Modelling and Analysis of Resistive Superconducting Fault Current Limiter.

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF TECHNOLOGY
IN
“CRYOGENIC AND VACUUM TECHNOLOGY”

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CERTIFICATE

*This is to certify that the thesis titled "***Modelling and Analysis of Resistive Superconducting Fault Current Limiter***", submitted to the National Institute of Technology, Rourkela by* **Mr. Shounak Dutta, Roll No***.* ***212ME5405*** *for the award of Master of Technology in Electrical Engineering, is a bonafide record of research work carried out by him under my supervision and guidance.*

The candidate has fulfilled all the prescribed requirements.

This thesis which is based on candidate's own work, has not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required in partial fulfillment of the requirements for the degree of Master of Technology in Cryogenics and Vacuum Technology.

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ABSTRACT

Increase in the demand and consumption of electrical energy has led to increase in the system fault levels. Superconducting Fault-current limiters (SFCL) offer ideal performance in electrical power system. Superconducting Fault Current Limiters (SFCLs) are used in power system network to mitigate the overcurrent and its prominent effects. Nowadays, Coated Conductors (CCs) are widely used for novel design of SFCL for such applications. The thermal and electrical behaviors of different configurations of SFCL in the presence of over-critical current are studied in detail to master its performance in a power grid. An algorithm to solve the differential equations characterizing the superconducting material is developed using the Runge-Kutta method.

In this report, comparative study on the operational characteristics of Resistive-SFCL based on BSSCO and YBCO Coated Conductors under fault condition is analyzed for an 110KV/9KA power system. Also Electro-thermal Model of Coated Conductor is implemented in MATLAB software. The developed models accurately predicted the current-time waveforms achievable with the limiters for an improved current limiting behavior during fault condition and even the restraining the conditions upsetting the thermal stability of the SFCLs. To verify the effectiveness of the proposed Resistive-SFCL, several case studies of Coated Conductors have been carried out in MATLAB. The results show the choice of optimal configuration of CCs as SFCL which effectively improves the thermal stability and current limiting characteristics under fault condition in the network.

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1. ***INTRODUCTION***

2. ***RESEARCH METHODOLOGY: MODELLING OF RESISTIVE-SFCL***

3 ***SIMULATION RESULTS AND DISCUSSION***

LIST OF SYMBOLS

c(T)	Specific heat (temperature dependent), J/(kg·K),
k(T)	Thermal conductivity of HTS, W/m·K,
Ec	Value of critical electric field intensity, V/m,
Ic	Critical current, A,
Ip	Prospective Current, A,
J	Current density, A/m^2,
Jc	Critical current density, A/m^2,
ΔT	Temperature gradient, K,
n	Power factor in power law, which depends on the HTS material,
q(T)	Generated heat, J,
ρ	Resistivity in superconducting state, Ω·m,
T	Actual temperature, K,
T_c	Critical temperature, K,
T_0	Initial Temperature, K,
α	Flux-creep region exponent
β	Flux-flow region exponent
E_0	Initial electric field, V/m
R	Load resistance, Ω
L	Initial inductance, H
A	Area, m^2

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The ever-increasing demand for electrical energy had resulted in increased size of generating stations and interconnected distribution network called power grids which leads to the risk of increasing abnormal operation. The conventional Circuit Breakers can't be used in the network as the rising fault current levels may soon cross its rated fault current breaking capacity. This increasing level of fault current will result in replacing a large number of devices in power systems, like transformers and circuit breakers.

Superconducting Fault Current Limiter (SFCL) is one of the most novel alternate solutions to avoid the problem of increasing fault current. It improves power system reliability and stability by reducing the fault current instantaneously. SFCLs have large impedance in fault conditions and have very low impedance in normal conditions and also instantaneous recovery to zero impedance post fault clearance. Superconducting materials have a highly non-linear behavior which is ideal for the application as FCLs. The high temperature superconductors, called Second-Generation (2G) superconductors with critical temperature around the boiling point of nitrogen (77K) have been studied here.

