Application of Active Superconducting Fault Current Limiter in Nine Bus Ring System and its Impact on Distance Protection

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Submitted by

Sanchita Kumari

(Reg. No. 801642011)

Under the Guidance of

Dr. Amrita Sinha

Assistant Professor, EIED

THAPAR INSTITUTE
OF ENGINEERING & TECHNOLOGY
(Deemed to be University)

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Electrical and Instrumentation Engineering Department

Thapar Institute of Engineering & Technology

Post Box No. 32, Patiala – 147004

Punjab (India)

DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "**Application of Active Superconducting Fault Current Limiter in Nine Bus Ring System and its Impact on Distance Protection**", in partial fulfilment of the requirements for the award of the degree of Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department (EIED) of Thapar Institute of Engineering & Technology (TIET), Patiala is as authentic record of my own work carried under the supervision of **Dr. Amrita Sinha**. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

Sanchita Kumari.

Place: Patiala
Date: 29-06-2018

(Sanchita Kumari)
Roll No.: 801642011

It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

Date: 30/6/18

(Dr. Amrita Sinha)
Assistant Professor
EIED
TIET, Patiala

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Sanchita Kumari.

Sanchita Kumari
(801642011)

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AC	Alternating Current
AEP	American Electric Power
CB	Circuit Breaker
CLR	Current Limiting Reactor
CT	Current Transformer
DG	Distributed Generation
DC	Direct Current
EMTP	Electro-Magnetic Transients Program
EHV	Extra High Voltage
EM	Electromagnetic Force
FCL	Fault Current Limiter
GTO	Gate Turn Off Thyristor
HTS	High Temperature Superconducting
HSFCL	Hybrid Superconducting Fault Current Limiter
HV	High Voltage
IDMT	Inverse Definite Minimum Time
IGCT	Integrated Gate Commutated Thyristors
IGBT	Insulated Gate Bipolar Transistor
LTS	Low Temperature Superconducting
MFCL	Matrix Fault Current Limiter
MG	Microgrid
MTDC	Multi-terminal Direct Current
NRDE	Numerical Relay Development Environment
OC	Overcurrent
OCR	Overcurrent Relay
PT	Potential Transformer
RFCL	Resonant Fault Current Limiter
PWM	Pulse Width Modulation
SCR	Silicon Controlled Rectifier
SFCL	Superconducting Fault Current Limiter
SGCC	State Grid Corporation of China

SSFCL	Solid State Fault Current Limiter
SC	Superconductor
SISFCL	Saturated Iron Superconducting Fault Current Limiter
THD	Total Harmonic Distortion
TMS	Time Multiplier Setting
TLS	Transmission Line Simulator
UHV	Ultra High Voltage
UFCL	Unidirectional Fault Current Limiter

ABSTRACT

With the increasing load demand and interconnection of distributed generations, there has been a significant rise in short circuit levels in transmission as well as in distribution networks. The increment in fault current has imposed burden on the existing system equipments and also cause system instability. The application of Fault Current Limiter (FCL) has helped to overcome these problems. Active Superconducting FCL (ASFCL) and Resistive Superconducting FCL (RSFCL) have been compared in nine bus ring system with SFCL placed near all three sources using Matlab/Simulink. Different types of faults have been simulated at various locations of the transmission lines in the bus system under consideration. The effect in the magnitude of fault current and voltage profile on the swing bus with inclusion of SFCL for line to ground fault has been compared for both the types of fault current limiters. The percentage reduction in the current magnitude of the faulty phase after fault inception has been observed to be more in ASFCL compared to RSFCL along with the improvement in the voltage profile. Furthermore, the inclusion of ASFCL impact on the distance protection scheme of the transmission line has been scrutinized. Considerable change in the reactance as seen by the distance relays has been observed due to superconducting air core transformer used in ASFCL while there is negligible change in the resistance. The effect on overcurrent protection used as back up protection has also been analysed due to reduction in the amplitude of the fault current.

CHAPTER 1

INTRODUCTION

1.1 Overview

Electrical energy is the most versatile and important form of energy in today's technological world. To meet the demand, the size of generating station as well as interconnection network has been increased [1]. Due to continual enhancement in the interconnection of several grids as well as power demand and consumption of electrical energy, the system fault levels have also been enhanced which is beyond the capabilities of the existing equipment, causing over-duty conditions for existing circuit breakers and other substation components [2]. The short circuit current contains abundant energy which might cause damage to electrical equipment. During fault condition, circuit breakers open automatically in three to six cycles. But sometimes, they cannot handle the intensity of fault and thus fail to break which further increase the possibility of abnormal operation in the system. The ratings of the existing equipment cannot be changed for accommodating the increased fault current levels. The thermal as well as dynamic effects because of increased fault current, the existing technical infrastructure present in the system may get damaged.

Fault currents can be limited artificially by increasing of the short-circuit impedance. There are many conventional methods to limit over duty fault current over which includes major substation upgrades, splitting existing substation busses and upgrading multiple circuit breakers present in the system. These solutions are very costly and require unwanted extended outages, resulting in declination in reliability of power system. Less expensive solutions comprises of current limiting reactors. There are many drawbacks such as rise in system losses, voltage regulation issues or which might lead to system instability.

One of the alternative ways to reduce short circuit current is inclusion of fault current limiters (FCL) in the existing system. The use of FCL approach are acquiring preference over conventional solution for limiting fault current because these devices can limit the current during faulted condition without injecting high impedance in the system under normal operation. They might affect the protection scheme and system characteristics due to their transient and steady state behaviours. With the development of superconducting materials, magnetic technologies and power electronics techniques, various types of FCL have been developed in past few years.

However, owing to the integration of FCL in the existing system new issues such as coordination with the other protective devices are to be addressed. Use of FCL increase the impedance of the line during fault condition which further might affect the impedance seen by the distance protection scheme. The reduction in the fault current might exceed the set value of the installed overcurrent relays resulting in mal operation of the protection system. Thus proper coordination between the existing protective schemes is needed when limiters are attached to the power system.

1.2 Literature Review

A. Morandi [3] examined fault current limiting devices based on superconducting materials. He briefly recommenced about superconducting FCL applications as well as its operation and impact on power system has been investigated. Magnesium Diboride (MgB2) as a superconducting material has been outlined. Furthermore, it has been depicted that by use of the limiter the disturbance in voltage profile due to interconnection of Distributed Generation (DGs) can be reduced.

Kovalsky *et al.* [4] discussed the benefits of SFCL over the conventional solution for limiting the over duty of equipments due to increased fault current level. A particular type of limiter i.e. MFCL (Matrix FCL) has been considered at transmission level voltage for mitigating the problems caused due to increased fault current levels. The use of MFCL in AEP (American Electric Power) 138 kV transmission grid has also been discussed.

G. Ganev *et al.* [5] explained fault current limiters for in medium voltage and high voltage grids. The operating principles of different structures of FCL have been proposed. The comparative analysis for different types of FCL has been carried out. The possible estimation has also been made in each case.

H. Schmitt *et al.* [6] presented a comprehensive perspective about the deeds of the CIGRE Working Group (WG). The activities emphasize over the interaction of various current limiting techniques with that medium as well as high voltage power system. A survey has been carried out about the need of checking the raised fault current and the different ways to achieve it. The potential implementations of FCLs along with their affect on other protective schemes have been discussed.

S. Alam *et al.* [7] presented a comprehensive review on different types of fault current limiters and its applications in power system. FCL’s application in different fields of power system such as transmission and distribution network, renewable energy resources integration etc. has been reviewed and documented. Many challenges like minimising losses during normal operation, coordination with other protective devices have to be considered in the future application of the limiters in the real system.

A. Abramovitz [8] presented a comparative reviewed about various types of solid state FCL technologies along with their principal of operations for distribution system. The benefits and need of implementing the fault current limiters in the existing system has been discussed. The need of advancement of limiter by exploring its diversity has also been depicted.

M. Rezaee *et al.* [9] presented the application of resonant FCL (RFCL) to check the fault current. Several types of RFCL based on the ability of limiting fault current have been explored. Sensor less operation of the limiter has also been investigated for making its function equivalent to that of superconducting limiter. The limiter has been modelled in Matlab/Simulink environment and result showed its effective functioning for limiting the fault current. The impact of inductive and capacitive resultant impedance of RFCL has been investigated individually. It has been observed that the inductive resultant impedance has better influence over the fault limitation and other aforementioned problems during fault condition.

Z. Li *et al.* [10] analysed the operating principle and technical properties of Resonance FCL (RSFCL) for EHV network. A model has been successfully made by simulation centre of State Grid Corporation of China (SGCC). Simulation tests have been carried out for confirming its performance and control designing under various operating conditions.

S. Y. Kim *et al.* [11] proposed a model of SFCL for distribution system and afterwards examined impact of SFCLs on the basis of reliability considering the improvement in the rate of failure of vicinal protective devices. From the results of case studies, it has been observed that the use of SFCL enhance the distribution system reliability. The interconnection of DGs to the system has also been considered.

Y. Shirani *et al.* [12] proposed an inductive SFCL having a resistor and ZnO device connected in parallel to investigate its effect on the transient stability of the system. The considered model consists of a machine connected to an infinite bus transmission system along with the suggested limiter and is simulated in EMTP for analysing the characteristics of the limiter. The results depicted in the improvement in the system stability with the use of suggested limiter as it suppress the voltage sags together with consuming immoderate energy during fault occurrence.

Z. Zhang *et al.* [13] proposed a DCSFCL for limiting fault current level. Zhoushan MTDC (Multi-terminal DC) system along with the proposed limiter has been considered as the simulation model. YBCO wire has been taken as the superconducting material. The current limiting effect of smoothing reactor and DCSFCL has been analyzed. From the simulation result it has been observed that only transient fault current could be reduced using smoothing reactor whereas the limiter under study could reduce the transient as well as steady fault current level in the DC line system.

J. Shi *et al.* [14] presented active DCSFCL and implemented it in a hybrid AC/DC power system. By exchanging the power between DC and AC system, the fault current of DC system could be suppressed in the presence of FCL. The proposed limiter could be acted as an active filter for both the system, thus solving the power quality problem. The model taken under the study has been simulated using MATLAB and the results validated the theoretical analysis.

T. Ghanbari *et al.* [15] proposed Unidirectional FCL (UFCL) for achieving proper interaction between the downstream (microgrid) and upstream (main grid) of power system. Voltage sag compensation capability of UFCL has been evaluated by simulating the model in EMTP (Electro-Magnetic transients Program) and has been verified by experimental results. The fault current contribution of the upstream network during fault in downstream could not limited by UFCL resulting in improvement in power quality of microgrid during fault in downstream. The coordination between both the stream OCRs (Overcurrent Relays) has also been preserved.

Y. Lin *et al.* [16] developed a resistive SFCL model using EMTP/ATP environment for distribution network. The model has been build on the basis of E-J characteristics of high temperature superconducting (HTS) material using different parameters i.e. length of material, its cross section and current density. The behaviour of HTS material under quench transition has been studied. It has been observed that economically, increment in critical current density by decreasing the operating temperature could be better option for limiting current.

Y.J. Tang *et al.* [17] proposed a design for single phase voltage compensation type SFCL. The influence of employment of the SFCL on the system has been investigated on one machine infinite bus system. Under different current limiting modes, the power angle characteristics of generator with SFCL have simulated using MATLAB/Simulink. It has been proved that mode 1 could improve the transient stability more than the other two modes. The corresponding reasons have also analyzed.

S. Jing *et al.* [18] presented an active DCSFCL based on flux compensation and the model has been simulated using MATLAB/Simulink. DC and AC system (through PWM converter) has been connected to primary and secondary winding of the superconducting transformer respectively. DC side current could be limited to different levels as per system demand by regulating the active power exchange between AC side and secondary winding of SFCL. The PWM converter could be controlled as a reactive power source for supplying voltage to the AC side which has very diminutive influence on the working of SFCL.

M. Firouzi *et al.* [19] investigated the impact of bridge type SFCL on the impedance seen by distance relay. The study has been conceded out for two types of faults i.e. single-phase to ground and phase to phase fault using PSCAD/EMTDC software. From simulation results it has been observed that for single phase fault the impedance seen by the distance relay has significantly influenced by the zero sequence component of potential across the limiter considered.

H. You *et al.* [20] proposed a design for fully controlled bridge Superconducting Fault Current Limiters and compared it with traditional bridge FCL. The characteristics of the proposed limiter has been analysed considering different operating conditions. Several conclusions have been deduced on the basis of the inductance of the High Temperature Superconducting coil (HTS).

P. Manohar *et al.* [21] explored the application of resistive type SFCL to surpass the impact of fault current. The performance of the limiter has been well executed for VSC (Voltage Source Converter)-HVDC (High Voltage DC) system. Transient analysis for AC/DC faults on the both side of VSC has been performed. From results it has been concluded that implementation of SFCL for the system with over head lines is an efficient way for providing protection.

S. Nemdili *et al.* [22] investigated the operational characteristics as well as limitation behaviour of resistive type SFCL. Bi2223 material as HTS has been used. The modelling of SFCL has been carried out using MATLAB environment. The quenching and current limiting characteristics of SFCL have been validated. The simulated results demonstrated the effectiveness of the SFCL model used.

S Xue *et al.* [23] introduced the working of resistive SFCL and further DC short circuit fault characteristics for DC distribution system has been analysed. A 10-kV DC distribution system model with an SFCL has been utilised and simulated in PSCAD/METDC. Current protection based on peak value of the current and its transient time to reach the peak value has been proposed. The analysis and protection principle have been validated by the simulation results. The proposed protection principle ensured coordination between upstream and downstream relays.

X. Zhang *et al.* [24] considered the behaviour of SFCL as per the temperature dynamic power law based on electric field and current density. Power system based on UK network standards interconnected with wind farm has been considered for study. The model has been compared with the step- resistance model of SFCL. A systematic study has been carried out on the performance as well as optimal location of SFCL in the system considered.

Samantray *et al.* [25] tested and analysed the working of resistive type SFCL in a microgrid. A test-bed has been considered comprising of two renewable sources i.e. wind farm and solar farm as DG (distributed Generators) units and loads including both domestic and industrial. It has been observed that the penetration of DG in the existing system altered the fault current levels causing imbalance of the system. The test-bed has been modelled in MATLAB environment and the results depicted suppression in fault current due to presence of the limiter. Moreover, it has been observed that the recovery time of RSFCL lead to some operational complications for which some action has been recommended.

S. M. Blair *et al.* [26] demonstrated the current time characteristics of RSFCL. It is inverse in nature i.e. quenching time of superconductor is inversely proportional in to the initial magnitude of fault current. A comprehensive equation for estimating quenching time on the basis of initial current as well as temperature has been derived. The characteristics have been verified mathematically and the results obtained are near to that of practical limiters.

U.A. Khan *et al.* [27] introduced a feasibility analysis for optimal positioning of SFCL in a system. A resistive type SFCL has been modelled in MATLAB environment and implemented it in a system along with a MG comprising a wind farm. It has been observed that the installation of SFCL either at substation or on the branch network feeder is not desirable. Rather installing SFCL at the point of integration of wind farm to the system would be the appropriate position.

B. C. Sung *et al.* [28] studied about the determination of optimal resistance value for resistive SFCL so that the transient stability could be more effectively enhanced. Several case studies have been carried out by simulation as well as experimental tests. It includes 2220 kV, 300 A laboratory and 13.2 kV, 600 A scale distribution system network tests. From the results it has been observed that the selected resistive value dramatically affect the reduction in fault current in the presence of SFCL.

L. Chen *et al.* [29] conducted experimental test on a prototype of voltage compensation type SFCL. The application of the SFCL has been securitized in a PMSG based wind turbine system for its transient performance enhancement. Different types of tests i.e. commissioning test and current limiting tests have been carried out according to which the limiter prototype could suppress the fault current level automatically along with offe ring a high controllable compensation voltage in series with the main circuit. It has been found that use of SFCL could help improvement of wind energy system in maintaining the PCC power balance as well as investigating its voltage current fluctuations.

L.Chen *et al.* [30] studied about active SFCL based on voltage compensation via theoretical and simulation analysis. The injection of DGs along with its location in the distribution system has taken into consideration for investigating the effect of limiter on the increased current level as well as voltage sags during fault. From the results, it has been observed that the limiter functioned efficiently. Furthermore, distance between limiter and fault location effect the current limiting capability of the limiter. It would increase with decrease in distance between them.

H. Yamaguchi *et al.* [31] presented theoretical analysis for air-core superconducting transformer. Single phase transformer has been considered for investigation which was further expanded for three phase. The load tests have been carried out on three phase air-core superconducting transformer. The obtained results validated the theoretical analysis made.

P. Bodger *et al.* [32] presented a partial core made of laminated silicon steel, high temperature superconducting transformer. The transformer was based on open or a partial core which means magnetic circuit is incomplete. Its performance has been tested taking liquid nitrogen as cryogenic. Open circuit and short circuit tests supported the viability of the designed partial core while full load test indicated transformer's high efficiency and low regulation. The tests conducted on the transformer endorsed its befitting operation in the real network..

L. Chen *et al.* [33] presented active SFCL which could be used in AC as well as DC system. Its operation was similar to the flux compensation based FCL. It has been observed that the limiting capacity could be increased by controlling the amplitude and phase of transformer secondary winding's current. The current limiting effect has been validated using MATLAB/Simulink. The current limiting experiment has been done using small conventional transformer and its results served the simulation results.

C. Nan *et al.* [34] introduced an active SFCL for a grounded neutral three phase power system. The model has been simulated using MATLAB and from the results it has been observed that the fault current has been suppressed effectively in the very first peak after the fault occurrence. Each phases of the limiter has separated control and fault detection part.

S. Hwang *et al.* [35] presented feasibility analysis for positioning of SFCL along with its effect on the fault current reduction. A smart grid consisting AC microgrid (MG) with a wind farm and a DC MG connected with a photovoltaic farm has been considered for study. From the simulation results it has been depicted that best current limiting performance could be get when SFCLs are located in the direct path of fault current occurred in AC and DC microgrid.

J.Sim *et al.* [36] investigated reliability improvement of fast switch by utilizing PE (power electronics) switches i.e. IGCT (integrated gate commutated thyristors). Test results depicted the efficient working of the limiter and is successfully implemented for protection of three phase, 22.9 kV/630 A machine.

S.H. Lim *et al.* [37] analyzed the working of hybrid SFCL (HSFCL) and its impact on other protective scheme mainly overcurrent (OC) protection on the basis of the experimental results. The limiter has been placed at gateway of feeder towards distribution system. From the analysis of the results obtained it has been observed that the resistance of the current limiting reactor (CLR) of the HSFCL affects the functioning of OC relay. There would be more delay in the working of the OC relay with the increase in the CLR resistance.

S. Lee *et al.* [38] developed a model of 22.9 kV hybrid SFCL using PSCAD/EMTDC and its influence over Korean Power System (KPS) has been analyzed. The model has been developed on the basis of test data by KEPRI and LS system. The specifications of current limiter reactor (CLR) for the developed limiter have been proposed. The aforementioned limiter expected to be implemented in KPS.

D. N. Vishwakarma *et al.* [39] presented numerical relay for distance protection scheme using microcontroller. Numerical filtering algorithm based on block pulse function has been employed. The relay has been effectively tested for quadrilateral characteristics and the results procured assure the reliability, accuracy, flexibility and swift operation of the relay.

G. Revati *et al.* [40] presented the performance of a quadrilateral relay on Transmission Line Simulator (TLS) Estimation of current and voltage readings has been carried out for realizing relay characteristics by utilizing NRDE (Numerical Relay Development Environment). Different zones of protection have also been taken into consideration during the work. The results depicted the effectiveness of the relay under various fault cases along with different zones.

L. Chen *et al.* [41] introduced principles and impedance characteristics of active saturated iron core SFCL (SISFCL). The impact of the proposed limiter as well as its coordination with distance protection for EHV lines has been evaluated. The non linear characteristics of the limiter checked the overreach condition of the distance protection. Furthermore, for EHV transmission, a setting scheme for the distance protection has been proposed.

L. Zhnag *et al.* [42] studied the impact of the integration of SMES and bridge type SFCL on the operation of circle distance relay. The relay’s tripping characteristics to transmission line with and without the presence addition of SFCL and SMES integration has been analysed. The influence of the SFCL and SMES integration on the impedance measured by the distance relay during faulted condition has been demonstrated using MATLAB/Simulink. It has been observed that the SFCL has more impact on the measured impedance while a very minor effect of SMES has been depicted for the same. Thereafter an improved distance relay has been proposed and verified to avoid mal operation.

B. Li *et al.* [43] illustrated the operation of saturated iron-core SFCL and its impact on the distance relay protection. A 550 KV double circuit transmission line model has been considered taken for study. The model has been simulated using Electromagnetic Transients Program which includes DC software package (EMTDC). The results verified the theoretical analysis as well as feasibility of the proposed protection scheme.

