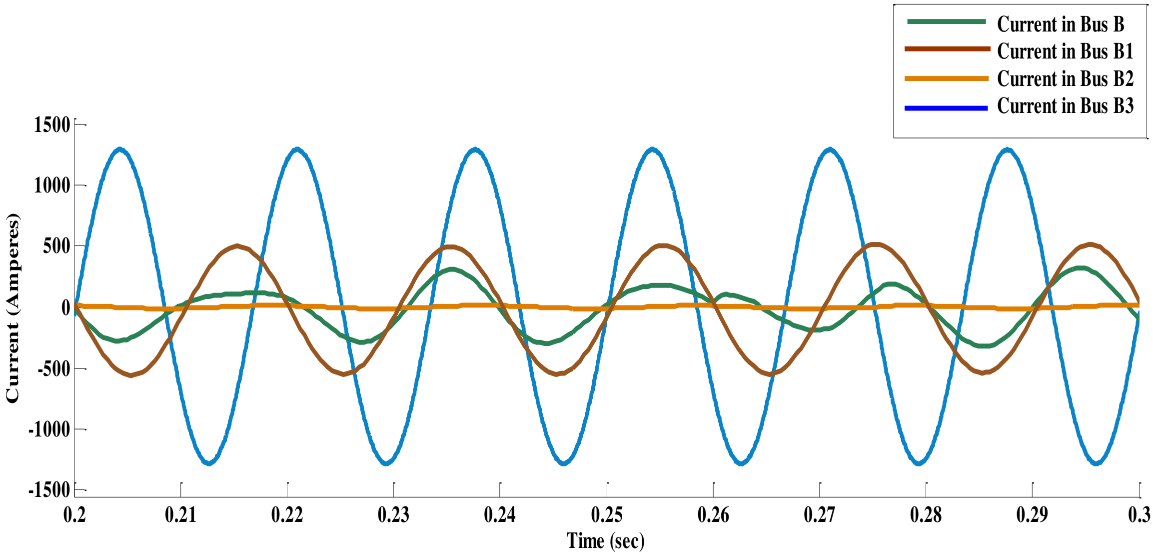

Fig.4.36 Comparison of Current when SFCL in Branch Network (Location2) and Fault in Transmission Line (Fault 3)

Fig.4.36 shows the current waveform of different buses with fault in transmission line and SFCL at Branch Network (Location 2).

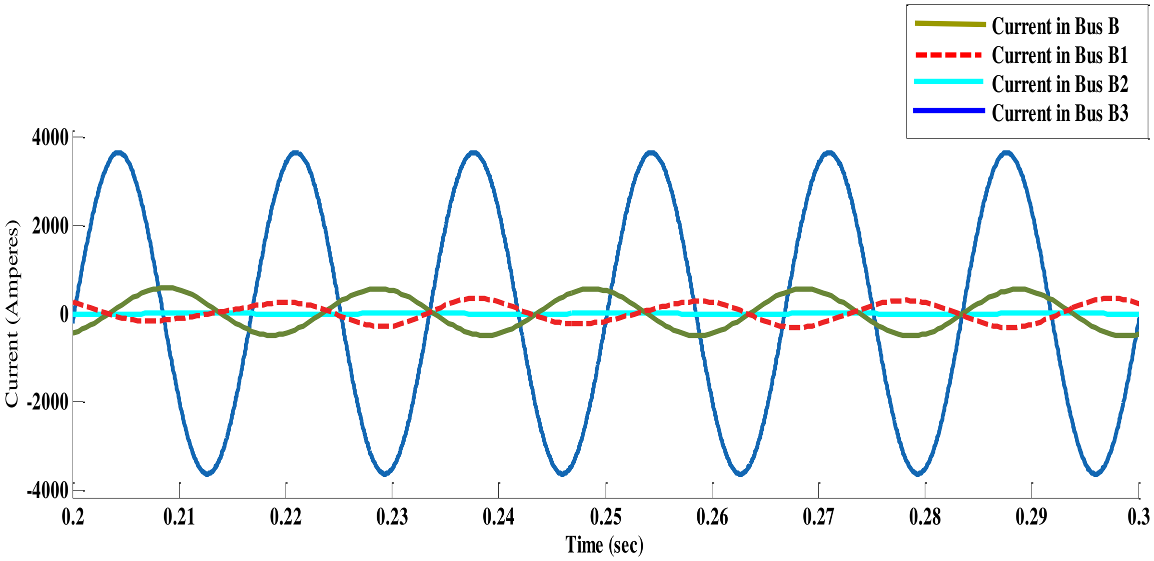

Fig. 4.37 Comparison of current when SFCL at Integration Point (Location 3) and Fault in Transmission Line (Fault 3)

Fig4.37 shows the current waveform of different buses with fault in transmission line and SFCL at integration point(Location 3).