1.2 SUPERCONDUCTORS TO SFCLS

The Superconducting Fault Current Limiter (SFCL) presents unique characteristics inherited from the properties of superconductors. This chapter introduces basic elements of superconductivity that are used to present the origin of the electrical resistance occurring in the flux-flow regime in high temperature superconductors. Superconductivity is a state of the matter characterized by a weak attractive interaction between conduction electrons. In this particular state, that occurs for many elements of the periodic system, this weak interaction reduces the system entropy and allows the in-phase motion of correlated-electrons over important distances. This long-range phase coherence is thought to be responsible of the perfect conductivity observed in superconductors. In addition to the zero-resistance hallmark, ideal superconductors are characterized by a perfect and reversible diamagnetism. This special behavior is termed the Meissner effect i.e. the nonexistence of any magnetic flux into the material bulk for any initial conditions.

Those unique features of the superconducting state are overcome when an external input of energy (thermal, magnetic or kinetic) is sufficient to break down the fragile phase equilibrium. More specifically, the superconductor becomes a normal metal if the critical surface defined by the critical values (the temperature, magnetic field and current density) is reached as shown in fig. 1.

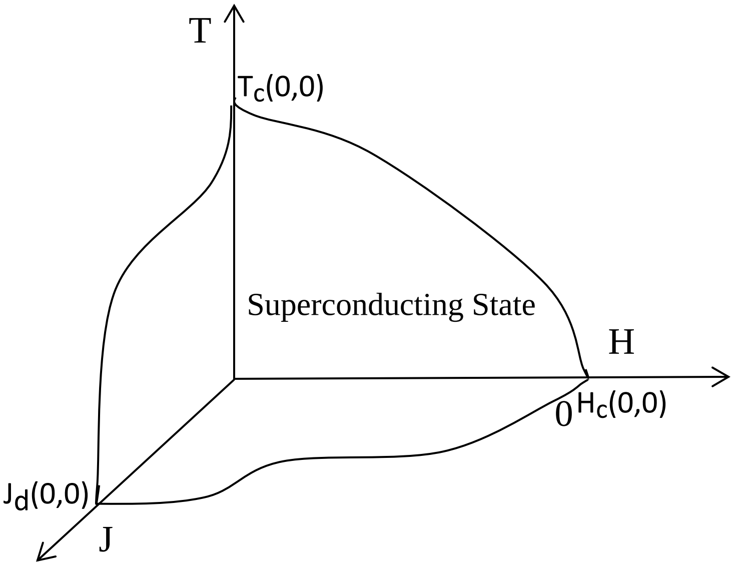

Fig 1: The critical surface of a Superconductor.

Superconductors are classified into two main groups according to their behavior at the state transition. The fig. 2 presents the typical responses of these groups to an applied magnetic field. As depicted in the figure, the first group, termed type-I, shows a first-order transition i.e an abrupt and complete loss of the Meissner state at H = Hc, the thermodynamic critical field. This value is related to the maximal magnetic pressure the material can stand to hold the field out (condensation energy). For the second group, named type-II, the "pure" Meissner state exist only below a minimum field H = Hc1. Above this value, the magnetic flux start to penetrate the material. Once the penetration starts to occur the superconductor is said to be in the mixed-state (Shubnikov phase) which is a state characterized by the nucleation, in the superconductor, of normal metal filaments called vortex, each carrying a quantized magnetic flux ϕ_0. For type-II superconductors, the flux penetration allow a second-order phase transition (continuous) that reduces the energy needed to hold the field out. This allows the complete penetration of the magnetic field to occur in a larger field Hc2 than the thermodynamic critical value Hc.

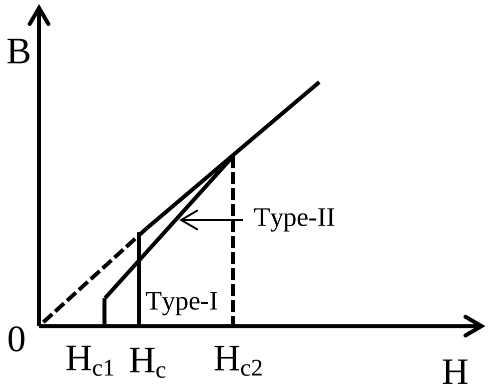

Fig 2: B-H phase diagram for type-I and type-II superconductors

Table I: The classification of the different types of Superconductors.