L. Chen *et al.* [44] studied the impact of voltage compensation type SFCL on the distance protection scheme of the system. The modified formulae as per different modes of operation of SFCL for the measured impedance by distance relay have been introduced. It has been observed that the effect of current limiting impedance could be eliminated by implementing the modified formulae, thus reflecting the actual impedance between fault point and relay.

S. Ahmed *et al.* [45] executed the comparative analysis between resonant type and bridge type FCL in IEEE nine bus system. Balanced as well as unbalanced faults have been considered for the study. Harmonic study has been carried for the system according to which none of the limiter could reach the satisfactory THD level. However, for harmonic analysis, the bridge type FCL’s THD could be easily controlled as compared to the resonant type.

W. Rebizant *et al.* [46] investigated about the coordination of OC protection relay in power system with SFCL. Selected problems were considered related to OC protection operation when SFCL has been introduced in the system. Instantaneous OC devices have been taken into consideration. It has been concluded that if the critical current of SFCL coincide with the network’s first protection zone, then only proper operation and coordination of OC could be achieved otherwise settings has to be changed accordingly. Thus both protection selectivity and sensitivity could be achieved only by adaptive settings.

S. H. Lin *et al.* [47] analyzed about the impact of implementation of SFCL on the operation of OC relays and reclosures by performing short circuits experiments. It has been concluded that by varying the value of shunt resistance of SFCL, its coordination with other protective devices i.e. OCR and relay can be governed. The alternative way for coordination is to modify the setting parameters which are time delay and pick up current of OCR.

S. Lee *et al.* [48] reviewed the impact of the application of 154 kV SFCL on the protection scheme of power system in South Korea. A 22.9 kV hybrid SFCL has been already developed and successfully operated at Icheon Substation, Korea. A new adaptive protection algorithm has been developed to overcome the problems associated to the existing protection scheme. The algorithm has been tested using PSCAD/EMTP in a simple distance relay system.

1.3 Objective of the Work

The aim of the work is to implement SFCL for limiting the fault current and its impact on distance protective schemes. The formulation of objective is carried out in following steps:

- Modelling of Fault Current Limiter (FCL).
- Modelling of a system (nine bus system) for fault analysis.
- Application of FCL for limiting the fault current.
- Impact of FCL on distance protection schemes.

1.4 Organization of the Dissertation

Presented work is divided in to five chapters.

Chapter 1 contains introduction to Fault Current Limiters (FCLs) in the existing system along with its impact on other protective scheme. It also includes review over different types of limiters and their application for power system protection.

Chapter 2 covers brief description over fault current limiters and their types.

Chapter 3 includes different type of protection schemes along with the impact of the use of limiter on other existing protective schemes.

Chapter 4 is the result and discussion considering nine bus ring system. The modelling of resistive type and active type Superconducting Fault Current Limiters has been carried and are implemented on the bus system one at a time. Furthermore, the effect of the presence of the limiter in the system on the impedance and its components has been studied.

Chapter 5 is the conclusion of the thesis work along with scopes for the future research work.

CHAPTER 2

FAULT CURRENT LIMITERS

A **Fault Current Limiter** (FCL) is a device that is able to limit fault current level during fault occurrence in the system. With the increase in size of generating station as well as interconnection network due to trend of deregulation and restructuring of power system, the possibility of abnormal operation in the system has also increased. There may of sudden change in the impedance of the power system leading to increase in current, known as fault current. One of the main reasons for increasing the fault current level is the introduction of new dispersed generation (DG) units in a grid [3]. Increased fault current level may exceed the rating of the existing network's equipment and disrupt the working of protection schemes available. Use of FCL turn out to be a viable solution for reducing fault current within the short circuit ratings of the system in order to expand the existing system's capacity and service life. Implementation of FCL allows existing utilities to meet the growing electricity demand reliably as well as cost effectively. Current limiters can reduce short-circuit currents resulting from plant power source additions or any fault at any location of the system to the level that can be adequately handled by existing distribution equipment. FCL response is fast and independent. It restrains the transient fault current from reaching excessively large values. The function of an FCL is to protect a system until the circuit breaker gets activated. The circuit breaker operates after receiving the trip signal from relay which in-turn requires the sensing time. Whereas the FCL response solely depends on the amplitude of fault current in the system. They both require few cycles for the system restoration. FCL returns to its low-impedance state when the fault subsides i.e. the normal condition reinstated depending on its recovery time. It would continue to be in high impedance state till the opening of circuit breaker if the fault is permanent in nature.

2.1 Conventional Methods of Fault Current Limitation

There are many conventional ways to limit fault current and are as follows [4, 5]:

- Fuses – They are simple, reliable and are usually used in low and middle voltage distribution grids. The main disadvantages include onetime use and its manual replacement.
- Circuit-breakers – These are commonly used reliable protective devices to isolate the faulty parts. The drawbacks of circuit-breakers are high cost and have huge dimensions.

They require periodical maintenance and have limited number of operation cycles.

- Increase System Impedance – Current limiting reactors and high impedance transformers can be used to increase system impedance and thus consequently limit the short-circuit currents. There are disadvantages in increasing system impedance and are as follows:
  a. Capital investment for the additional equipments. However, the installation of reactors is easier and might be cheaper than the current limiters.
  b. They act as a constant source of losses as there is voltage drop across it under normal loading conditions. Moreover, their interaction with other system components can cause instability.
  c. Result in power quality impediment like reduction in transient stability margin and increment in voltage harmonic distortion because of the voltage drop across additional equipments.
- Reduce Network Interconnections – This can be done by system reconfiguration and bus-splitting.

  System reconfiguration would rectify immediate problems caused by the increased fault current along with providing further growth of the existing system. Nevertheless, it is the most expensive solution compared to all other conventional solutions.

  Bus splitting can be done by using bus coupler as shown in Fig.2.1 or a sectionaliser. It requires segregation of sources which could possibly furnish a fault. Although, this method effectively reduces the fault current by reducing the number of sources feeding the fault point, but it also affect the normal operating conditions of the system.

  For proper disconnection of sources might require additional changes in the operational philosophy as well as control methodology.

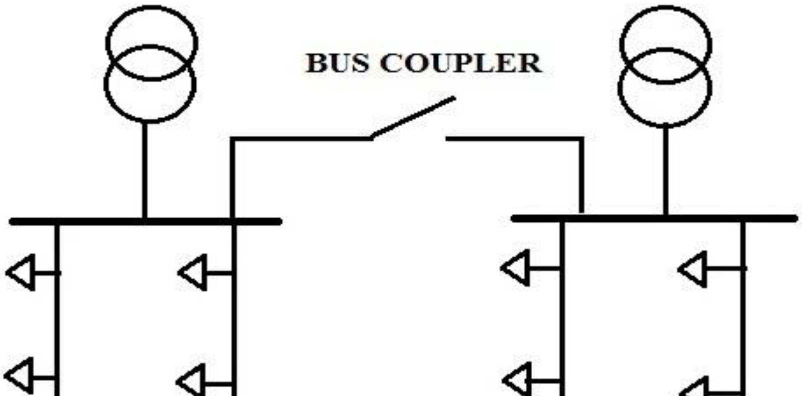


Fig.2.1. Bus coupler at Tie Line

- Multiple circuit breaker upgrades – During fault more than more breaker comes into play. Due to increased fault current level, those breakers get affected. Up gradation of the multiple CB is not cost effective. Mal operation of any CB leads corresponding hazards, as well as often prohibited because of high expense of replacement of the switchgear within station.
- Sequential breaker tripping – It is a protective scheme that prevents CB from interspersing excessive fault currents. It involves tripping of an upstream breaker that is located far from the fault location. The upstream breaker is rated to carry maximum prospective current. Because of which there is reduction in the fault current seen by the downstream CB (ideally located nearest to the fault), which is of lower rating, within its zone of protection. Now the downstream breaker can operate adequately due to reduced current flow. The upstream circuit breaker is re-closed afterwards.

  The disadvantage of this process is that it increases the overall fault clearing time. Furthermore, opening the breaker upstream during the fault affects zones of protection which were not originally intended to be.

  These conventional solutions can be summarises as shown in Table 2.1:

Table2.1: Different solutions for limiting fault current

Solution	Advantage	Disadvantage	Expense
Bus splitting	Separates sources of fault current	Separates sources of load current from load centres and decrease system reliability	High if not already installed
Multiple CB Upgrades	Direct solution with no adverse effects	Difficult to schedule outages	Depend on type of CB
New Substation	Good for future growth	Costly and time taking process for installation	Most expensive solution
Sequential Breaker tripping	No Major hardware installation required	Expands impact of fault to wider range of the system	Low
Current limiting Reactors	Easy to install	Voltage drop and power losses. Also cause instability	Medium to low
Fuse	Simple and reliable	One time use. Manual replacement is done	Low

Aforementioned conventional techniques have negative impact on system reliability and integrity, thus the use of FCL (fault current limiters) comes into existence. FCLs with fast action can limit the instantaneous magnitude of the short-circuit current during fault conditions to a predefined value. Appropriate positioning and optimal parameters of the FCL are significant in the fault current limiting process. Installation of FCLs is generally in the DG unit's feeders, bus tie and load feeders.

2.2 Characteristics of ideal FCL

The characteristics of Ideal FCLs are as follows:

- Exhibit zero impedance during normal operating condition (healthy system). However, this condition cannot be fully meet by practical FCL systems but can reach near to it.
- Zero power loss during normal condition.
- Limit the rate of increase of current immediately within first cycle of the fault occurrence.
- Impose high impedance instantly during fault occurrence.
- Improve voltage profile of the system.
- Quick and automatic recovery after fault clearance.
- Minimal impact on existing protective schemes.
- Require less maintenance.
- Low weight and smaller in size.
- No or only few auxiliaries.

2.3 Types of Fault Current Limiter

FCL can be classified in many ways. According to CIGRE WG A3.10 [6], they can be classified as Passive and Active. Passive FCL increases the impedance at normal as well as fault condition. While, active FCLs impose negligible impedance under normal condition and there is rapid increase of impedance under faulted condition.

The commonly used FCL according to the material can be classified as non-superconducting and superconducting fault current limiters [7].

2.3.1 Non superconducting FCL

They can be further subdivided as following:

2.3.1.1. Saturable Core FCL – It makes use of the nonlinear characteristics of ferromagnetic materials for achieving a variable value of inductance. Its construction comprises of a wounded coil over an iron core. It is connected in series with the load that has to be protected as shown in Fig.2.2. There is negligible effect of inductor in normal operating condition. During fault, the core overcomes its saturation state resulting in insertion of high inductance. Consequently, the fault current is fettered.

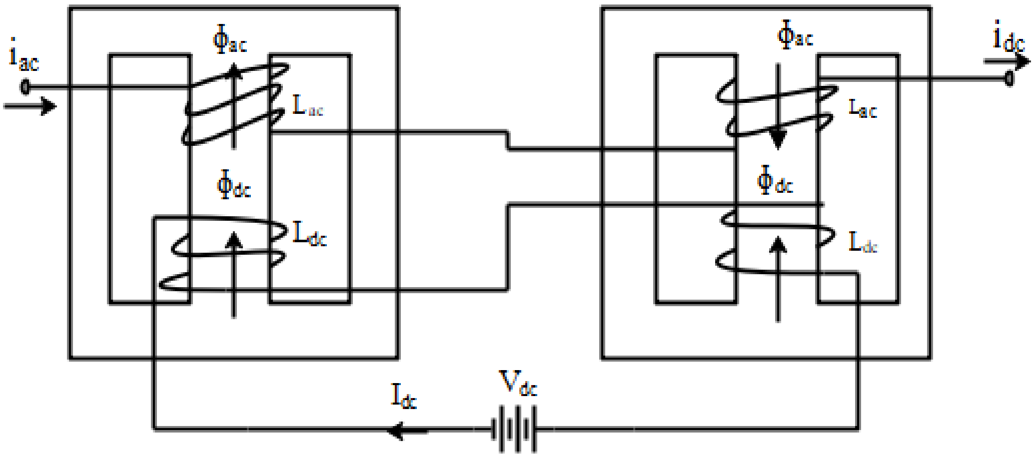


Fig.2.2. Generic Structure of Saturable Fault Current Limiter

2.3.1.2. Solid State FCL – Advancement in high power semiconductor technology such as switches (IGBT, IGCT etc) with higher voltage and current ratings aids in implementation of solid state FCLs (SSFCL). These can be classified into three major groups and are as follows [8]:

- **Series Switch type FCL**

It comprises of a bidirectional controlled semiconductor switch (S_{CS}) along with a bypath network. S_{CS} can be implemented with any semiconductor devices. The bypath network comprises of several branches i.e. normal state bypass (S_{NB}), fault current bypass (F_B), over voltage protection bypass (ZnO) and a snubber circuit connected in parallel as shown in Fig.2.3. Generally, S_{NB} is implemented using electromechanical switch. It provides low resistance path thus reducing semiconductor losses as well as normal state waveform distortion. F_B is deployed using non interruptive fault current limiters using either resistive or inductive components. The working of this branch is to check the flow of fault current along with permitting the other existing protective scheme to take relevant actions. ZnO varistors are utilized for overvoltage bypass. It provides an alternative path to the flowing current. It limits the voltage across the switch used along with absorption a part of line inductance energy. The snubber network is utilized for limiting the rate of rise of voltage across the switch during its turning-off process. The network tries to keep the *dv*/*dt* within the allowed maximum value as per the specifications provided by manufacturer.

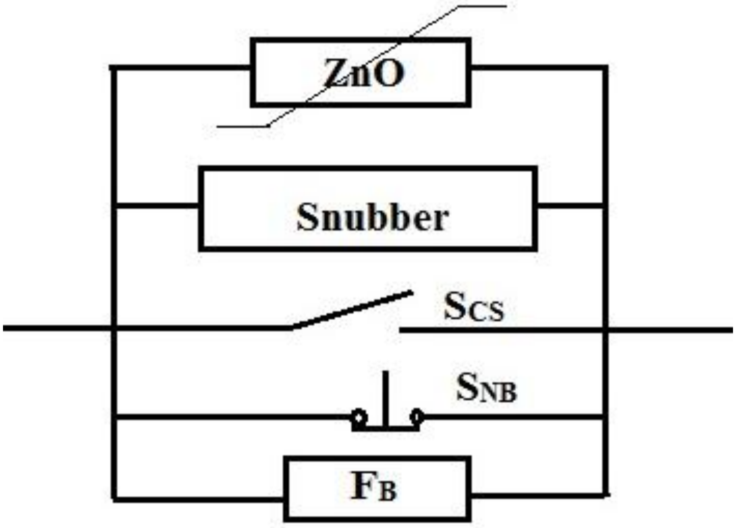


Fig.2.3. Series Switch Type FCL

- **Bridge Type FCL**

This type of FCL is realized by utilizing a current fed switch arrangement. The current rating of switches is governed by the peak fault current and system voltage. Normal state bypass is not there but do have overvoltage protection bypass shown in Fig.2.4. Fault current bypass may or may not be there. During normal condition, all the elements are in ON state, thus providing unrestrained trail for ac line current. The operating principle of the limiter depends on incorporation of a dc current source with the line connected in series. In practical purpose, reactors are used as current source because which it possess some disadvantages. It includes saturation of the inductor used during high voltage resulting in failure in accomplishing current limiting properties. There is a notable loss during normal operating condition. The switches used (generally diodes) should have the capabilities to withstand the current flowing during normal as well as in faulted condition. ZnO is used for overvoltage protection along with providing path to reactor for discharging at the instant of CB opening.

They can be further classified as single reactor rectifier bridge FCL, Rectifier Bridge Transformer Inrush Current Limiter, Transformer Isolated Three-Phase Rectifier Bridge FCL, Two-Reactor SCR Bridge FCL, Half-Controlled IGCT Bridge FCL, Single-Switch IGCT Bridge FCL, Transformer Isolated GTO Bridge FCL, Saturated DC Reactor Bridge FCL, GTO FCL With an Emergency Power Source Function, Superconducting Fault Current Limiter–Magnetic Energy Storage System [8].

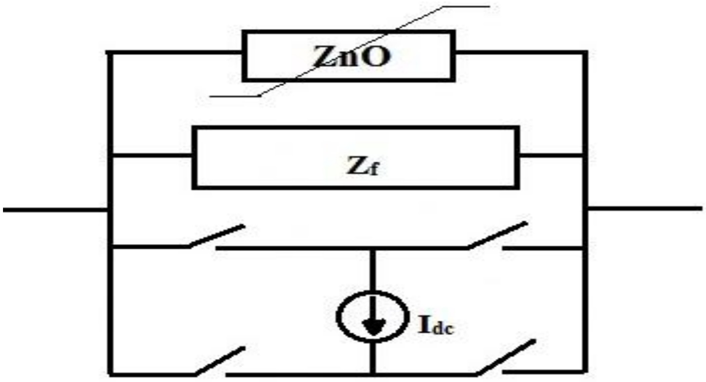


Fig.2.4. Generalized Topology of Bridge FCL

- **Resonance FCL**

In RFCL, the by-pass CB is open during healthy condition due to which the inductor/reactor and capacitor are in resonance. During fault condition, the capacitor is by passed, injecting the reactor in the transmission line which further limits the fault current. RFCL uses switches to reconfigure its network either into normal state or faulted state rather than having individual normal and faulted state bypass elements as shown in Fig.2.5. Series resonant circuit is employed and is tuned to line frequency to achieve zero series impedance. Under faulted condition, the circuit is set out of resonance and thus more impedance is introduced to the line. These FCLs do not have interruption capability but can reduce fault currents. This can be further subdivided in series and parallel configuration [9, 10].

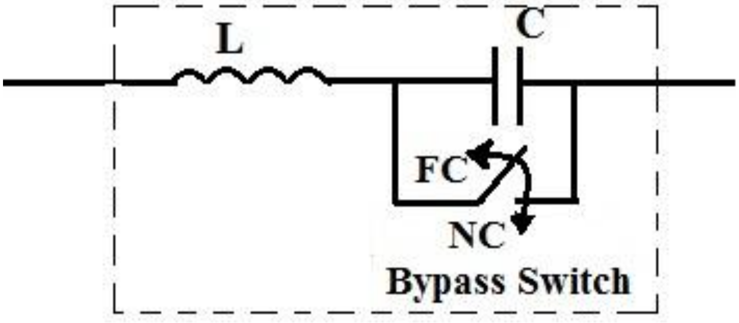


Fig.2.5. Generic Topology of Resonant Type FCL

2.3.2 Superconducting FCL (SFCL)

Introduction of superconducting materials also leads to up gradation of current limiters. SFCL is innovative electric apparatus having many advantages such as limiting the fault current level within the first cycle of fault occurrence resulting enhancement of transient stability of the high rated power system [11] and improves system reliability [12]. Various type of SFCL have been developed using different types superconducting materials and designs like resistive, inductive, bridge, active types SFCLs [13-17].

2.3.2.1. Bridge type SFCL

Bridge type SFCL comprises of auto transformers whose primary is connected in series with the line and secondary winding is connected to a superconducting coil through a diode bridge circuit which converts the AC current to DC allow to flow through the superconducting coil as shown in Fig.2.6. During normal condition, the limiter does not impose any load to the system. Under fault condition, the current can be suppressed by controlling the output current of the converter [19, 42]. There are some disadvantages related to it. They are as follows [20]:

a. The use diode bridge circuit is beneficial to check the transient current only, and no effect on the steady state fault current.
b. The thyristor bridge circuit can check transient as well as steady fault current. However, its action becomes slow after occurrence of fault.
c. The need for the heat sinks is more for the bridge circuit.

Because of the aforementioned problems fully controlled brides also termed to be active SFCL comes into existence.