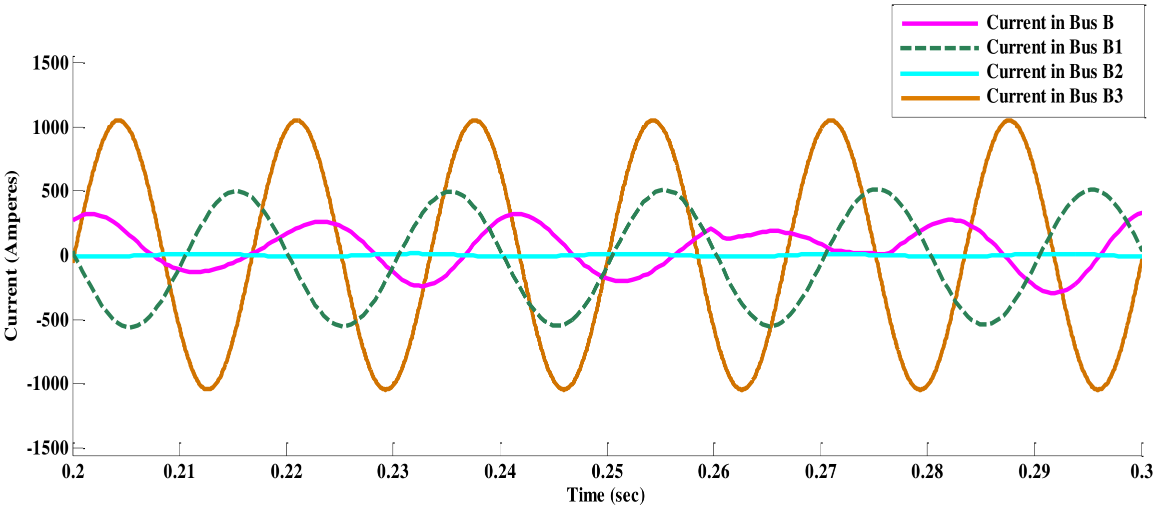

Fig. 4.38 Comparison of Current when SFCL at Substation (Location1) and at Wind Farm (Location4) and Fault in Transmission Line (Fault 3)

The fault current contribution from the wind farm (current in Bus B3) has been increased the magnitude of fault current and it is higher than 'No SFCL' situation. Installation of two SFCL at substation (Location 1) and SFCL at wind farm (Location 4) has been reduced the fault current contribution from the wind farm as shown in Fig.4.38.

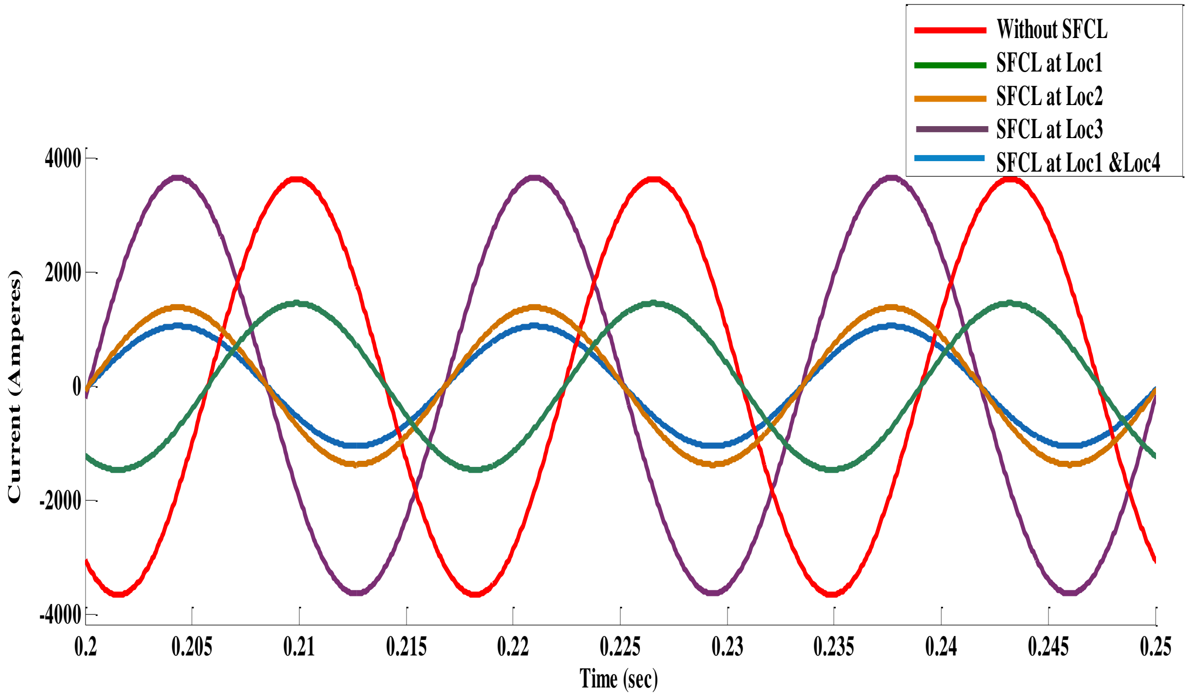

Fig.4.39 Comparison of the Wind Farm Fault Current for SFCL Locations in Case of Fault in Transmission Line (Fault 3)