Type	Material	Tc [K]
I	Al Pb	1.2 7.2
II-LTS Tc <30 K	NbTi Nb3Snz	9 18
II-HTS Tc ≥30 K	MgB2 Bi2Sr2Ca2Cu3O10 Bi2Sr2Ca1Cu2O8 YBa2Cu3O7	39 110 85 90-92

Recently, 1G tape is being replaced with the second-generation (2G) tape due deflation of these HTS and are now available in long lengths for SFCL applications. The classifications of the different types of Superconductors are given in Table I. The two most important 2G superconducting ceramics used as a coated conductor are:

- Yttrium-Barium-Copper-Oxide $YBa_2Cu_3O_{7-x}$ (YBCO).
- Bismuth-Strontium-Calcium-Copper-Oxide $Bi_2Sr_2Ca_nCu_{n-1}O_{2n+4+x}$ (BSCCO, compound Bi-2212 / Bi-2223).

1.3 RESISTIVE TYPE SUPERCONDUCTING FAULT CURRENT LIMITERS

Resistive-type Superconducting Fault Current Limiters (SFCLs) made with High Temperature Superconductor (HTS) tapes provides the most operational and reliable protection against the faults due to their characteristics behavior of high critical current density and quick Superconducting to Normal (S/N) state transition .The resistive type SFCLs is shown in series with the source and load (Fig.3). During normal operation the current flowing through the superconducting element R_{SC} dissipates low energy. If the current rise above the critical current value the resistance R_{SC} increases rapidly. The dissipated losses due to the rapid raise in resistance heats the superconductor above the critical temperature T_C and the superconductor R_{SC} changes its state from superconducting to Normal state and fault current is reduced instantaneously. This phenomenon is called quench of superconductors. When the fault current has been reduced, the element R_{SC} recovers its superconducting state.

The parallel resistance or inductive shunt Z_{SH} is needed to avoid hot spots during quench, to adjust the limiting current and to avoid over-voltages due to the fast current limitations. The resistive SFCLs are much smaller and lighter than the inductive ones. They are vulnerable to excessive heat during the quench state.