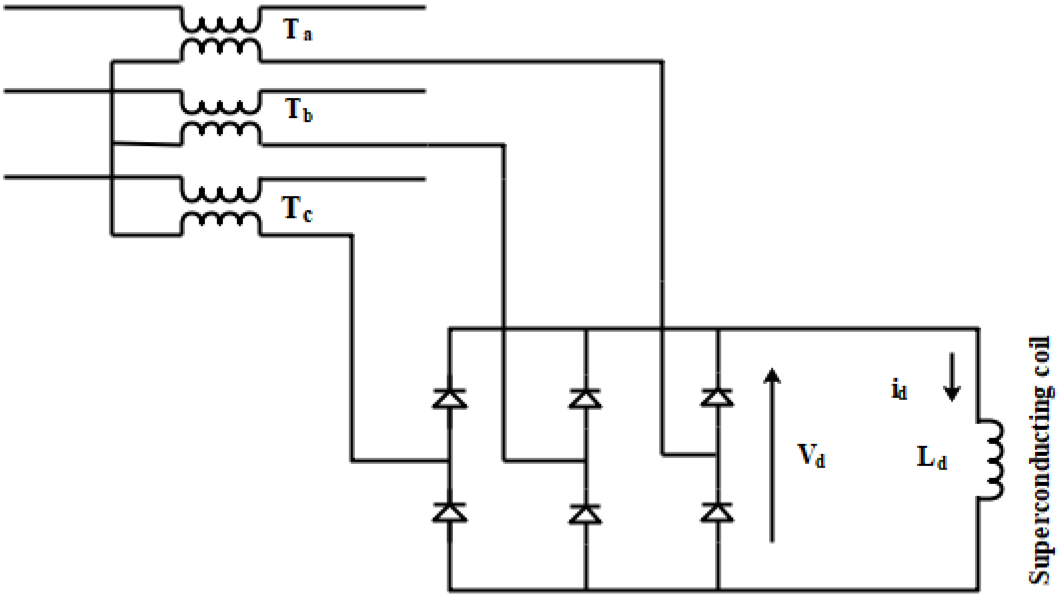


Fig.2.6. Bridge Type SFCL

2.3.2.2. Inductive type SFCL

There are many designs for this type of limiter among which transformer prototype is the most common. The basic concept for inductive SFCL is that it acts as a transformer with a closed superconducting coil made of HTS (High Temperature Superconducting) as secondary as shown in Fig.2.7. During unfaulted condition, the secondary resistance is negligible and thus it suffices low inductance. Under fault state, the increased current cause loss of superconducting characteristics of the secondary winding made thus makes it resistive. Due to this, there is a rise in voltage across primary winding of the transformer which further opposes the fault current. The advantage of this limiter is that the cryogenic power load may be lower because no heat ingress is caused through current into the superconductor. However, there are certain disadvantages such as large size and weight significant losses, and inductive behaviour.

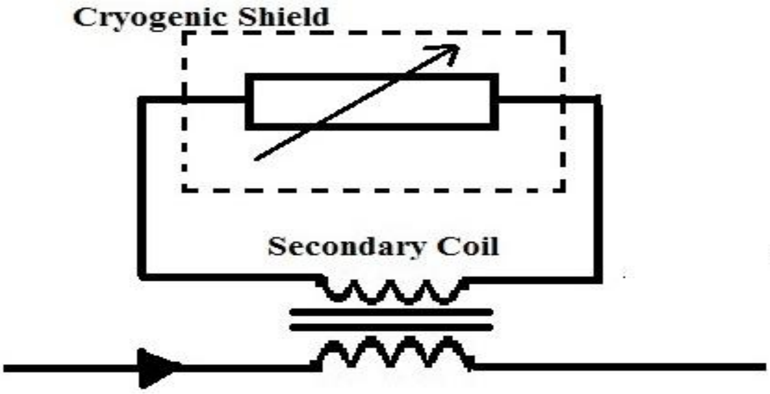


Fig.2.7. Inductive Type SFCL

2.3.2.3. Resistive type SFCL

Superconducting materials can be of low temperature or high temperature. Due to the low operating temperature, the cooling costs are extremely high and thus FCL based on Low temperature Superconducting (LTS) are not expected to be commercialised. RSFCL made of High Temperature Superconducting (HTS) materials are more in use. These are connected in series with electrical circuit. Advantages of HTS technology include self detecting, self recovery and fast responding. There are various HTS materials have been preferred for power applications. The major material systems among them under intensive research for SFCL application are YBCO (Yttrium Barium Copper Oxide) films, Bi2223 wires and Bi2212 bulk (Bismuth Strontium Calcium Copper Oxide) [21]. With the development of these superconducting materials, the application of resistive limiter comes into existence [22, 23].

Under normal operating condition, it has zero electric resistance as the element remains cooled under its critical temperature using cryostat as shown in Fig.2.8. While under faulted condition, the current flowing through the superconductor crosses the critical current limit condition resulting in abrupt increment in its resistance. Superconductor (SC) exhibits normal metal properties when the critical surface defined by temperature, current density and magnetic field is attained [24].

The current limiting behaviour of superconducting limiter is basically according to HTS E-J characteristic. The characteristic is further divided in three sub-regions: Superconducting/ flux creep, Flux-flow and Normal conducting/ resistive state. The entire E-J characteristics can be summoned (for Bi2212 material) as Eq. (2.1) [24, 26]:

$$E(T,t) = \begin{cases} E_c\left(\frac{J(t)}{J_c(T(t))}\right)^{\alpha}, & for\ E(T,t) < E_0\ and\ T(t) < T_c \\ E_0\left(\frac{E_c}{E_0}\right)^{\beta/\alpha}\left(\frac{J_c(77K)}{J_c(T(t))}\right)\left(\frac{J(t)}{J_c(77K)}\right)^{\beta}, & for\ E(T,t) > E_0\ and\ T(t) < T_c \\ \rho(T_c)\frac{T(t)}{T_c}J(t), & for\ T(t) > T_c \end{cases} \tag{2.1}$$

Where,

$$J(T,t) = J_c(77K)\frac{T_c - T(t)}{T_c - 77}, for\ J > J_c\ and\ T(t) < T_c$$

T is the superconductor’s temperature, J is current density. ρ is resistivity

J_c, T_c, E_c are critical current density, temperature and electric field respectively. Depending upon the material used the range of the parameters can be defined as:

$10^7 \leq J_c \leq 10^8$ A/m^2,

$0.1 \leq E_0 \leq 10$ mV/cm,

$100 \leq \rho \leq 2000$ μΩ – cm,

$5 \leq \alpha \leq 15$, $2 \leq \beta \leq 4$

The values of these parameters have to be selected precisely as the performance of the limiter depends on these parameters.

Graphically, the above equations can be depicted as Fig.2.9.

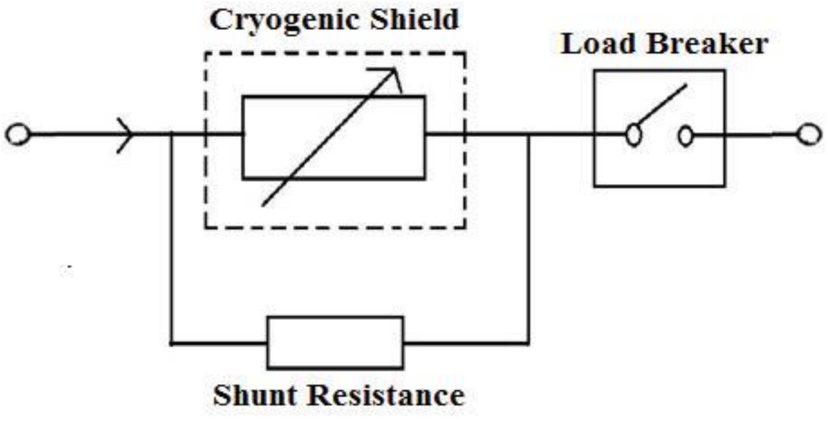


Fig.2.8. Resistive Type SFCL

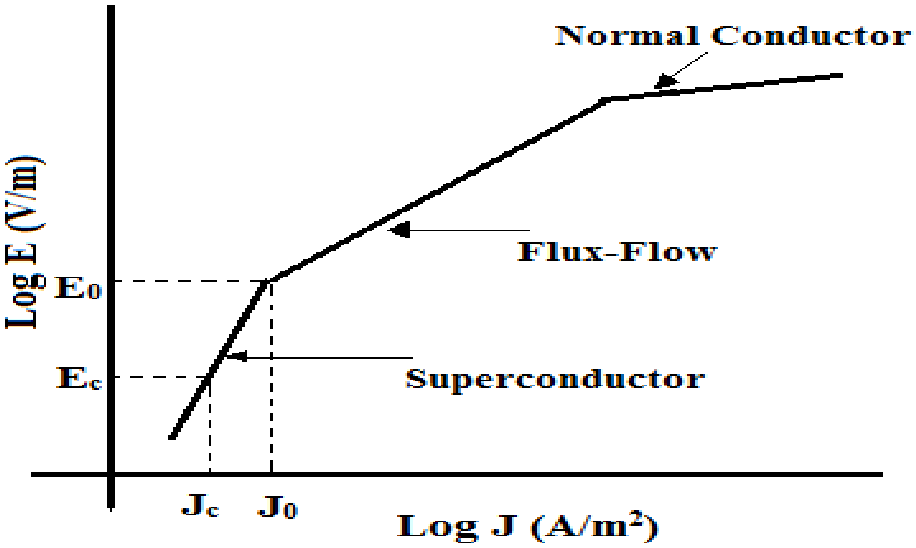


Fig.2.9. E-J Characteristics

The resistance of the limiter is almost zero under normal operating conditions. However, it exhibits non linear characteristics with respect to time during flow of heavy fault current and is called as quenching process. The overall process of variation of resistance from superconducting to normal state can be defined by following equation [26]:

$$R_{sfcl}(t) = \begin{cases} 0 & (t < t_0) \\ R_{max}\left[1 - \exp\left(\frac{-\mathrm{t} + \mathrm{t}_0(\mathrm{quench})}{\mathrm{T}_{sc}}\right)^{1/2}\right], & (t_0 \le t < t_1) \\ \alpha_1(t - t_1) + \beta_1\,, & (t_1 \le t < t_2) \\ \alpha_2(t - t_3), & (t > t_2) \end{cases} \tag{2.2}$$

Where,

R_{max} – maximum resistance of SFCL in quenching state.

T_{sc} – time constant of limiter in course of transition to normal state from superconducting state.

t_0 – quenching start time.

t_1 – first recovery time

t_2 – second recovery time

α_1 and α_2 are temperature coefficients.

Above equations can be represented as graphically as shown in Fig. 2.10.

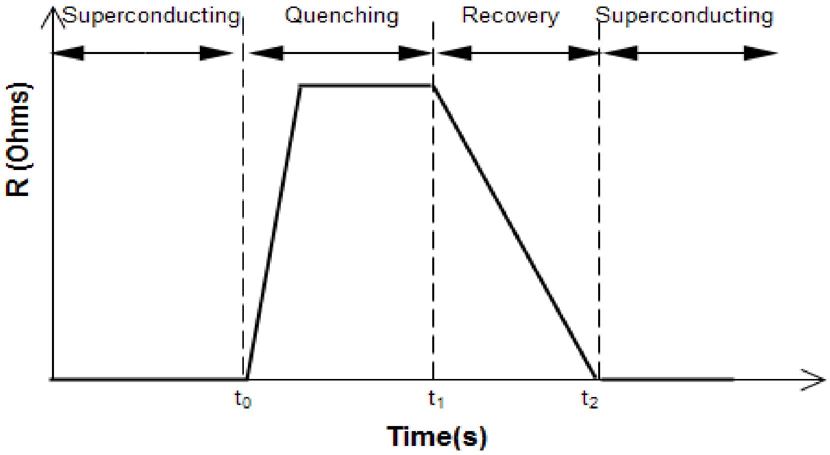


Fig.2.10. RSFCL Behaviour Characteristics

2.3.2.4. Active SFCL

Active SFCL comprises of air core superconducting transformer together with a PWM converter. The primary winding of the transformer is connected in series with the main circuit while its secondary winding is connected with the superconducting coil through a PWM converter [29, 30].

Proper switching of IGBTs helps in maintaining coordination with other protective devices and also suppressing of harmonics. Superconducting transformers specially air core have many advantages compared to conventional technique such as reduction of energy losses, reduction in weight due to absence of iron core, increase in efficiency can raise the efficiency of power transformers [31]. The judgement of normal or fault state depends on the amplitude of current measured [33].

The source is connected to the load through superconducting transformer. U_A, U_B, U_C are voltage sources, I_A, I_B, I_C are circuit's line current while I_a, I_b, I_c are converter's output current. SC is the superconducting coil. Under normal condition, PWM's output current would keep to a certain value so that the magnetic field in the core of transformer is approximately compensated to zero [34]. C_d and L_d are used as filter for the harmonics caused by the converter.

Because of the presence of superconducting coil, PWM converter can be considered as controllable current source. The Fourier series of the instantaneous current for phase A of a Y- connected load to the converter can be expressed in (2.3).

$$i_a = \sum_{n=1,2,3\ldots\ldots}^{\infty} \frac{4I_L}{n\pi} sin\frac{n\pi}{3} \sin n\left(wt + \frac{\pi}{6}\right) \tag{2.3}$$

The circuit construction of three-phase active SFCL has been presented in Fig.2.11.

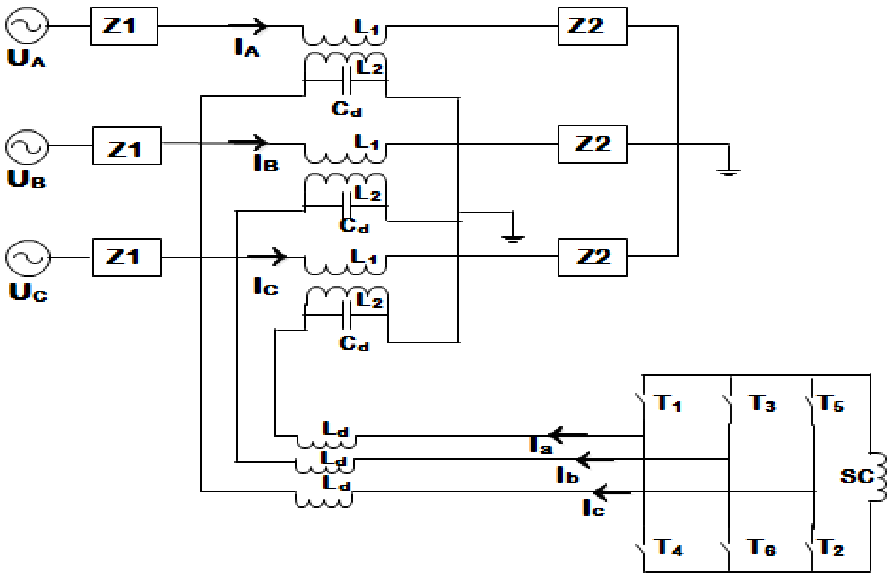


Fig.2.11. Structure of three phase ASFCL

Under normal operating condition, the phase A voltage can be expressed as (2.4)

$$U_A = I_A(Z_1 + Z_2) + jwI_AL_1 - jwMI_a \tag{2.4}$$

Where Z_1 and Z_2 are circuit impedance and load impedance respectively. M is the mutual inductance of two windings of transformer. Three single-phase transformers have been considered, so the mutual inductance between the phases can be neglected.

Considering LG fault, the line current in phase A will rise from I_A to I_{Af}, while the other two phases will remain in their normal states. Replacing I_A by I_{Af} in (2.4), I_{Af} can be expressed as (2.5)

$$I_{Af} = \frac{U_A + jwMI_a}{Z_1 + jwL_1} \tag{2.5}$$

Eq. (2.5) shows that controlling I_a can regulate I_{Af}.

I_a can be controlled by three different modes. They are as follows [32]:

Mode 1: When I_a is in original state.

$$I_{Af} = \frac{U_A}{Z_1 + Z_L} \tag{2.6}$$

Where Z_L is the limiting impedance and can be defined as (2.7)

$$Z_L = jwL_1\left(1 - \frac{I_A}{I_{Af}}\right) \tag{2.7}$$

Mode 2: Controlling the amplitude of I_a to zero. The short circuit current would be written as (2.8)

$$I_{Af} = \frac{U_A}{Z_1 + jwL_1} \tag{2.8}$$

From Eq. (2.8), Z_L (limiting impedance) will be as shown in (2.9)

$$Z_L = jwL_1 \tag{2.9}$$

Since, in this case, the complex value of Z_L is greater than that of mode 1 resulting in better limiting effect.

Mode 3: Regulation of phase angle of I_a to make phase angle of jwI_a lead U_A by 180.The equivalent limiting impedance Z_L is shown as (2.10)

$$Z_L = jwL_1 - \frac{jwMI_a}{I_{Af}} \tag{2.10}$$

From literature survey it has been observed that the limiting effect in the mode 3 is the best of the three; therefore the same has been chosen for reduction of current under faulted condition.

2.3.2.5. Hybrid SFCL

This type of limiter mainly consists of four parts: a) resistive SFCL components along with cryostat, b) a fast switch (FS), c) power fuse, and d) conventional current limiter which might be a resistor or inductor (reactor) [37, 38].

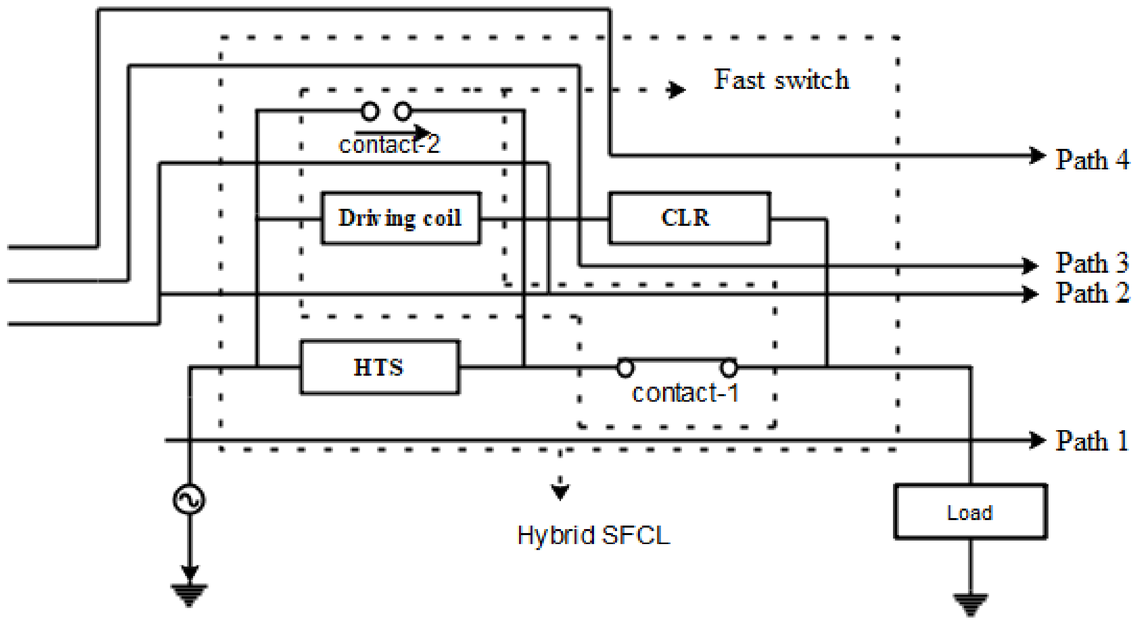


Fig.2.12. Hybrid SFCL

The working of the hybrid SFCL can be illustrated as follows [38]:

During normal condition, current flows via HTS path (path 1). The contact 1 is closed while second is open as shown in Fig.2.12.

Under faulted condition, the HTS transits to its quench state due to the increased (greater than critical value) current flowing through it resulting in enhancement in the resistance. Most of the current follows the path 2 i.e. via driving coil. EM (electromagnetic force) induces in the coil because of the flow of huge current through it which further operate the FS. As a result, the contact 2 as depicted in Fig.2.12 would be closed and thus the maximum current flow via contact 2. Simultaneously, contact-1 is mechanically opened, but still electrically closed because arcing. It opens when current flowing across it reached zero i.e. after extinguishing of arc. Finally, the fault current flow through current limiting reactor and is suppressed (path 4).

After the recovery of the limiter, it recloses and would be available for further fault occurrence.

CHAPTER 3

IMPACT OF SFCL ON TRANSMISSION LINE PROTECTION

The purpose of protective system is isolating the faulty section of the remaining healthy part of the power system. It does not mean that it would prevent flow of fault current. Rather it only check the perpetuation flow of fault current as quickly as possible by disconnecting the short circuit path using breakers. A protective scheme are based on the fundamental parameters i.e. voltage, current and frequency. It comprises of one or more relays for protection of single equipment or a section of line. Distance protection is one of those schemes.

Distance protection is a non-unit protection system i.e. the zone of protection is not exact. It can be used for primary along with back up protection. It is used for HV and EHV transmission and sub-transmission lines protection. The impedance or its components (i.e. reactance and resistance) between location of relay and fault point is the key factor for the working of distance relay. Its basic working principle is based on the ratio of the voltage at relaying point to the measured current at faulted point and the angle between them. The calculated apparent impedance is compared with the pre defined value i.e. impedance of reach point. If the measured impedance is less than the reach point impedance, it is considered as internal fault and the relay will take the appropriate action. The reach point depicts the range of a relay within which it can operate.

These relays can be categorized as phase relay and ground relays. Phase relays are used for transmission line protection during phase faults (L-L-L, L-L) whereas ground relays are used for protection for ground faults such as L-G, L-L-G etc. Distance relay yield primary protection to the line where relay is connected and back up protection to adjacent lines (according to philosophy). The primary protection should be fast, ideally without any delay whereas back up protection is provided in case primary protection fails to work adequately.

The working of distance relay can be divided into three different zones. Zone 1 is taken as primary line protection which is generally set to 80% of the total length. Zone 2 is of 120% of primary line. Zone 2 also provides back up protection to the adjacent line. For back up protection of the remaining adjacent line zone 3 comes into play.