When fault occurs in the transmission line the installation of SFCL in location 1, location 2, reduces the magnitude of fault current, but installation of SFCL in location 3 increased the magnitude of fault current as shown in Fig.4.39. Thus optimal location for SFCL installation in this case is location1 and location2. Table4.8 shows the magnitudes of fault current from the wind farm (measured at output of TR3) without and with SFCL at different locations and fault in the transmission line. From Table4.8, it is concluded that optimal location for SFCL installation is this case is location 1 and location 2.

The performance of SFCL at this location was even better than dual SFCL located at Location 1 and Location 4 at a time. Thus, multiple SFCL in a micro grid are not only costly but also less efficient than strategically located single SFCL.

Table 4.8 Current Magnitude in Case of Fault in Transmission Line (Fault3), for Different SFCL Locations

S. No	With and without SFCL	Current (A)
1.	Without SFCL	3500
2.	SFCL in location 1	1500
3.	SFCL in location 2	1400
4.	SFCL in location 3	3500
5.	SFCL in location 1 and location 4	1000

Table 4.9 Percentage Change in Wind Farm Fault Current due to SFCL Locations

S. No	SFCL Location	Fault at Distribution Grid		Fault at Customer Grid		Fault in Transmission Line	
	SFCL Location	**%**	**Affect**	**%**	**Affect**	**%**	**Affect**
1.	Location 1	40 %	Increased	50 %	Increased	57 %	Decreased
2.	Location 2	36 %	Increased	38 %	Increased	60 %	Decreased
3.	Location 3	68 %	Decreased	69 %	Decreased	0 %	Decreased
4.	Location1 and Location 4	40%	Decreased	38 %	Decreased	71 %	Decreased

The Reduction in wind farm fault current for various SFCL locations were summarized in Table 4.9. When fault occurs in distribution grid the presence of SFCL at location 1 and location 2, increases fault current but SFCL at location 3, location 1 and location 4 reduces the fault current.

When fault in the customer grid the presence of SFCL at location 1 and location 2, again increases the magnitude of fault current but SFCL at location 3, location 1 and location 4 reduces the fault current. When fault in the transmission line the presence of SFCL at location, location 2, location 1 and location 4, reduces the magnitude of fault current but SFCL at location 3 increases the fault current.

Thus when fault occurs in distribution grid and customer grid the optimal location of SFCL is location 3 but when fault occurs in the transmission line the optimal location of SFCL is location 1 or location 2.

CONCLUSION

The main objective of the thesis was to reduce the magnitude of fault current when distributed generation sources are connected to the existing conventional grid with the SFCL technology and conduct a feasibility analysis of positioning of the SFCL in rapidly changing modern power grid. The wind farm was used as distributed generation source. The different types of models were designed in Matlab/Simulink.

A complete power system along with a micro grid (having a wind farm connected with the grid) was 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 SFCL should not be installed directly at the substation or the branch network feeder. This placement of SFCL results in abnormal fault current contribution from the wind farm. Also multiple SFCL in micro grid are inefficient both in performance and cost. The strategic location of SFCL in a power grid which limits all fault currents and has no negative effect on the DG source is the point of integration of the wind farm with the power grid.

The main findings of thesis are given as:

(i) Penetration of DG into a distribution system causes an increase in the fault level of the network at any fault location.

(ii) Penetration of a DG in the system causes it to lose its radial power flow characteristics.

(iii) It has been observed that the optimum location of SFCL for reduction in wind farm fault current for all types of fault is at location 3 and location 3 is the grid integration point.

FUTURE SCOPE

(i) Implementation of Current Division Discrimination (CDD) in Modern power system. CDD offers a number of advantages such as: Automatic isolation of the minimal faulted circuit, or zone without communications, automatic backup if an SFCL is out of service and the scheme remains applicable if the electrical network topology changes.

(ii) Another method which can be utilized to find out the optimum location is the Sensitivity Factor Calculation with the help of Genetic Algorithm.

(iii) In AC type SFCL, AC losses take place across SFCL impedance in fault condition this results non-uniform heating of the superconductor (hot spots), it can be reduce by implement DC SFCL in place of AC SFCL.

(iv) The Resistive SFCL, saturated iron-core SFCL and DFCL can be installed at distribution substations to maintain downstream overcurrent protection without current harmonics disturbance.

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