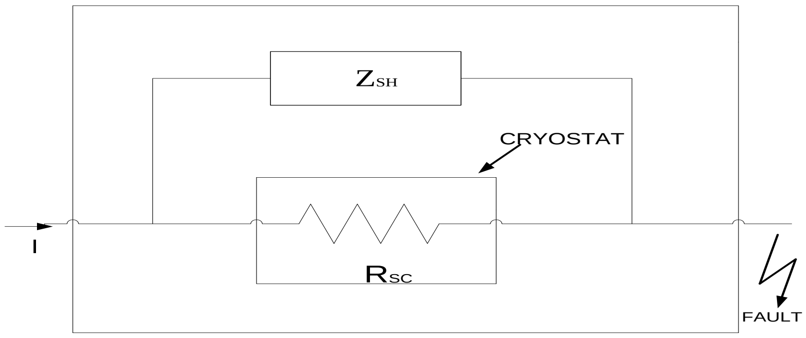

Fig 3: Resistive SFCL

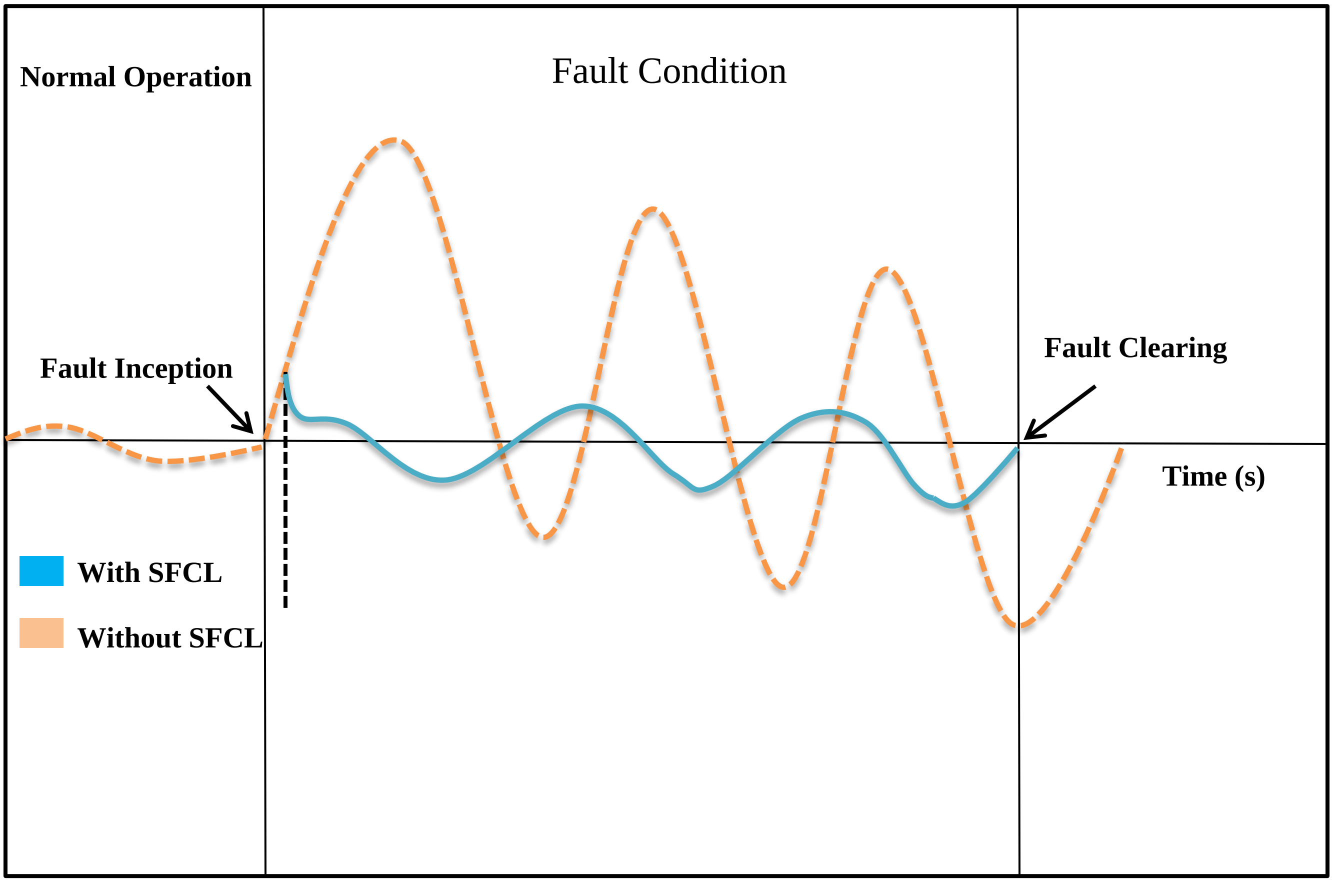

Fig 4: The current waveform with and without SFCL during a fault.

1.4 LITERATURE REVIEW

Before the research and development of the fault current limiter, the main area of research was to break the circuit during fault in order to save the expensive equipment at power grids from large fault currents generated during fault. In order to handle large fault currents circuit breaker with large rating were developed. But the problem with the circuit breakers is that they have a limited life period, and cannot break the circuit until the first current cycle goes to zero. The research and development of fault current limiters started many years ago. The Superconducting Fault Current Limiter (SFCL) presents unique characteristics inherited from the properties of superconductors of having a highly non-linear behavior. The review of the different concepts of SFCL, the different types of SFCL and to an extent non-superconducting fault current limiter was explained and compared with SFCLs by M.Noe [1]. It also shows application and the R&D status of the SFCLs. The Superconducting Fault Current Limiters (SFCLs) improves the reliability and stability of the system by limiting the fault current instantaneously.

H.Hatta [2] explains the reliability of the system by SFCLs with adjusting the trigger current level in an artificial transmission line with a synchronous generator. It confirms that SFCLs improves the transient stability is improved.

M. C. Ahn et al. [3] proposed a non-inductive coil with HTS wire in parallel producing resistive as well as inductive impedance. The short circuit test results show the impedance characteristics.

Will Paul [4] discusses the different types of SFCLs and their characteristics. Detailed aspects of the Resistive Superconducting Fault Current Limiters are discussed along with its shortcomings. The different Superconductor materials in HTS-based FCLs are explained in this paper.