3.1. Classification of Distance Relays

Distance relay can be of different types and are as follows [49]:

- Impedance relay
- Reactance relay
- MHO relay
- Quadrilateral relay
- Other conic section relays

3.1.1. Impedance relay

The characteristic of this relay is realized by comparing current and voltage at fault location. The operating torque is developed by the current component whereas voltage produces the restraining torque. During normal operating condition, the voltage is more than that of current. But during fault occurrence, the magnitude of current increases and that of voltage dips resulting in reduction in the impedance seen between fault and relay location within reach of the relay. Impedance relay is non directional and has a circular characteristics having centre at the origin of R-X coordinates.

The universal torque equation is:

$$T = K_1 I^2 + K_2 V^2 + K_3 VIcos(\theta - \propto) + K_4 \tag{3.1}$$

Where,

K_1, K_2, K_3 are constant. K_4 is the spring constant.

V and I are voltage and current fed to the relay.

Considering K_4=0, voltage to be negative (as it causes restraining torque) in the above equation, the torque equation for the impedance relay can be deduced as Eq. (3.2)

$$T = K_1 I^2 - K_2 V^2 \tag{3.2}$$

The operating torque has to be more than that of restraining one for relay to operate, i.e.

$$K_1 I^2 > K_2 V^2 \tag{3.3}$$

0r,

$$\frac{V}{I} = \sqrt{\frac{K_1}{K_2}} \tag{3.4}$$

Therefore,

$$Z < \sqrt{\frac{K_1}{K_2}} = Constant \tag{3.5}$$

From the above equation, it has been observed that when the impedance identified by the relay is below the preset value, thus impedance relay will operate.

Fig.3.1 shows the operating characteristics of an impedance relay on V-I diagram. The characteristic line is slightly bends near the origin because of the control spring effect.

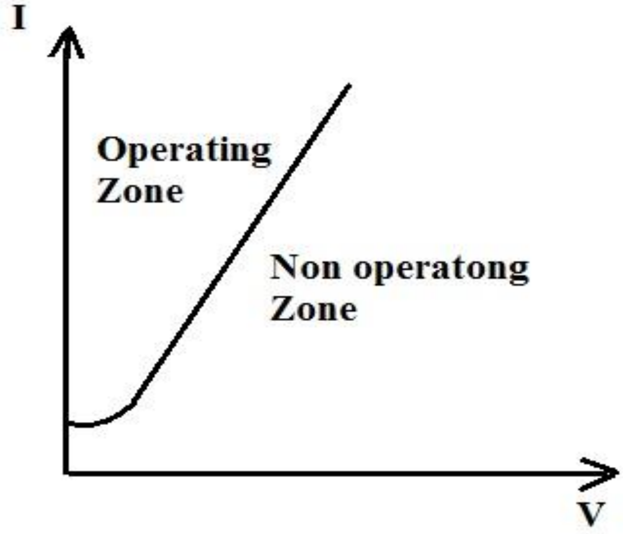


Fig.3.1.Operational Characteristics of Impedance Relay On V-I Diagram

Fig.3.2 shows the operating characteristics on R-X diagram. If the fault point lies within the circle (whether it will be in forward or reverse direction) it will be considered as internal fault and the relay will operate otherwise not. ө is the angle between the current and voltage. Here negative resistance refers to the 180 degree phase lag of current with respect to the voltage not that that the resistance has negative value.

As the characteristic of impedance is circular that means it is non directional relay. However, additional directional element can be added to make it directional shown in Fig.3.3. The directional unit has straight line characteristics and allow the relay to detect fault in forward direction only.

For static impedance relay, either amplitude or phase comparator can be utilized for the working of the relay. In amplitude comparator, Rectifier Bridge is used for realization of the relay characteristics Current proportional to load and that to system voltage provide operating torque and restraining torque individually.

The relay characteristics can also be achieved by incorporating phase comparator by considering voltage, current, IR_r, IXr and IZr, where Z_r impedance circle radius. For impedance relay characteristics realisation, the phase angle between (IZ_r+V) and (IZ_r+ V) has to be compared with ±90 degree.

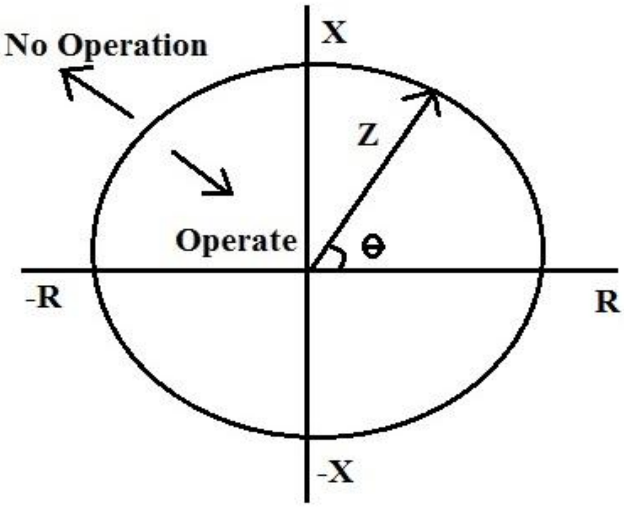


Fig.3.2. Operational Characteristics of Impedance Relay on R- X Diagram

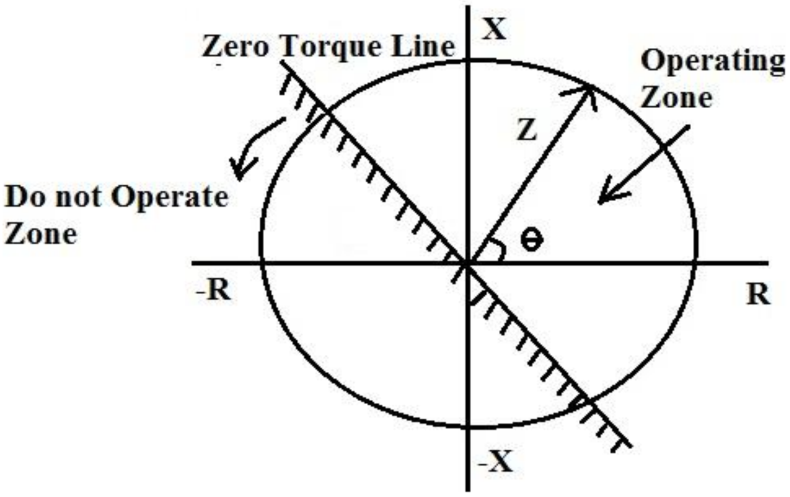


Fig.3.3. Operational characteristics of Impedance Relay with Directional Unit

3.1.2 Reactance Relay

This relay considers only reactance of the line and is not concerned about the variation of resistance. The operating torque for this relay is produced due to the current while the restraining torque is because of the voltage and current of the directional element.

The torque equation of reactance relay can extracted from universal torque equation is given by putting K_2, K_4=0 and $\alpha=90^0$. Thus the torque equation can be defined as Eq. (3.6)

$$T = K_1 I^2 - K_3 VIcos(\theta - 90) \quad (3.6)$$

$$= K_1 I^2 - K_3 VIsin(\theta) \quad (3.7)$$

For the relay operation, T > 0

$$K_1 I^2 > K_3 VIsin(\theta) \tag{3.8}$$

Or,

$$Zsin\theta\ (= X) < \frac{K_1}{K_3} = K\ (Constant) \tag{3.9}$$

From Eq. (3.9), it has been observed that reactance (X) seen must be less than the preset value. The reactance relay characteristic has been shown in Fig.3.4 which indicates it is non directional in nature. It will work for negative reactance also. Negative value indicates the reverse direction i.e. behind the relay location.

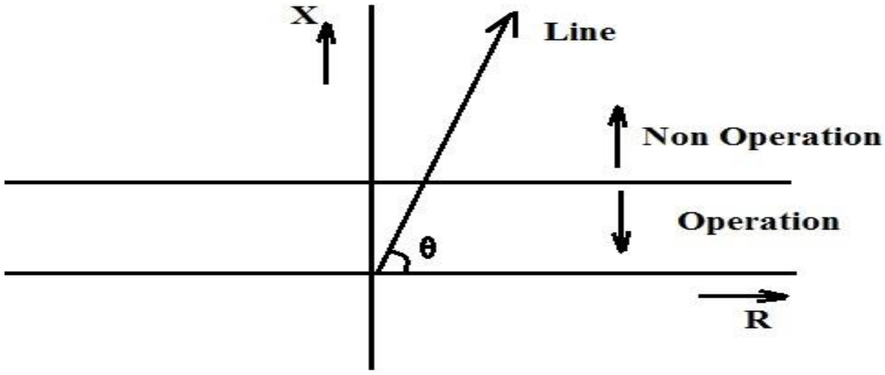


Fig.3.4 Operational Characteristics of Reactance Relay in V-I Diagram

In this case, a circular characteristics directional unit is used for this relay. A straight line characteristic cannot be used as directional unit in this relay as it would not trip for high power factor load conditions. The reactance seen might be greater than the set value for load with high power factor as shown in Fig.3.5. Thus, starting unit is used to prevent false tripping in such cases.

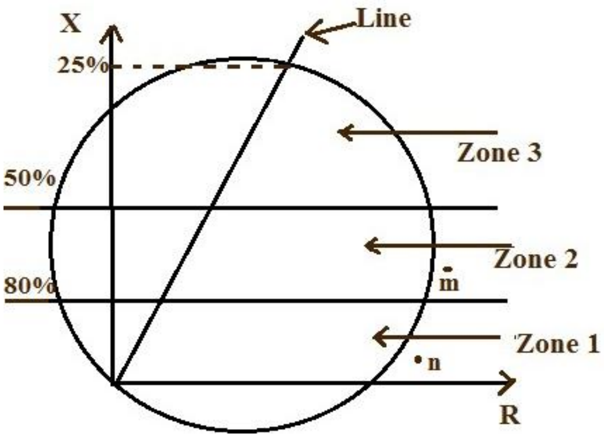


Fig. 3.5 Operational characteristics of reactance relay with directional unit

Static reactance relay can be realized by using both phase and amplitude comparator.

In case of amplitude comparator, the actuating quantities are (I-V/2X_r) and V/2X_r, where V and I are voltage and current sense by PT (Potential Transformer) and CT (Current Transformer). For the operation of the relay and Xr is the reactance of the line need to be protected.

$$\left|I - \frac{V}{2X_r}\right| > \left|\frac{V}{2X_r}\right| \tag{3.10}$$

Or,

$$|2X_r - Z| > |Z| \tag{3.11}$$

For phase comparator, characteristic of reactance relay can be perceived by analogizing phase angle between IX_r and |IZ_r -V| with ±90 degree.

3.1.3. MHO relay

MHO relay measures a component of admittance thus also called as admittance relay. The operating torque for the relay is acquired from the V-I element while restraining torque from voltage element. So, MHO relay is voltage restrained directional relay.

Putting K_1, K_4=0, K_2= -1 in universal torque equation,

$$T = -K_2V^2 + K_3VIcos(\theta-\propto) \tag{3.12}$$

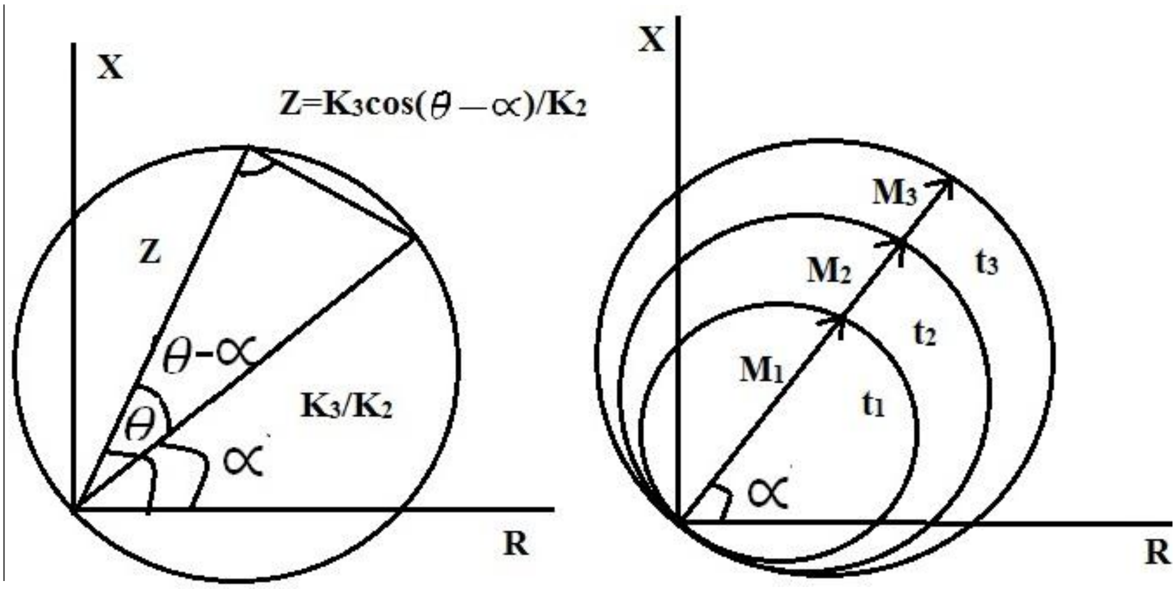
For the operation of relay T > 0

$$K_3VIcos(\theta-\propto) > K_2V^2 \tag{3.13}$$

Or,

$$Z < \frac{K_1}{K_2}(cos\theta-\propto) \tag{3.14}$$

The operating characteristics of MHO relay on R-X diagram is a circle that passes through origin. This relay is inherently directional in nature thus required no directional unit as shown in Fig.3.6. It is called as MHO relay because it has straight characteristics line when plotted on admittance diagram.



(a) (b)

Fig.3.6(a) Operational Characteristics of MHO relay (b) Different zones of protection

For realisation of static MHO relay using amplitude comparator, I and $|V/Z_r - I|$ are considered as actuating quantity. For the operation of the relay

$$|I| > \left|\frac{V}{Z_r} - I\right| \tag{3.15}$$

Or,

$$|Z_r| > |Z - Z_r| \tag{3.16}$$

3.1.4. Quadrilateral Relay – The characteristic of this relay is best fitted for EHV/UHV transmission lines protection because it is merely got affected by fault resistance, power surges and overload [39]. The design of its characteristics is to confine the fault area of the line that has to be protected. The set value for resistance and reactance can be done independently for this relay. It provides better functioning compared to MHO relay in resistance sensing for short lines particularly for determining earth fault impedance. The realisation of quadrilateral relay is carried out using multi input comparator where all the inputs are compared with each other. After all comparisons, the resultant output is obtained in the form of area enclosed with lines and circles. The R-X characteristic for the relay has been shown n Fig.3.7 [40].

The area is enclosed by different lines and can be described by equations as mentioned below:

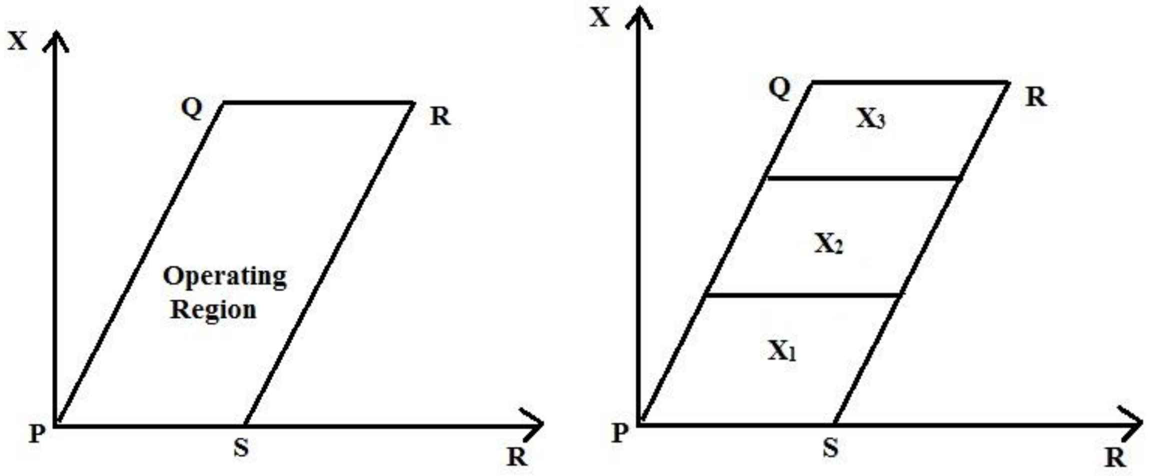
PQ line, $X = M_1 \times R$ (3.17)

QR line, $X = C_1\ (Constant)$ (3.18)

RS line, $X = M_2 \times R + C_2$ (3.19)

SP line, $X = 0$ (3.20)

Where, M_1 and M_2 are slopes of line PQ and RS respectively; whereas C_1 and C_2 are constant. If the R and X measured lie within the area enclosed, it would consider as internal fault and tripping of relay will take place.



(a) (b)

Fig.3.7(a) R-X Characteristic of Quadrilateral relay (39) (b) Different Zones of Protection

3.1.5. Other Conic sections – By time, many more other relay characteristics have been proposed such as elliptical characteristic [40], peanut characteristic, and lens characteristic. These characteristics reduce the reach of the relay in the direction of the R axis. Therefore these relays are used for protection of long transmission lines.

3.2 Overcurrent Protection

Overcurrent (OC) relay offers the simplest form and cheapest form of protection. Its working is based on the magnitude of the current flowing through the circuit. If the amount current flowing is greater than that of the relay's preset value, it would operate. These relays are mainly used for distribution network protection and as a back-up protection for transmission lines. Based on time current characteristics OC relays are further categorized and are as follows:

- Definite time OC relay
- Instantaneous OC relay
- Inverse time OC relay
- Inverse Definite Minimum Time (IDMT) OC relay
- Very Inverse time OC relay
- Extremely Inverse time OC relay

Among the aforementioned OC relay IDMT relays is widely used for protection purpose. In this relay, the operating time varies with the magnitude of the fault current. More will the amount of current, faster would the operation of the relay.

3.3. Impact of Fault Current Limiter on Protection Schemes

The implementation of limiter is considered as one of the appropriate solutions for limiting increased fault current as FCL response is fast and independent. It restrains the transient fault current from reaching excessively large values. The function of an FCL is to protect a system until the circuit breaker gets activated. The circuit breaker operates after receiving the trip signal from relay which in-turn requires the sensing time. Whereas the FCL response solely depends on the amplitude of fault current in the system. However, some issues are there which have to be encountered because of the application of SFCL in the system. One of them is the coordination with other protective devices already present in the system.

Various types of FCL have been discussed earlier. It has been analyzed that resistive SFCL would influence the principle of directional properties whereas inductive type SFCL has no effect on the phase correlation between voltage and current. Rather it mainly emphasize on limiting the magnitude of fault current [41]. The main principle behind the use of FCL is to inject impedance in the system during fault occurrence. Correspondingly current would be limited to safer value. However, the increased impedance altered the maximum magnitude of fault current as well as the overall impedance of the network. Fuses may not blow within the anticipated time if the fault current is not large enough. If the value of impedance is very high, it would limit the increased fault current notably due to which existing relays are unable to identify the fault current resulting in loss of coordination. Consequently, it might affect the altogether functioning of protective relays such as overcurrent (OC) relays, distance relays, reclosures etc.

3.3.1. Impact on Distance Protection Scheme

Distance relays are generally used for the protection of HV lines. In case of distance protection scheme, the relay operation based on the apparent impedance corresponding to the distance between installed location of the relay and the point of fault occurrence. The calculation of the apparent impedance would be achieved by measuring the voltage and current. With the insertion of impedance of SFCL the magnitude of voltage as well as current vary accordingly.

It can be expressed as [43]:

$$Z_{\emptyset\emptyset} = \frac{V_{\emptyset\emptyset}}{I_{\emptyset\emptyset}} (for\ line - line) \tag{3.21}$$

$$Z_{\emptyset} = \frac{V_{\emptyset}}{I_{\emptyset} + 3KI_0} (for\ ground\ distance\ protection\ ) \tag{3.22}$$

Where,

Φ Φ denotes phase to phase i.e. AB, BC or CA.

Φ denotes single phase i.e. A, B or C.

I_0 is zero sequence current.

K is a compensation factor for compensating the current due to mutual coupling of faulted phase with the remaining phases.

Z_0 and Z_1 are zero sequence and positive sequence impedance of the line respectively.

In the presence of SFCL, the impedance of the modifies as shown in Equation (3.23)

$$Z = Z_1 f_l + Z_{SFCL} \tag{3.23}$$

Where,

f_1 is the fault distance.

Z_{SFCL} is the impedance of the limiter. For the operation of distance relay [43],

$$|Z_M| \leq |Z_{set}| \tag{3.24}$$

Where,

$|Z_M|$ - impedance measured by the relay

$|Z_{set}|$ - set value of impedance.