M.Noe et al. [5] shows the experimental quench results carried for short and medium length YBCO Coated Conductors at different test conditions. The results confirmed the practicability of YBCO CCs wire for application in Resistive SFCLs.

Dong Keun Park et al. [6] proposed optimal deisgn of CC for FCL considering two different types of YBCO CCs. Short circuit test were performed on these samples and the experimental results were compared with current limiting characteristics of the CC by using Finite Element Method(FEM).

H-P Kraemer et al. [7] proposed a 2MVA fault current limiting module for medium voltage applcations consiting of 750m of AMSC's 344S superconductors, a stainless steel laminated 2G HTS wire. Power tests and dielectric tests were performed and showed the current limiting characteristics of 2G HTS wire.

Juan-Carlos H. Llambes et al. [8] carried out experiments on a 138kV 2G SFCL at SuperPower. This paper elaborates the testing and improvements made to optimize Recovery Under Load (RUL) in order to define where RUL is feasible. This establishes an ease to choose less Superconductor material, reducing the volume and overall conduction losses.

F.Roy et al. [9] proposes a new finite element model for the purpose of studying the thermal and the electromagnetic behavior of High Temperature Superconductor by coupling the electrical and the thermal equations in a single solver.

Coated Conductor is a composite conductor, the material properties, HTS, substrate etc affects the current limiting characteristics. Young Jae Kim et al. [10] shows a feasible HTS for application as SFCL by conducting experimental of fault current tests of commercialized CCs.

S. Nemdili,S. Belkhiat [11] proposes an Electro-thermal Model of Coated Conductors in the Matlab library much simpler than other literatures like FEM to solve equations defining the characteristics of the Superconducting material. This also shows a better configuration of HTS wire to be used as SFCL over different lengths.

Another important criterion for design of a Resistive SFCL for application in the power systems is the thermal stability and the recovery time for quick transition from normal state back to Superconducting state. A conceptual design of an HTS based SFCL is explained by Soumen Kar et al. [12]. Electro-thermal modelling is done for calculating fault current limitation, resistance as well as the temperature rise. The results showed a fast response time and instantaneous recovery validating the model for application in power systems.

For the design of the SFCL cooling is a very important factor of consideration as the Superconductors gets heated up very quickly so there is need of cryogenics cooling. The SFCL are immersed in a bath of LN_2 stored in a cryostat. Kwanwoo Nam et al. [13] present the visualization results of behavior of liquid nitrogen to identify the boiling characteristics during quench of SFCLs. This also shows a remarkable result in the improvement of the recovery time.

Z. Hong et al. [14] carried out an experiment of 10 kV/200A Resistive type SFCL prototype and performed various test including short-circuit test, recovery test and LN_2 boiling test . The results shows a 30%-70% reduction of fault current and the recovery time against fault duration shows a linear relation.

1.5 RESEARCH MOTIVATION

In USA, two 138 kV SFCL projects are being developed since 2008, respectively, by AMSC and Super Power Inc. In this report, comparative study on the operational characteristics of Resistive-SFCL based on BSSCO and YBCO coated conductors under fault condition is carried out in 110KV/9KA network. Electro-thermal Model of a Coated Conductor of different CCs is evaluated using MATLAB software for analysis of effectiveness of Resistive-SFCL.

1.6 THESIS OBJECTIVE

The objectives to be achieved in this study are:

- To apply the developed algorithm to solve the differential equations characterizing the superconducting material in Matlab M-file.
- Modelling of the SFCL with different layers of different materials with proper dimensions and properties of each layer material.
- To observe the Current limiting characteristic plot and thermal stability analysis of the SFCLS based on YBCO and Bi-2223 HTS from the developed Electro-Thermal Model of Coated Conductors.
- To do an analysis for the optimal configuration of the Coated Conductors (CCs) based SFCLs for the application in the prescribed power system network for improved power system stability.

CHAPTER 2

RESEARCH METHODOLOGY:MODELLING OF RESISTIVE-SFCL

2.1 DESIGN OF HTSFCL ELEMENT PARAMETERS

2.1.1 CURRENT

The critical current density of the Superconductor is Jc. In order to have tolerance during normal operation or condition the current density should not exceed k% of the Jc. In is the value of nominal current. In this case the Ip = 9000*sqrt2 is the peak current. The current Density is calculated by the dividing the current by the area it occupies (J = I/A). Here the Jc = Ip/A and the critical current density should not exceed k% of the Jc, so the value of the area should be calculated by A= Ip/(k*Jc). The value of critical current density Jc is 2e+7A/m^2. The current density is dependent on the material used.

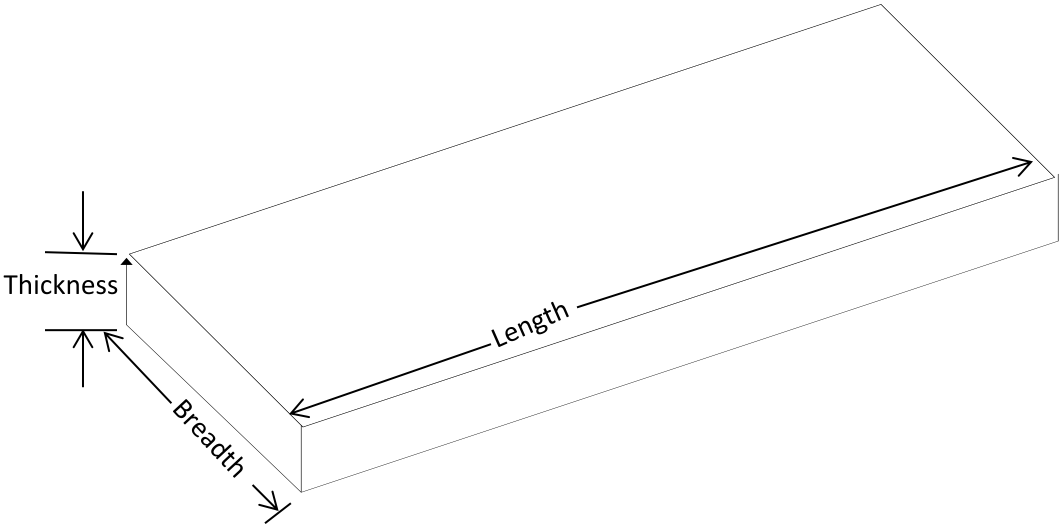

Fig 5: High Temperature Superconductor (HTS)

2.1.2 AREA OF THE HTS

A = Thickness*Width. Referring to the above Fig. 5 the area is calculated. In the modelling thickness is modelled such as 0.2mm. The corresponding widths are calculated.

2.1.3 LENGTH OF THE HTS WIRE

The sample used for modelling is on an 110kV and 9kA system. In the modelling various thicknesses are modelled and the corresponding width is calculated. The peak voltage (V_{peak}) of the system is given as 110000*√2V. This is related to the peak electric field (E_{peak}) and the HTSFCL length by the equation

$V_{peak} = E_{peak}$*HTSFCL length

Various E_{peak} values were used in the modelling. Results with different lengths of the superconductor are shown and analyzed. The value of the electric field in the three distinguishable states; zero resistance (State 1), Transition State (State 2) and normal conductance (State 3) are obtained using the following equations, which is approximated by a power law.

2.2 THEORETICAL MODEL

The simulation is carried out based on computer model of Resistive-SFCL installed in an 110kV/9kA network. The SFCL is connected in series in the circuit as shown in Fig.6. The circuit shows the working of SFCL during steady state condition operating at 77K as the superconductor is immersed in a bath of Liquid Nitrogen as cooling system. The SFCL is in Superconducting state during normal operation and the switch(S) is open in the circuit. At fault condition, the switch(S) is closed in the circuit and SFCL changes its state from Superconducting to Normal state where the resistance increases from zero to high value, resulting in temperature rise of the SFCL.