Due to increase in measured impedance, the relays would be incapable in order to make the CB trip because the impedance lays out of the zones of the protection i.e. the internal fault act as external one.

In case of Saturable iron core SFCL (SISFCL) or inductive type SFCL, there is significant variation in overall reactance measured and negligible change in resistance is observed. Therefore, the operation of various distance relays would be affected due to the modified value of reactance. The affect of inductive type mainly emphasize on the fault current amplitude not the phasor correlation of voltage and current [43].

In case of bridge type SFCL, the value of superconducting coil connected to the secondary of transformer through converter modifies the value of fault current as shown in Fig.3.8 [19]. With the increase in the value of inductance of the SC coil, there would be more reduction in current. From the literature review it has been observed that the impact of bridge type SFCL is more during single phase fault as compared to phase to phase fault. Convergence of impedance towards its steady value and evaluation of zones of protection retarded because of bridge type SFCL.

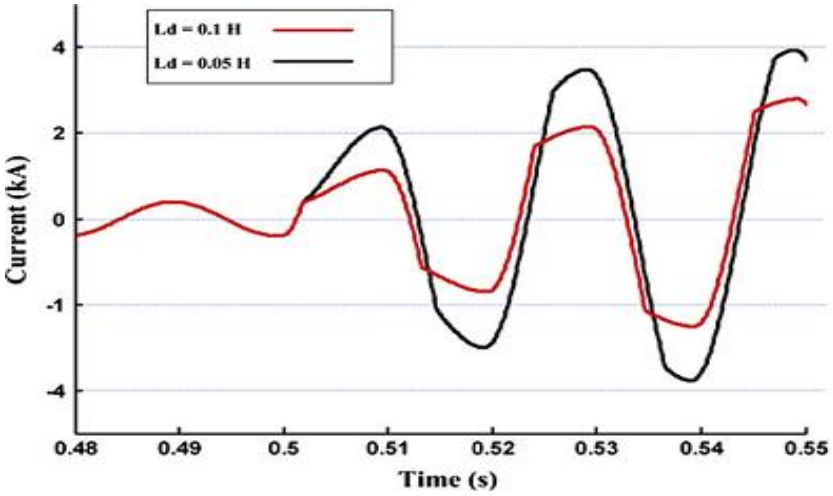


Fig.3.8 Current waveforms for Different Values of Inductance of Superconducting Coil

For resistive type SFCL, during fault condition the HTS material enter in quenching state and then further to high resistive state. Only the resistance of overall system increases which changes the net impedance of the system. However, there is very less impact over the reactance relay. For active SFCL, the impact on the distance protection varies with different modes of operation based on controlling of the output current of the converter [44]. Thus, the setting parameters of distance protection scheme should be modified considering line impedance along with that of the limiter. Alternatively, the values of the parameters of limiter should remain within permissible range so that coordination between the protection schemes endured.

3.3.2. Impact on Overcurrent relay and Reclosures

OC relays are generally employed for primary protection of distribution network as well as back up protection for transmission lines. Reclosures are also used for providing momentary halt to the transitory faults and thus improves the reliability of the system. The impedance of the SFCL immediately after fault occurrence reduce the fault current due to which the circuit breaker trip time has been noticed because of the current limiting action of limiter [46, 47].

Alternation in the reclosures working characteristics due to insertion of limiter has come into noticed. There is either closed out of reclosure for delay in the operation depending upon the shunt resistance of SFCL. Therefore resistance of SFCL needs to be selected confined values along with the time consumed by the SFCL to recover. Alternatively, setting specifications of the overcurrent relay such as TMS pick up current can be reset for well defined coordination [49].

CHAPTER 4

MODELLING AND SIMULATION RESULTS

4.1. Simulation for RSFCL

The modeling of RSFCL has been done by considering four fundamental parameters of a RSFCL as shown in Table 4.1 [27]. Three phase RSFCL has been created by replicating an independent single-phase superconductor model. The triggering current has been taken on the basis of peak value of normal current.

The simulink model for the RSFCL is shown in Fig.4.1 according to which phase current RMS value has been calculated and compared with the SFCL characteristic table. If the measured current magnitude exceeds the triggering current, limiter's resistance increases to the defined maximum value within a pre-defined response time. When the current level eventually decline below the triggering current level, normal state is achieved by the limiter after recovery time.

Table 4.1 Fundamental Parameters of RSFCL

No.	Parameters	Values
1.	Transition/Response time	2 msecs
2.	Minimum Impedance	0.01 Ohm
3.	Maximum Impedance	20 Ohms
4.	Triggering Current	1000 Amps

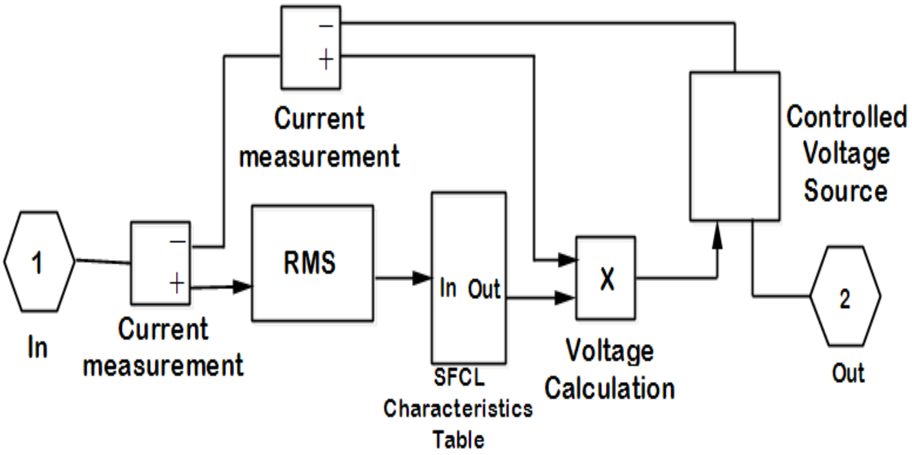


Fig.4.1 Simulink setup for RSFCL

4.2 Simulation model of ASFCL

The simulink modelling for ASFCL has been done as per the diagram shown in Fig.4.2 and IGBT has been used as switches. The modelling of the transformer has been done using the specifications provided in [32].

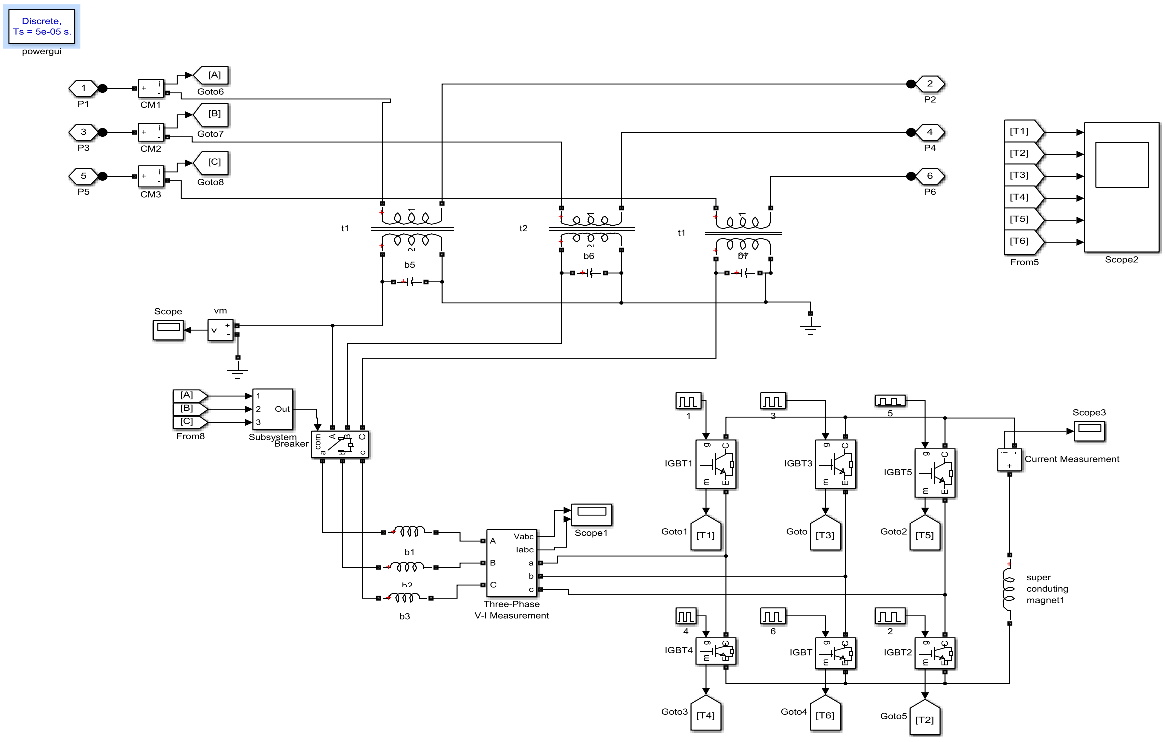


Fig.4.2 Simulation setup for ASFCL

4.3 Comparative Analysis of RSFCL and ASFCL

The modeling of standard nine bus ring system along with both SFCLs has been done using Matlab/Simulink as shown in Fig.4.3. Bus1 has been taken as swing bus while Bus2 and Bus3 as PV buses. Bus5, 6 and 7 are load buses. The details of the system have been in Table 4.2.

Table 4.2 Parameters of the equipments used

G1	500 MVA, 16.5 kV, 50Hz
G2	192 MVA, 18 KV, 50 Hz. Active power -163MVA
G3	128 MVA, 13.8 KV, 50 Hz. Active power - 85MVA
T1	100 MVA, 16.5 kV/230 V, 50 Hz
T2	150 MVA, 18 kV/230 kV, 50Hz
T3	100 MVA, 13.8 kV/230 kV, 50 Hz

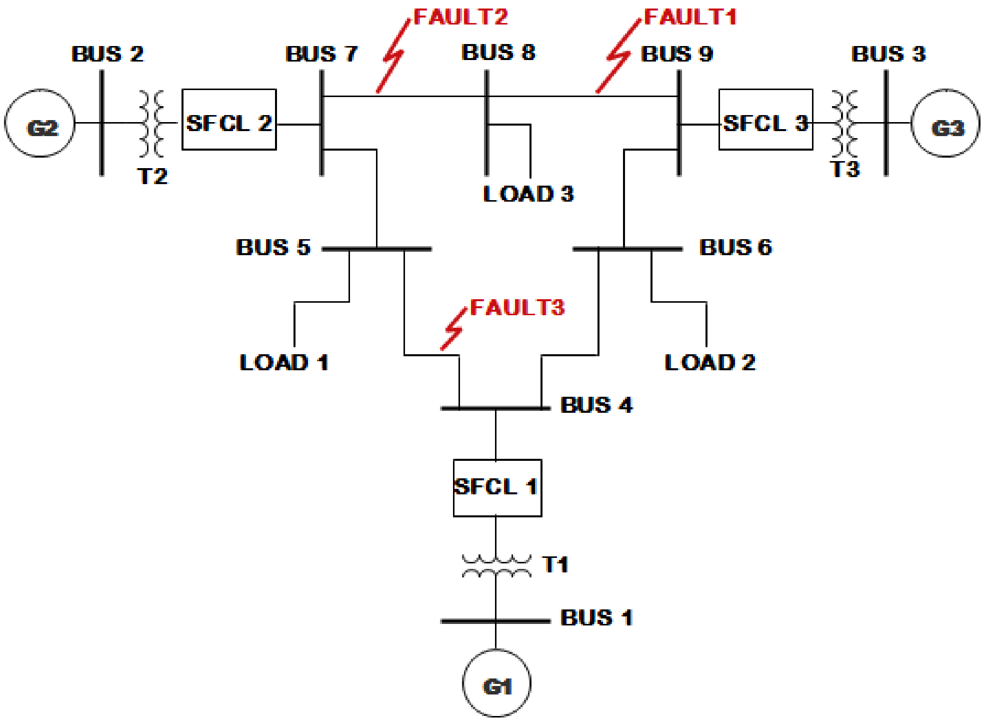


Fig.4.3 Nine bus ring system with SFCL

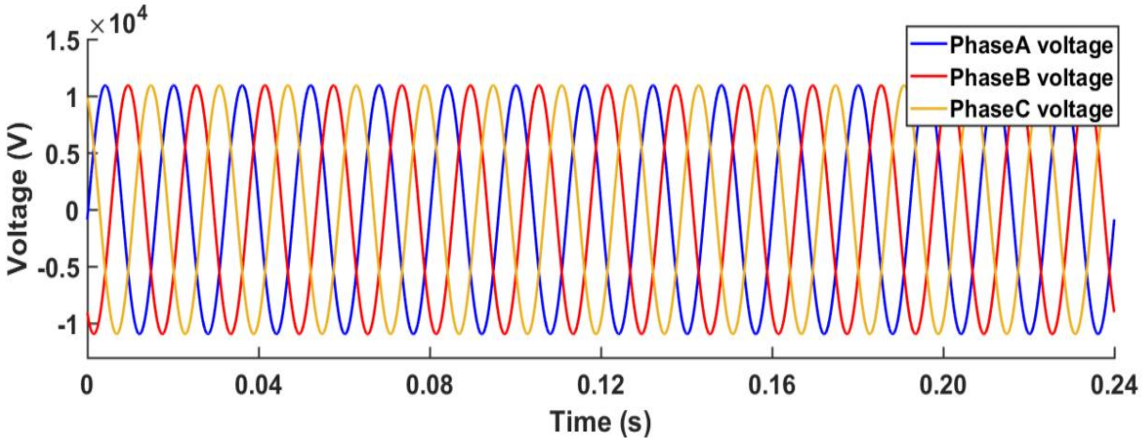


Fig.4.4(a) Normal three phases voltage waveforms at Bus1

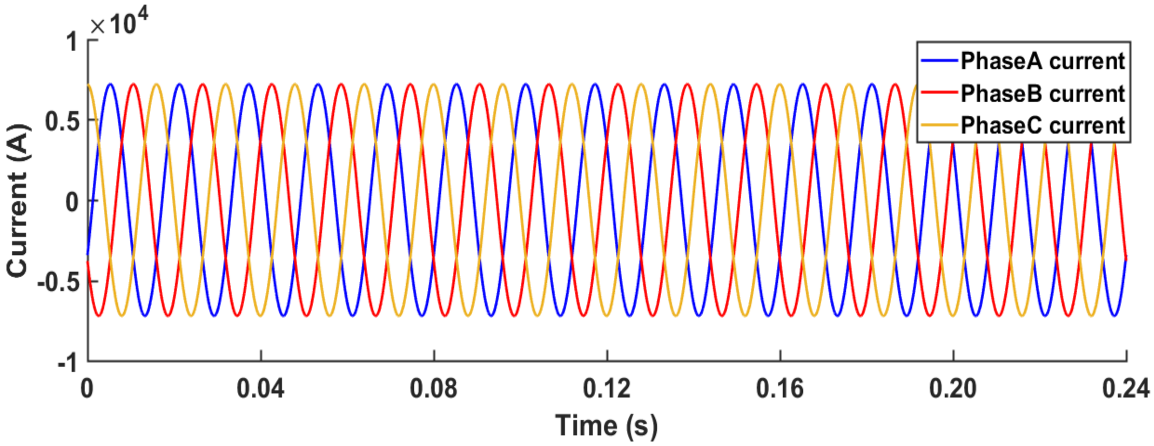


Fig.4.4(b) Normal three phases current waveforms at Bus1

Fig.4.4(a) and 4.4(b) shows the waveforms of three-phase voltage and current respectively under healthy condition at Bus1 (swing bus) with normal load. The SFCLs have been placed near the swing bus and the PV buses of the system and simulated independently for both the types. Single line to ground fault (LG) at different fault location as shown in Fig.4.3 has been considered for the comparative analysis.

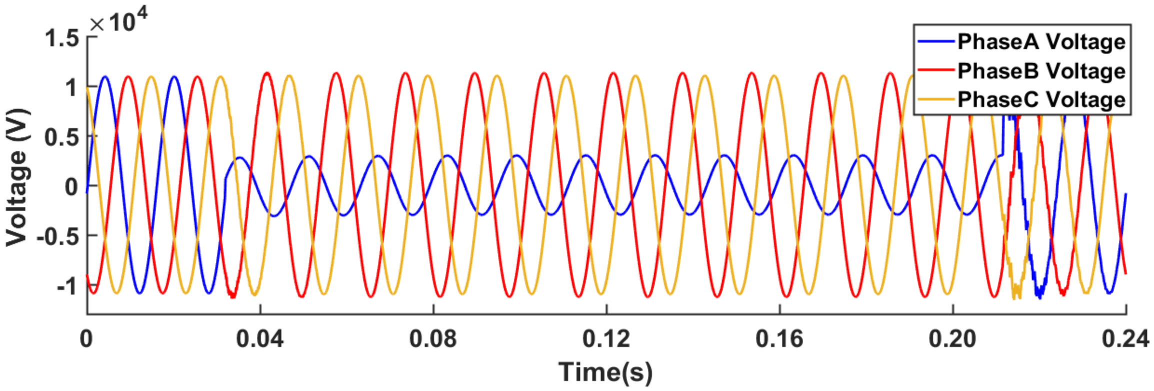


Fig.4.5(a) Voltage waveforms at Bus1 for LG fault at Fault3 without SFCL

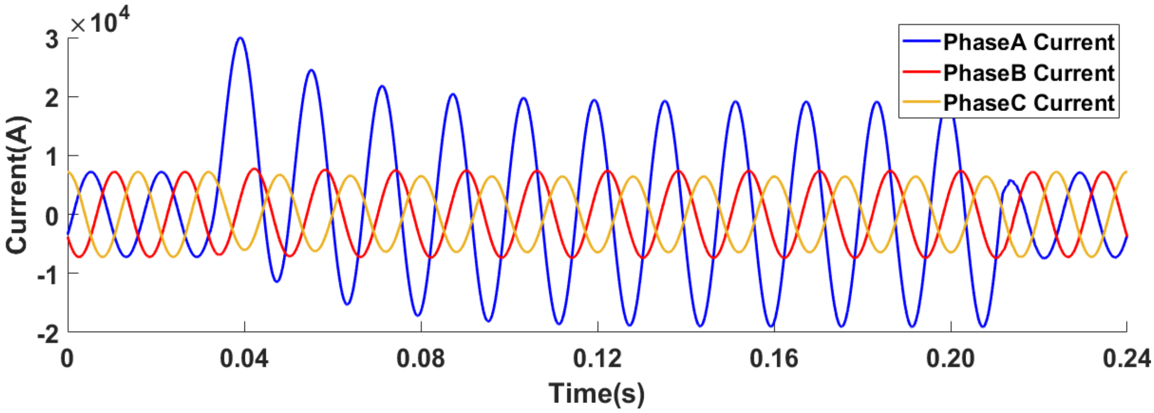


Fig.4.5(b) Current waveforms at Bus1 for LG fault at Fault3 without SFCL

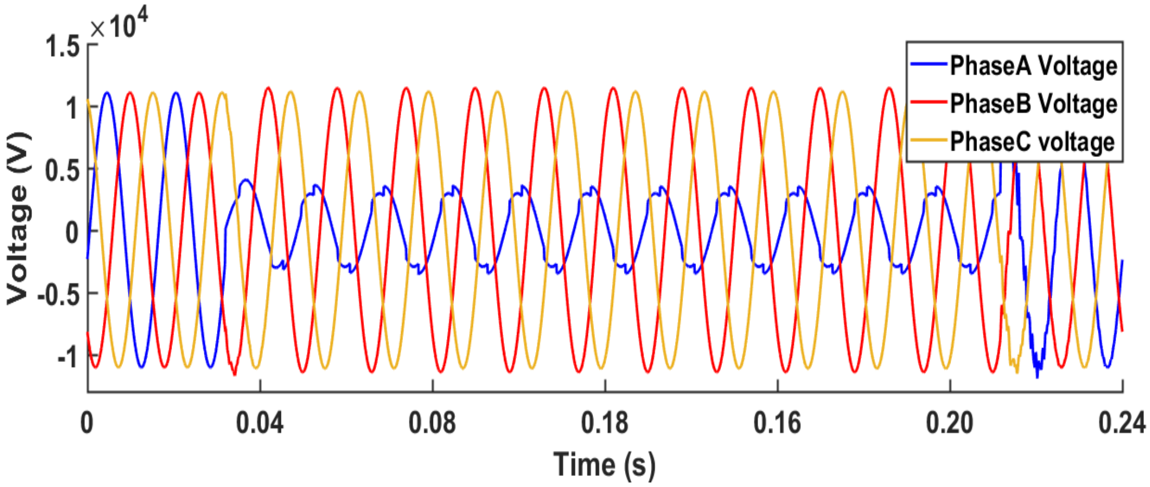


Fig.4.6(a) Voltage waveform at Bus1 for LG fault at Fault3 with RSFCL

Fig.4.5(a) and 4.5(b) depicts the voltage and current waveform at Bus1 during fault1 without utilizing any limiter. Fig.4.6and 4.7 shows three phase voltage and current waveform for LG fault at fault3 after implementation RSFCL and ASFCL one at a time in the nine bus ring system. .

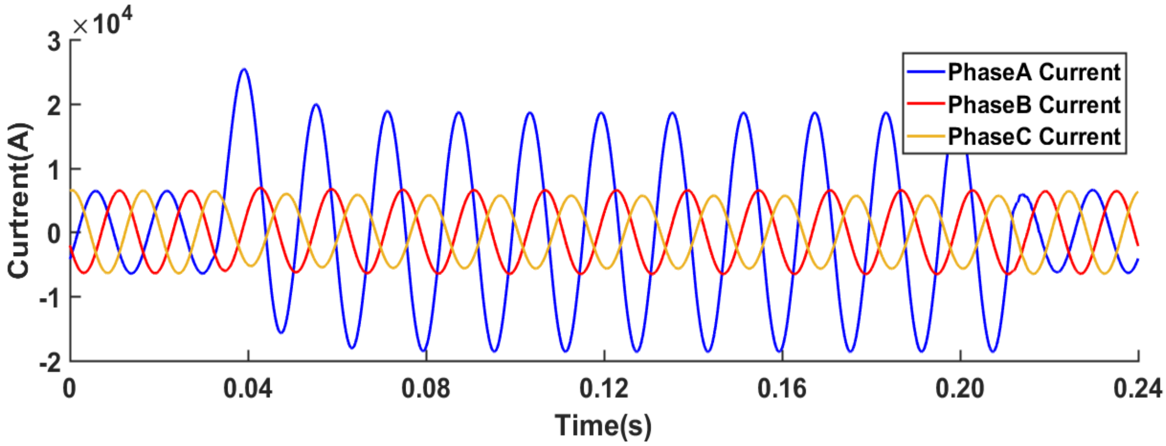


Fig.4.6(b) Current waveforms at Bus1 for LG fault at Fault3 with RSFCL

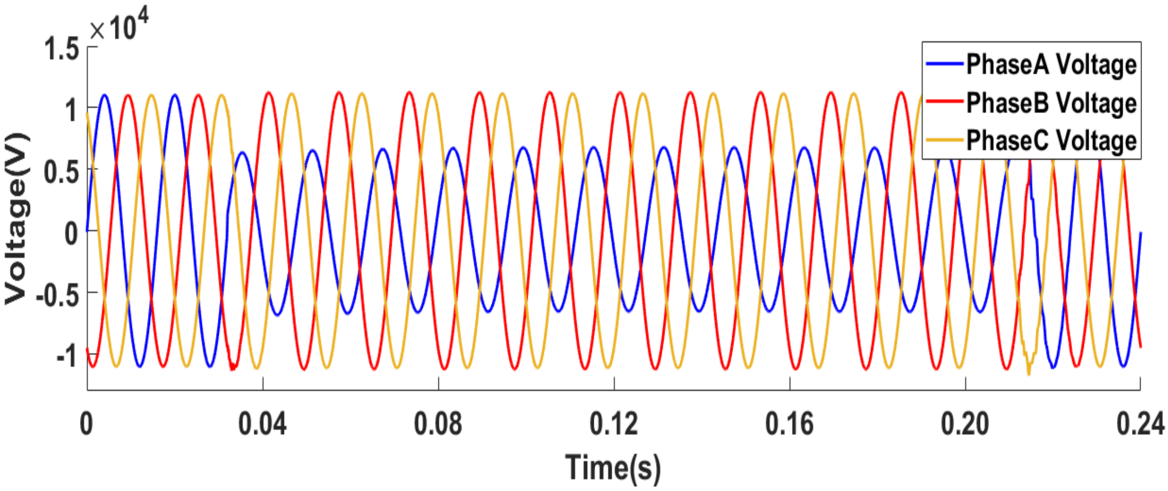


Fig.4.7(a) Voltage waveforms at Bus1 for LG fault at Fault3 with ASFCL

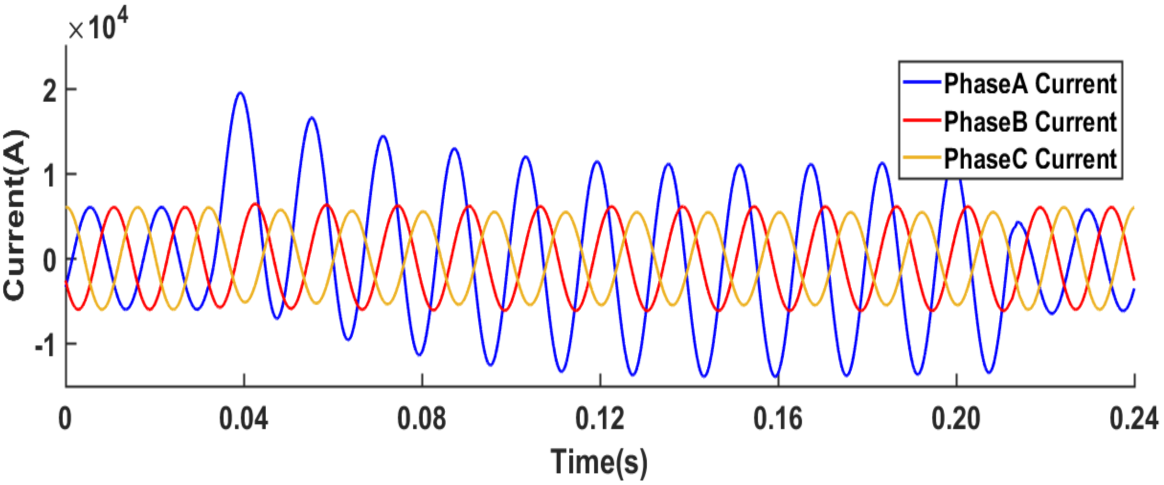


Fig.4.7(b) Current waveforms at Bus1 for LG fault at Fault3 with RSFCL

The current of the faulty phase increases while voltage dips for the duration of fault existence. The FCLs desired behavior during this fault period would be to decrease the magnitude of fault current and improve the voltage profile. Figs.4.8 - 4.10 show the comparison of current and voltage waveforms at Bus1 for single line to ground fault in Phase A, without and with use of both fault current limiters at different locations (1, 2 & 3) as depicted in Fig.4.3. The reduction in the amplitude of the fault current of the faulty phase with ASFCL is more as compared to RSFCL for all the fault locations. The percentage reduction in the peak value of the same with respect to without FCL in the network have been tabulated in Table 5.3. The result shows the percentage reduction of current to be more significant with ASFCL at Bus1 for all the fault locations. The reduction in current under healthy condition has been observed to some extent with the introduction of ASFCL in the bus system studied. The reduction in amplitude of fault current has also been observed at other PV buses for different locations of fault. The improvement in the profile of bus voltage with ASFCL has been also observed. The overall performance of ASFCL under fault conditions acquire the desired outcomes i.e. diminution in fault current along with betterment in voltage profile.

The influence of ASFCL can be seen in the first cycle of fault resulting in transient stability improvement. It can be also used for suppression of transient current during temporary faults on the system thus repress the unwanted disruption of supply.

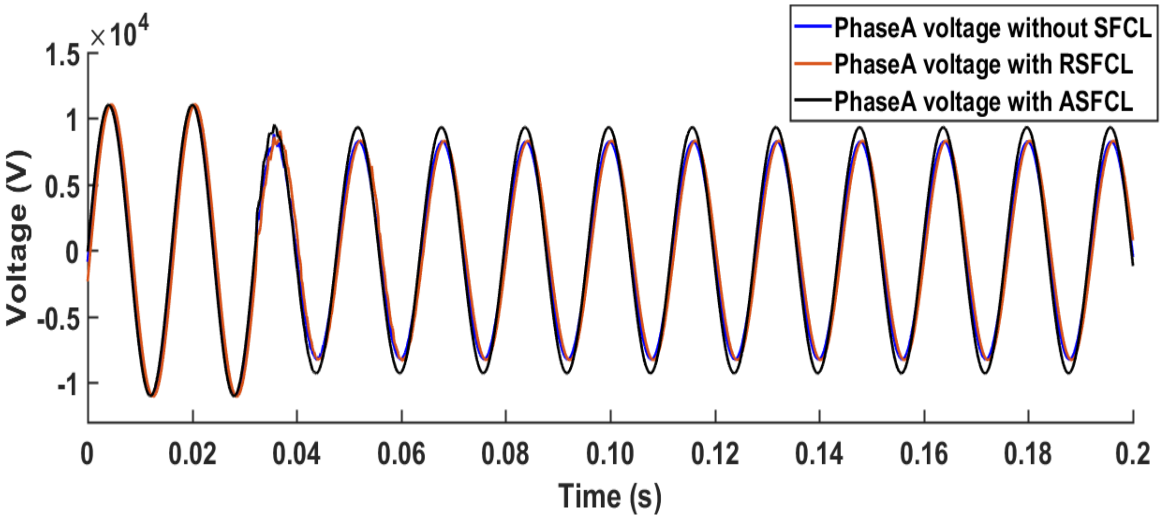


Fig.4.8(a) Phase A voltage at Bus1 for LG fault at Fault1

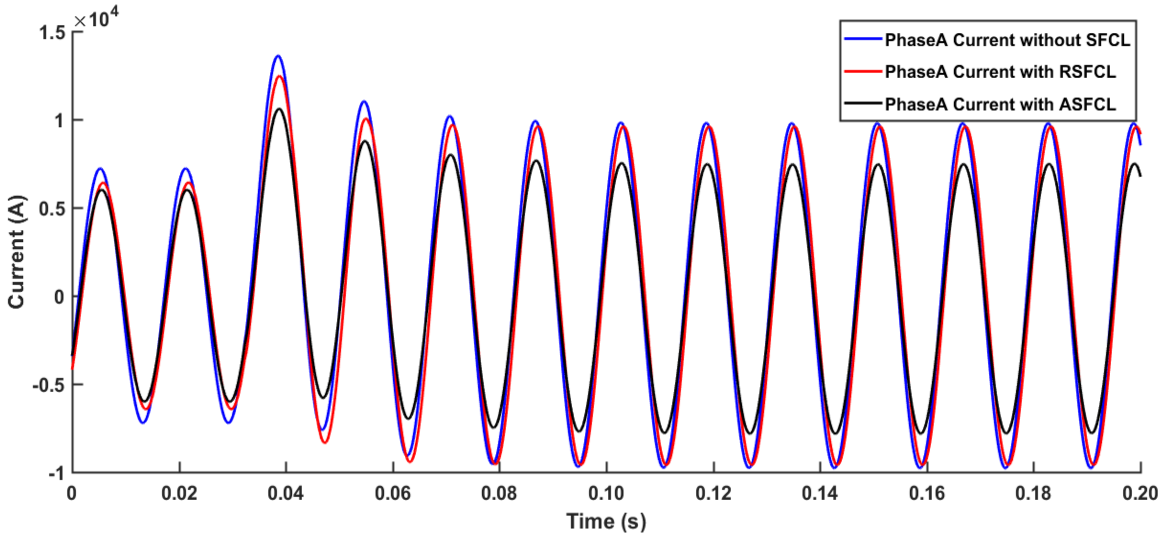


Fig.4.8(b) Phase A fault current at Bus1 for LG fault at Fault1

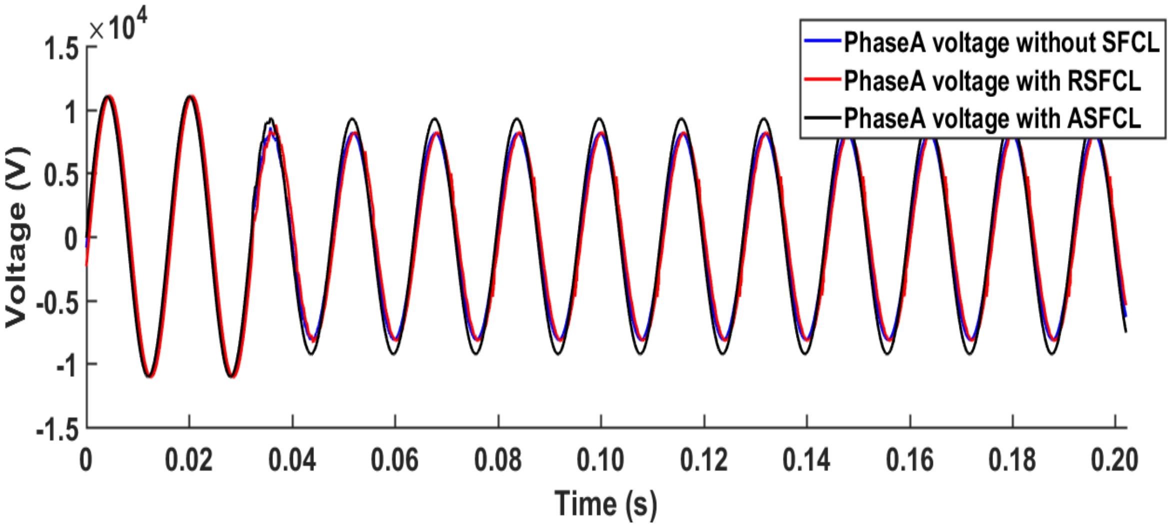


Fig.4.9(a) Phase A voltage at Bus1 for LG fault at Fault2

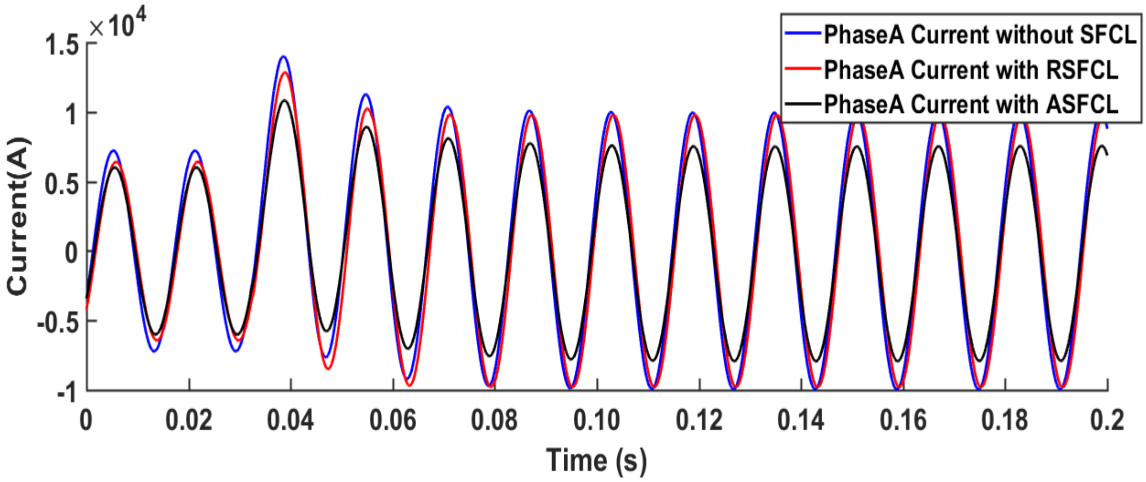


Fig.4.9(b) Phase A fault current at Bus1 for LG fault at Fault2

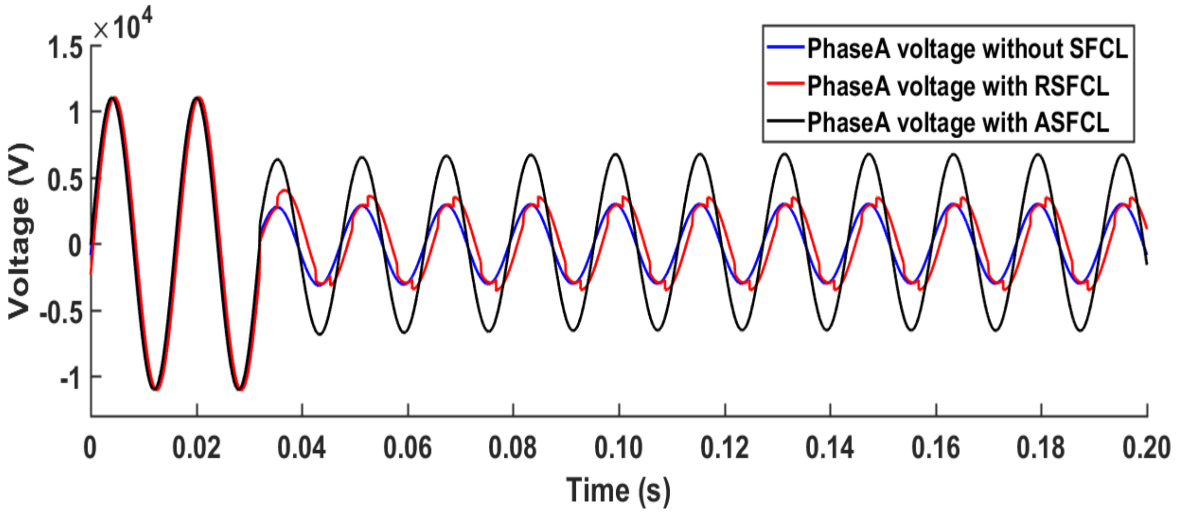


Fig.4.10(a) Phase A Voltage at Bus1 for LG fault at Fault3

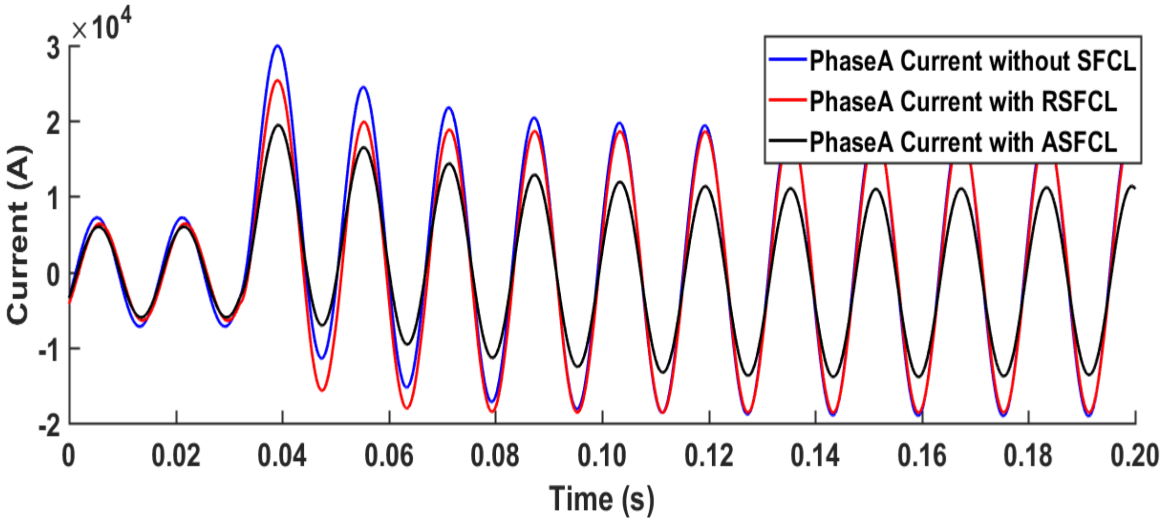


Fig.4.10(b) Phase A fault current at Bus1 for LG fault at Fault3

Table 4.3 Comparison of fault current for type of SFCL used

Fault location	Fault Current (KA)			% Reduction	
	Without SFCL	With RSFCL	With ASFCL	With RSFCL	With ASFCL
Fault1	13.62	12.46	10.59	8.5%	22.79%
Fault2	13.9	12.82	10.81	8.29%	22.75%
Fault3	29.9	25.37	19.46	15.61%	34.79%

4.4. Impact of ASFCL on Distance Protection

The working of distance relay depends on the impedance or its component between the fault location and the placement of the relay. However, the implementation of limiter in the existing system modifies the overall impedance of the network. Figs.4.11 (a) - (c) show the change in the value of resistance, reactance and impedance due to implementation of ASFCL during LG fault (fault3) at different distance from Bus1.

Fig.4.12 shows the voltage and current waveform for fault3 as LLG fault at a distance of 50 km from Bus1 without implementing SFCL. Fig.4.13 shows voltage and current waveforms for the same condition including ASFCL at all three location as shown in Fig.4.3. The waveform depicts improvement in voltage as wellas reduction in magnitude of current for both the pahases during fault condition.

Fig.4.14 shows the impedance and its component with and without ASFCL at different distance from Bus1 for LLG fault at fault3.

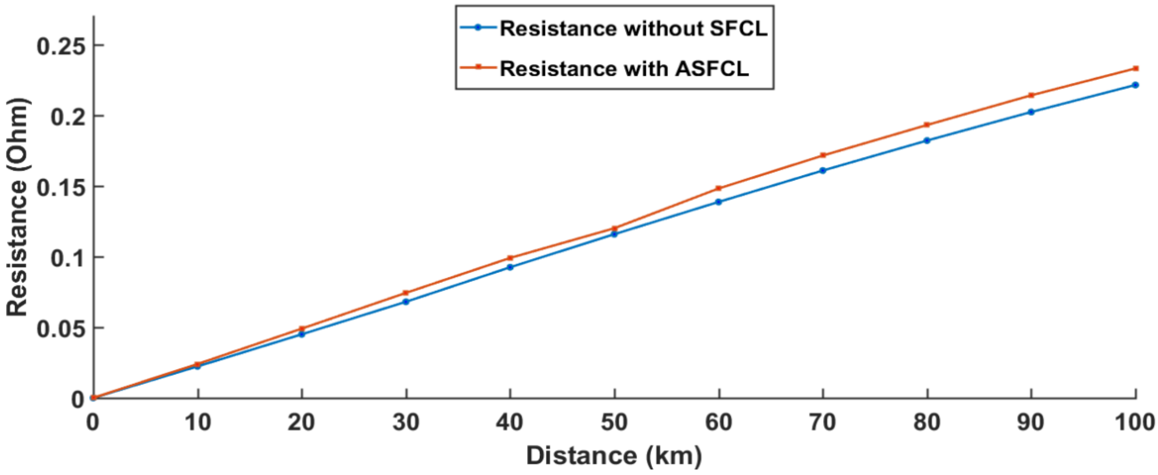


Fig.4.11(a) Resistance seen at Bus1 at various distances for LG fault (Fault3)

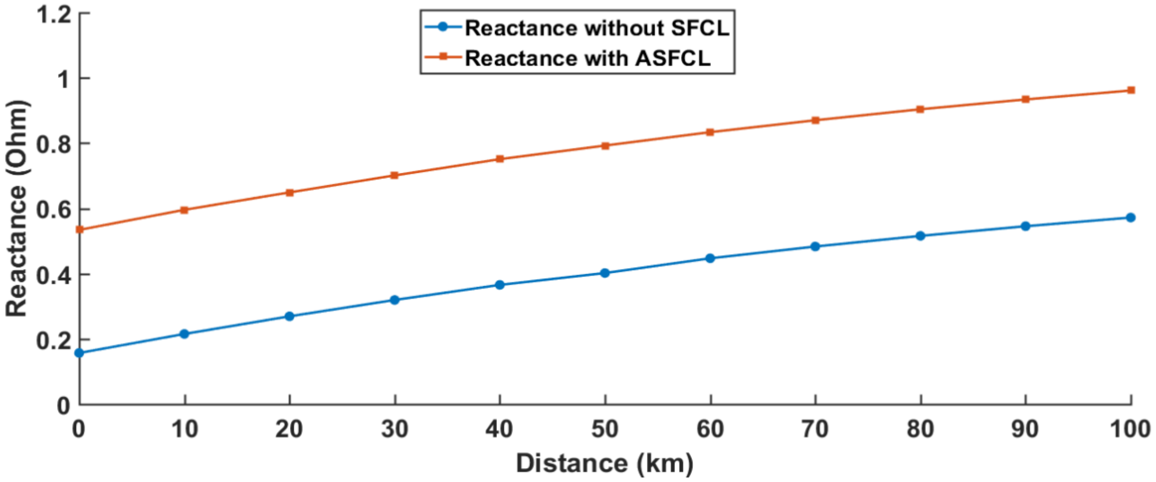


Fig.4.11(b) Reactance seen at Bus1 at various distances for LG fault (Fault3)

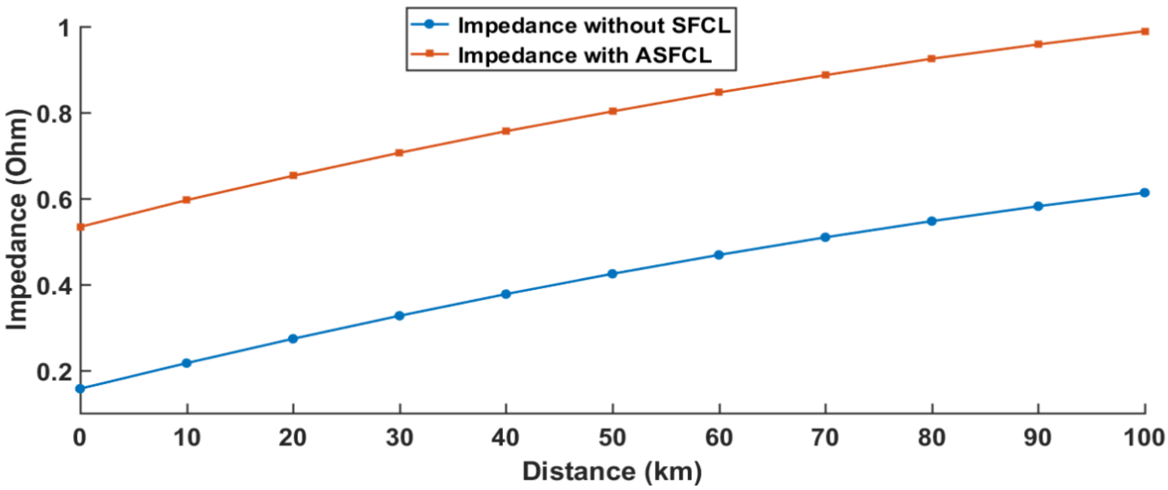


Fig.4.11(c) Impedance seen at Bus1 at various distances for LG fault (Fault3)

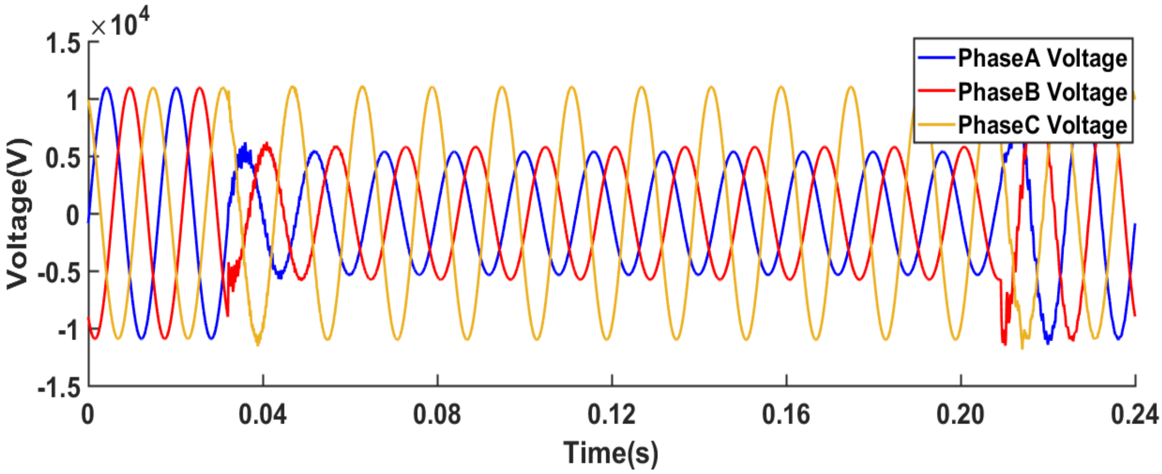


Fig.4.12(a) Voltage waveforms at Bus1 at 50 km distance for LLG fault (Fault3) without SFCL

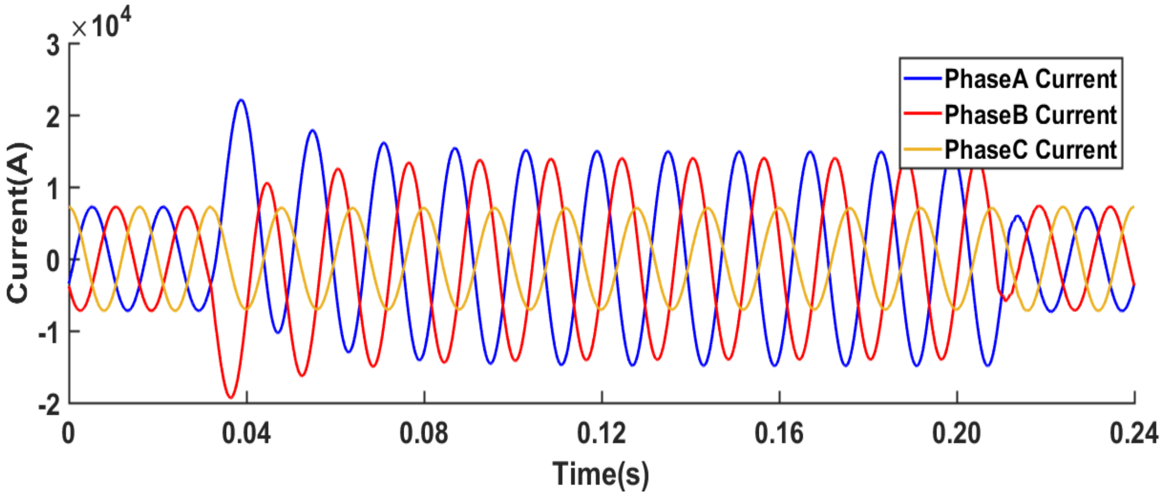


Fig.4.12(b) Current waveforms at Bus1 at 50 km distance for LLG fault (Fault3) without SFCL

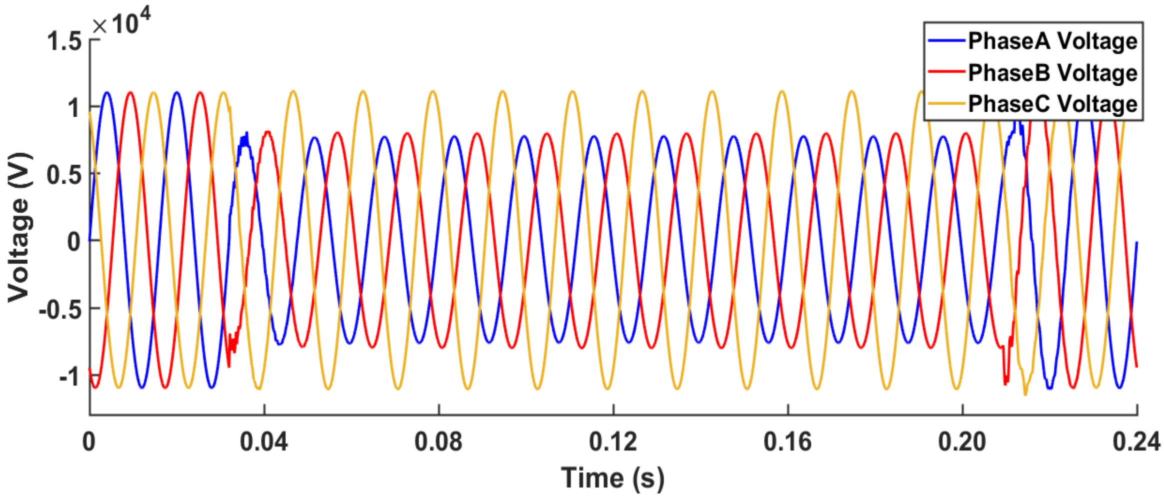


Fig.4.13(a) Voltage waveforms at Bus1 at 50 km distance for LLG fault (Fault3) with ASFCL

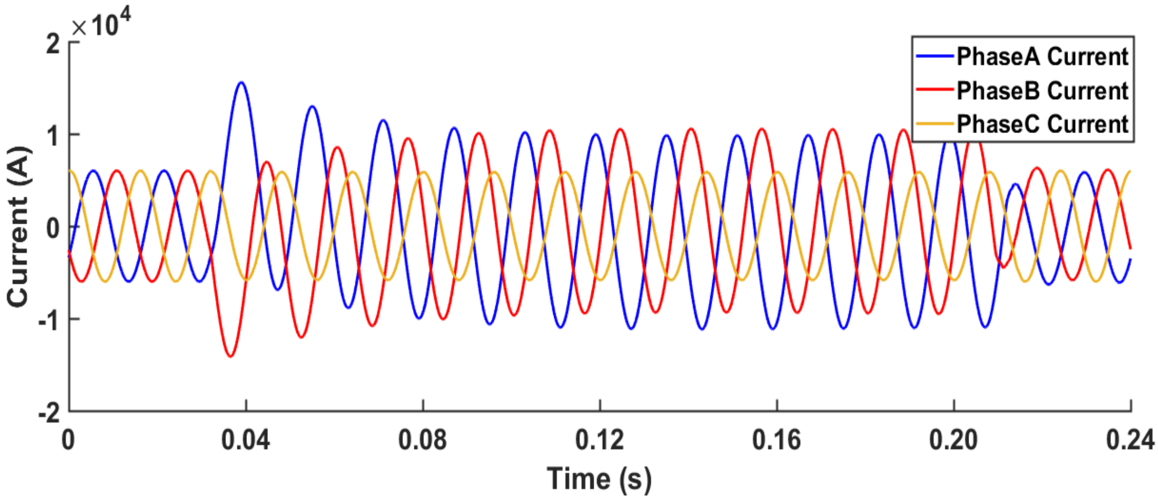


Fig.4.13(b) Current waveforms at Bus1 at 50 km distance for LLG fault (Fault3) with ASFCL

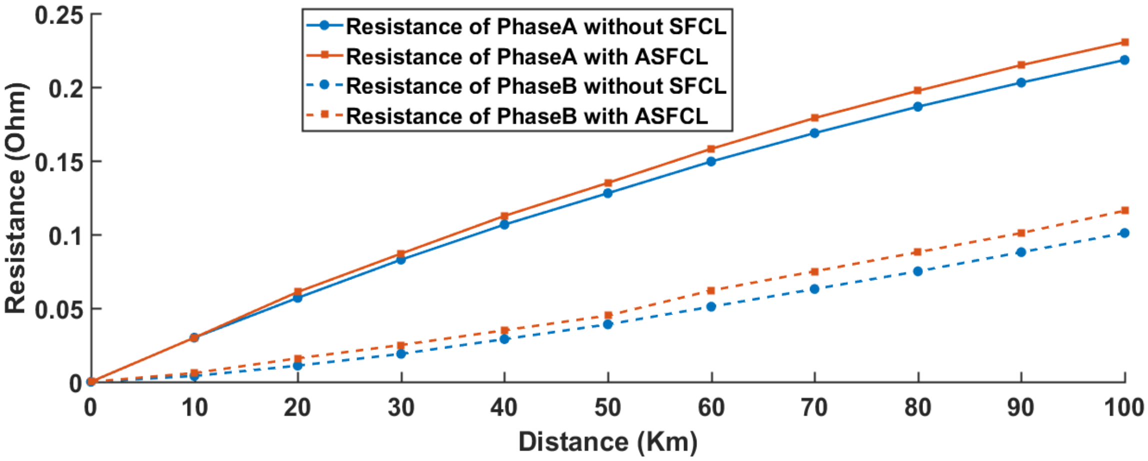


Fig.4.14(a) Resistance seen at Bus1 at various distances for LLG fault (Fault3)

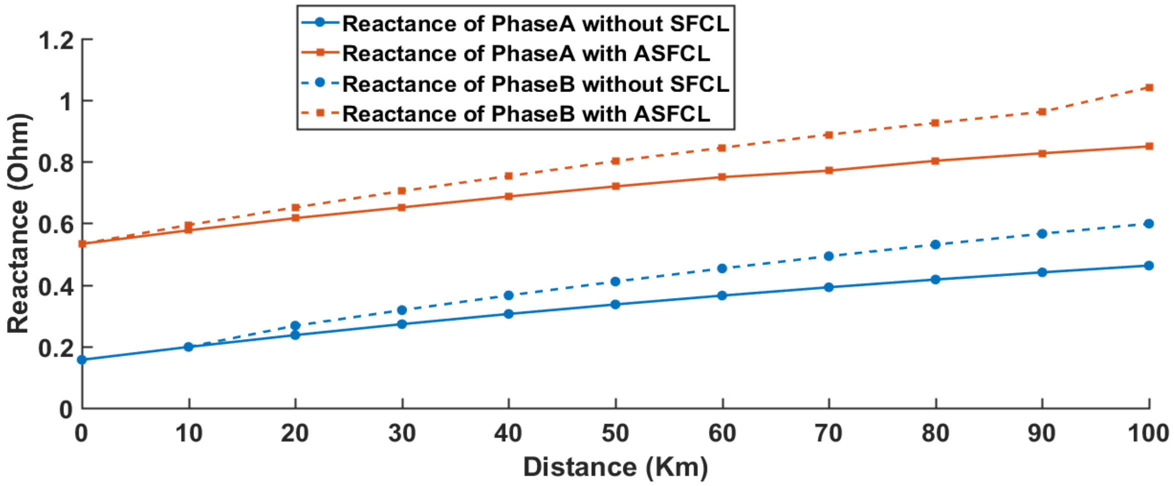


Fig.4.14(b) Reactance seen at Bus1 at various distances for LLG fault (Fault3)

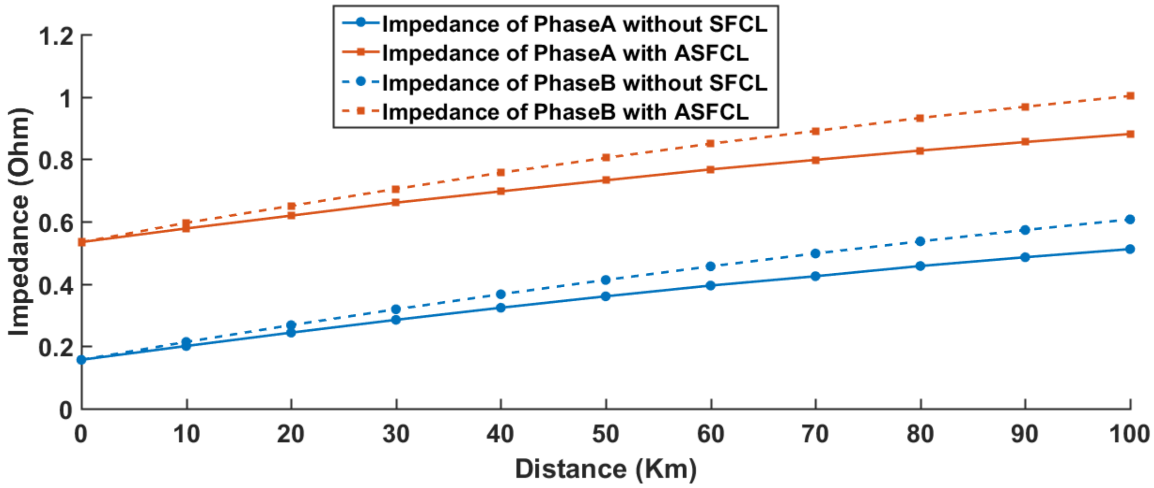


Fig.4.14(c) Impedance seen at Bus1 at various distances for LLG fault (Fault3)

Fig.4.15 and 4.16 show the voltage and current waveform for LLLG fault with and without ASFCL at 50 km distance from Bus1. After initial few cycles, the magnitude of voltage and current is almost equal during LLLG fault condition.

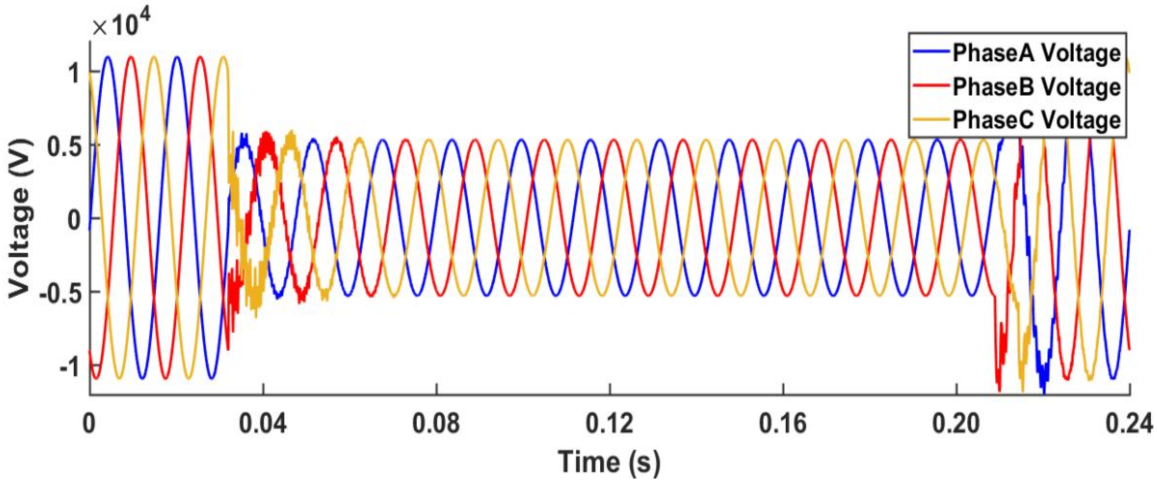


Fig.4.15(a) Voltage waveform at Bus1 at 50 km distance for LLLG fault (Fault3) without SFCL

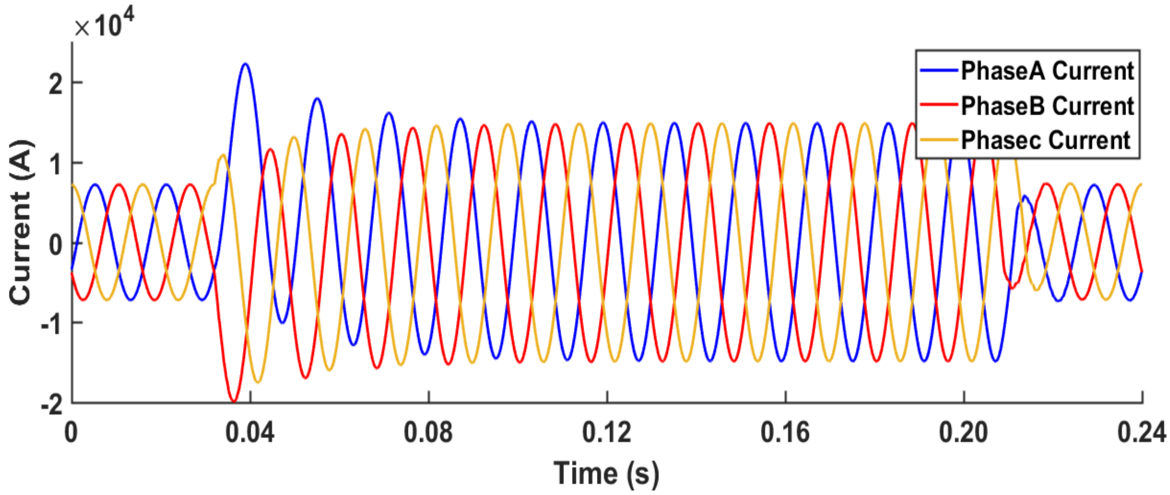


Fig.4.15(b) Current waveforms at Bus1 50 km distance for LLLG fault (Fault3) without SFCL

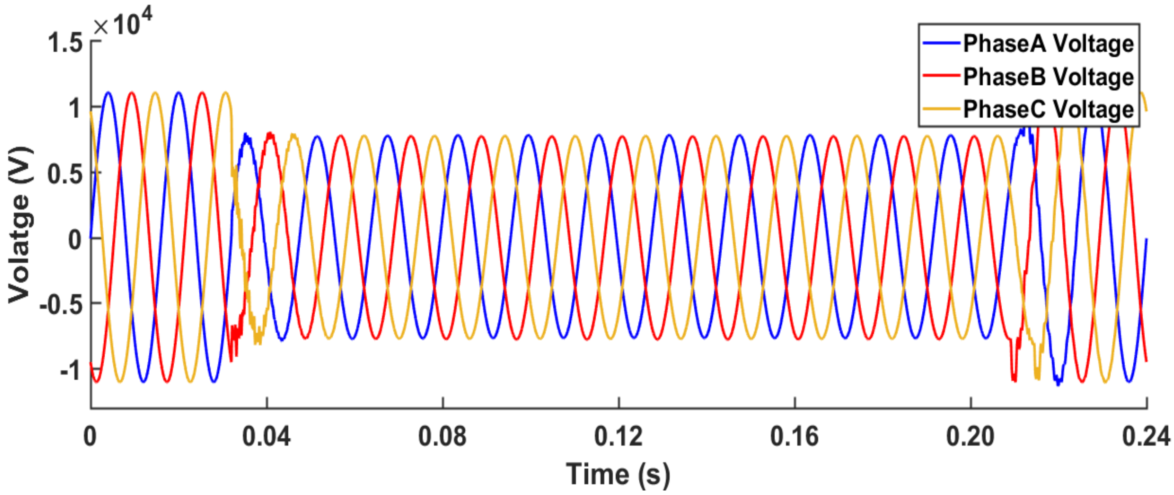


Fig.4.16(a) Voltage waveforms at Bus1 50 km distance for LLLG fault (Fault3) with ASFCL

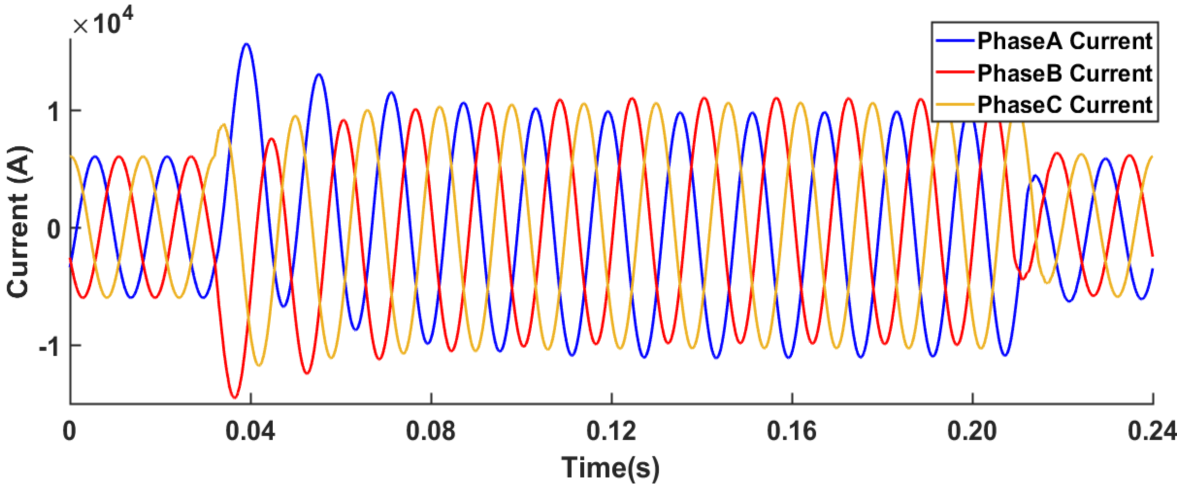


Fig.4.16(b) Current waveforms at Bus1 50 km distance for LLLG fault (Fault3) with ASFCL

Fig.4.17 depicts the impedance and its component seen for LLLG fault. Their values for different phases are almost coinciding with each other as the magnitude voltage and current are similar for the fault duration.

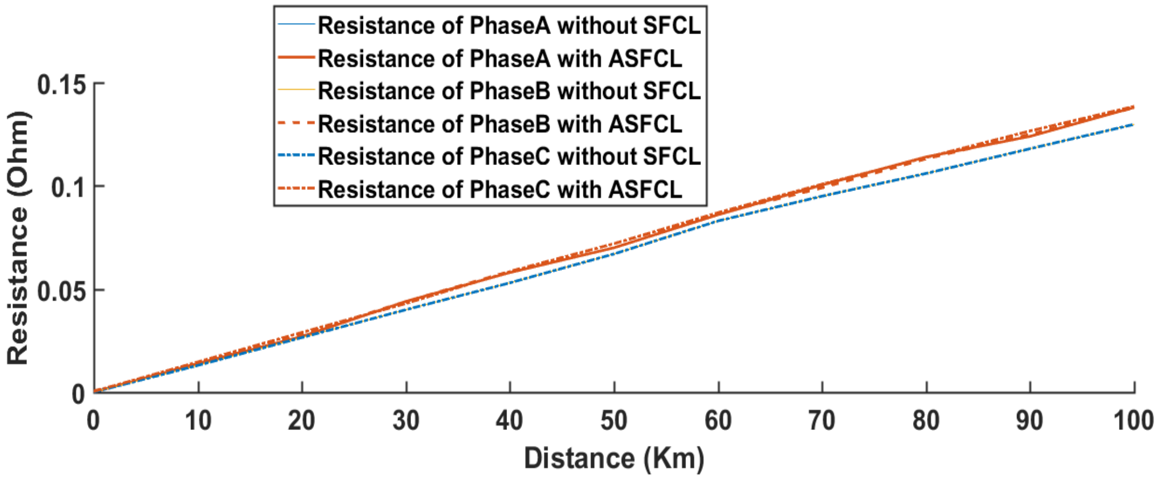


Fig.4.17(a) Resistance seen at Bus1 at various distances for LLLG fault (Fault3)

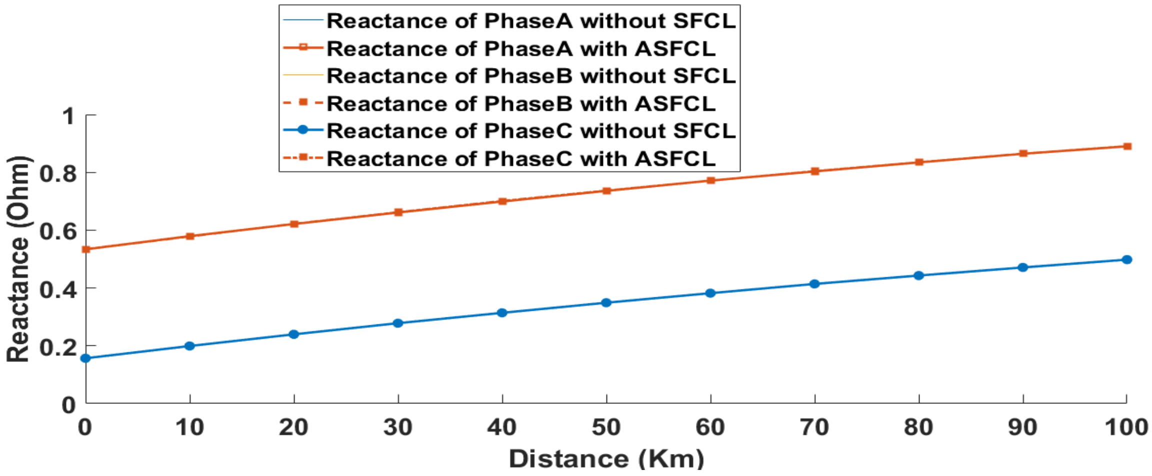


Fig.4.17(b) Reactance seen at Bus1 at various distances for LLLG fault (Fault3)

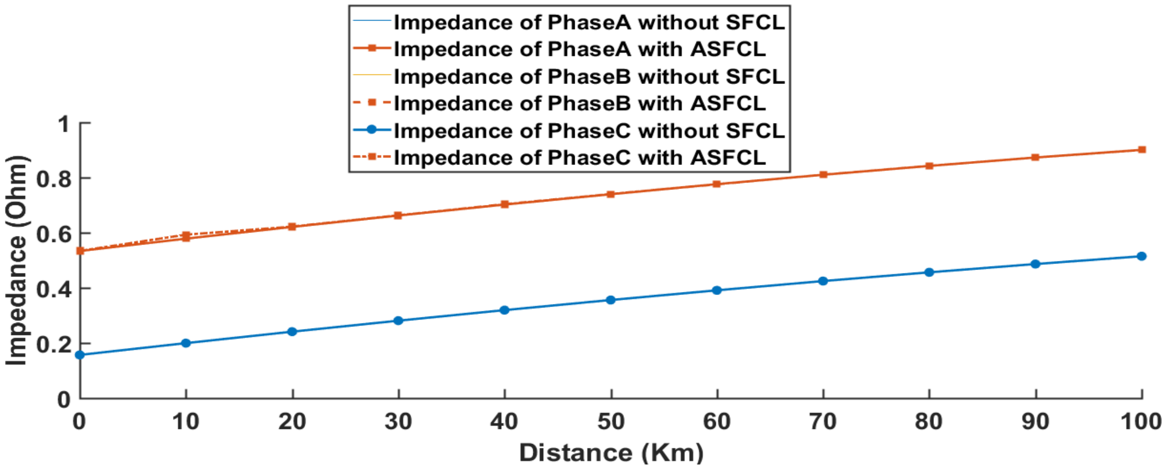


Fig.4.17(c) Impedance seen at Bus1 at various distances for LLLG fault (Fault3)

The results obtained depict significant change in measured value of reactance and impedance in the presence of the Active SFCL. There is negligible effect in the measured value of resistance. This is due the fact that the limiter used has negligible resistance and has superconducting coil at the secondary of the transformer. Air core superconducting transformer has been considered for the modelling of active SFCL which has high magnetising reactance and whose impact is noticed during fault condition. The resistance of the windings of superconducting transformer is also very low. During fault condition, the limiter comes into existence resulting in the increment in the overall reactance of the system which further modifies the net impedance during fault. The modified value would affect the zone of protection of distance relay implemented near the swing and PV buses. The set value of different types distance relays has to be modified as per the updated value of impedance and reactance for preventing them from maloperation.

For quadrilateral relay, the x-axis representing the resistance need not be changed. The inception angle and net operating area depends on the reactance injected by the limiter. Hence, the zones of protection for different buses need to be redefined as per the upgrade values of reactance and net reactance.

Generally, overcurrent relays are used as back up protection for the transmission lines in case of failure of distance protection scheme. The setting of the OC relay is on the basis of the magnitude of the fault current. Due to the increasing of the interconnection as well as penetration of DGs in the existing system, the amount of fault current shoots up which night affect the functioning of circuit breakers and reclosures installed in the system. The implementation of fault current limiters suppresses the magnitude of the increased fault current.

Fig.4.18 shows the change in magnitude of fault current for different types of faults due to the implementation of SFCL. However, the reduction in fault current because of SFCL might affect the working of overcurrent relays employed for the back-up protection of the system. The reactance of superconducting transformer has significant impact over the time constant of the system during the fault. Its affect can be realized from the change of slope of current in the presence of ASFCL. So, the setting parameters of the overcurrent relays should be redefined as per the reduced value of fault current for its proper functioning.

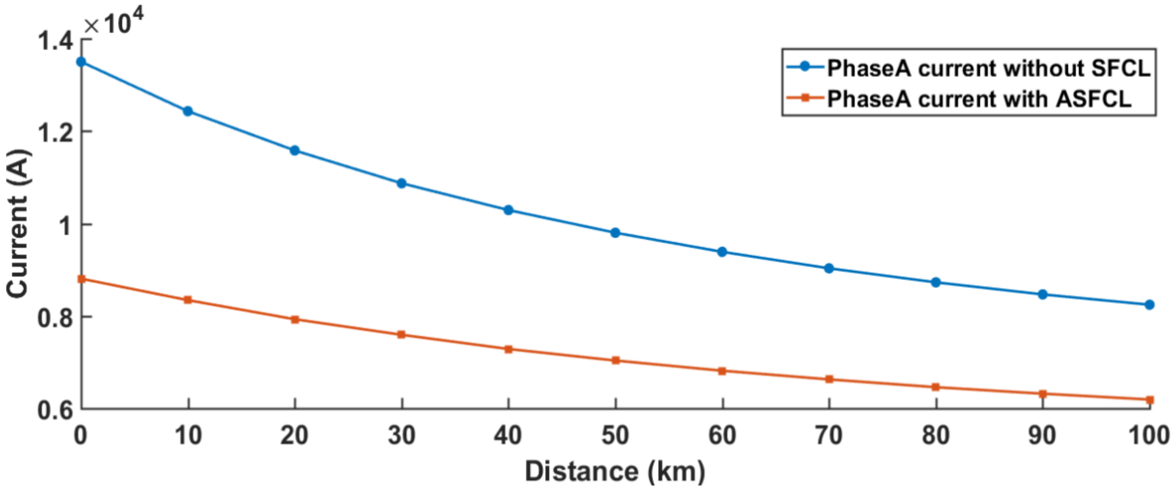


Fig.4.18(a) Current magnitude at various distances for LG fault (Fault3)

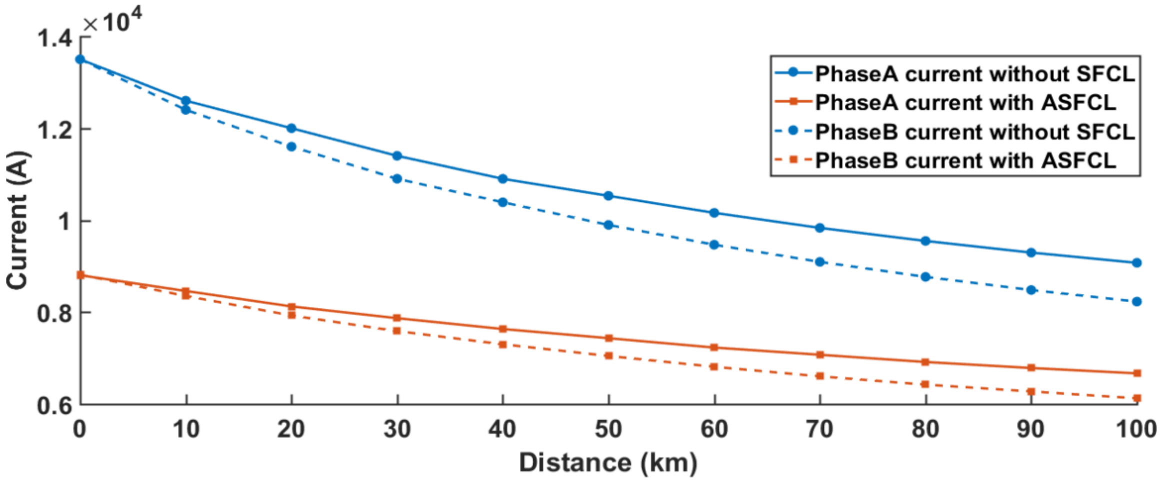


Fig.4.18(b) Current magnitude at various distances for LLG fault (Fault3)

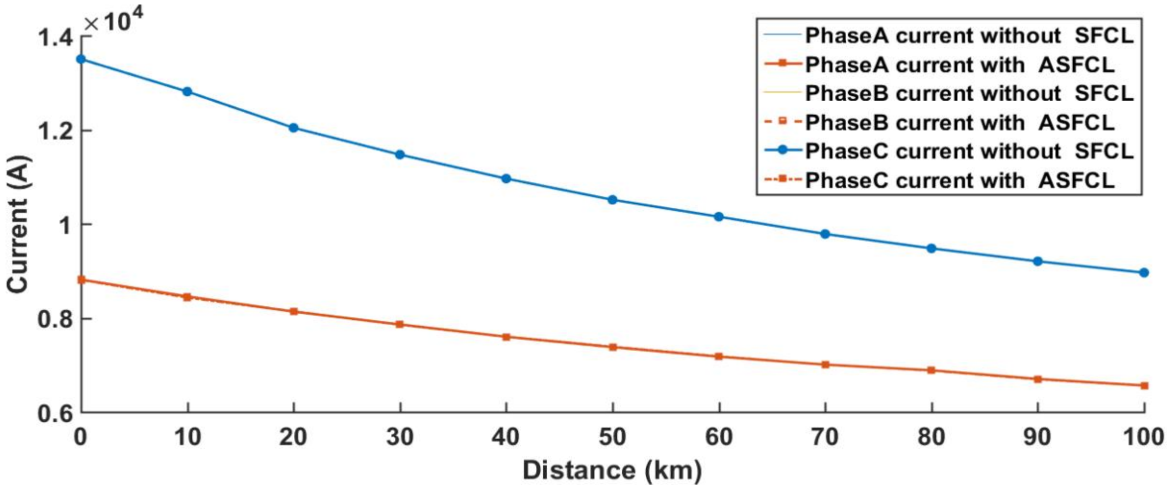


Fig.4.18(c) Current magnitude at various distances for LLLG fault (Fault3)

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1. CONCLUSION

In the presented work, the implementation of Superconducting Fault Current Limiters for reducing the fault current has been analysed. A comparative analysis of ASFCL and RSFCL in a nine bus ring system for single line to ground fault has been carried out. SFCLs have been placed at the source ends and simulated individually using Matlab/Simulink. The currents and voltages at Bus1 (swing bus) for faults at different locations with and without SFCLs have been analyzed. The percentage reduction in fault current has been observed to be more significant in ASFCL as compared to RSFCL. The simulation results also reveal improvement in voltage profile with ASFCL in the system. The effective submission of SFCL helps in reduction of fault current in the very first cycle of fault occurrence resulting in transient stability improvement. The reduction in amplitude of fault current in the presence of SFCLs has been also seen at other PV buses for different locations of fault.

However, with the submission of ASFCL has influence over the other protective schemes present in the system as the net impedance and its components seen by the relays altered because of the impedance of SFCL during fault duration. The modification in the impedance and its components for different types of faults at different distance has been analyzed. Considerable change in the reactance as seen by the distance relays has been observed due to superconducting air core transformer used in ASFCL while there is negligible change in the resistance Furthermore, the reduction in the amplitude of fault current has also been examined. Based on the modified value of net impedance and fault current, the setting parameters of existing protective devices need to be redefined.

5.2. FUTURE WORK

Future studies on this work can be carried out in following ways:

- Implementing SFCL for larger bus system as well as at different voltage levels.
- The hardware implementation of SFCL can be executed and its impact on distance protection using Transmission Line Simulator (TLS) can be analyzed.
- Its working along with FACTs devices can be also realized.

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