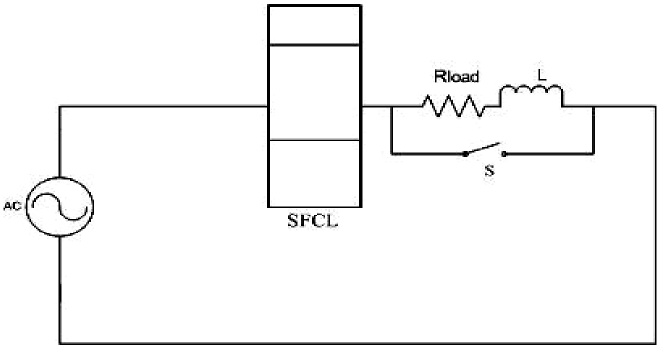

Fig.6: Electrical circuit with SFCL

2.3 CHARACTERIZATION OF COATED CONDUCTORS

The E~J characteristic of the High Temperature is the most important property prevailing the current limiting behavior of the SFCL and its dependence on temperature T. E~J can be practically subdivided into three sub-regions:

Superconducting state, Flux flow state and Normal conducting state. In the flux-flow regime of superconductor, the electric field E is related to the current density J as

$$E = E_c \left(\frac{J}{Jc} \right)^n \qquad \text{.... (1)}$$

where n is the index number, the critical electric field (E_C) is taken as 1 μV/cm when it reaches the Critical current density (Jc). High values of n determine the fast fault current limitation. Resistive power dissipation in the flux flow and normal state leads to a temperature rise. The physical equations of E(j) of the three sub-regions are stated as follows

State 1: Superconductor or Zero resistance state

$$E(j,T) = Ec * \left(\frac{j}{jc(T)} \right)^{\alpha(T)} \qquad \text{…. (2)}$$

Where α(T) = max [β, α'(T)], with

$$\alpha'(T) = \frac{\log\left(\frac{Eo}{Ec}\right)}{\log\left[\left(\frac{jc(77K)}{jc(T)}\right)^{\left(1-\frac{1}{\beta}\right)} * \left(\frac{Eo}{Ec}\right)^{\frac{1}{\alpha(77K)}}\right]} \qquad \text{…. (3)}$$

Where

Ec = 1μ V/cm,

Eo,α, β at 77k depends on the material processing conditions

0.1 ≤ Eo ≤ 10 mV/cm,

5 ≤ α ≤ 15 for 1G HTS,

15 ≤ α ≤ 40 for 2G HTS,

1 ≤ β ≤ 4.

State 2: Transition State or Flux Flow State

$$E(j,T) = Eo * \left(\frac{Ec}{Eo}\right)^{\frac{\beta}{\alpha(77K)}} * \frac{jc(77K)}{jc(T)} * \left(\frac{j}{jc(77K)}\right)^{\beta} \qquad \text{…. (4)}$$

State 3: Normal State or High Resistance State

$$E(j,T) = \rho(Tc) * \frac{T}{Tc} * j \qquad \text{…. (5)}$$

Here we assume the heat dissipation occurs in adiabatic and isotherm condition. The flow of heat across the superconductor is not transferred to the liquid nitrogen, so heat dissipation from superconductor to the liquid nitrogen is neglected. The High temperature superconducting composite is assumed to be homogeneous. The heat flowing along the layers is defined by Fourier's law for one-dimensional heat flow stated in equation (6)

$$\mathrm{q(T) = k(T)A \frac{\partial T}{\partial x}} \qquad \text{…. (6)}$$

Where k(T) is the Thermal conductivity of CCs, A is the Cross-sectional Area of CCs. The two-dimensional equation for heat conduction in the layers of the coated conductors is given by equation (7)

$$\nabla\left(k(T)\nabla T\right) + q(T) = c(T)\frac{\partial T}{\partial t} \qquad \text{…. (7)}$$

Where

c(T) is the specific heat of Coated Conductor.

Simulation of the high temperature SFCL is based on the E~J characterization along with thermal-diffusion equation.

2.4 DESIGN OF SFCL USING COATED CONDUCTORS

In this report analysis about various commercialized coated conductors (CC) is carried out for the optimal CC which is more appropriate to a Resistive-SFCL. The materials used as substrate and stabilizer in the CCs have a wide range varying in properties, to have anticipated performances of the CCs as the SFCL. Three commercial CCs were selected for the simulation: One of them was coated BSCCO tape and rest two was SF12100 and SCS12050 made by Superpower Inc. Fig7. Shows sample configuration of a 2G HTS wire.

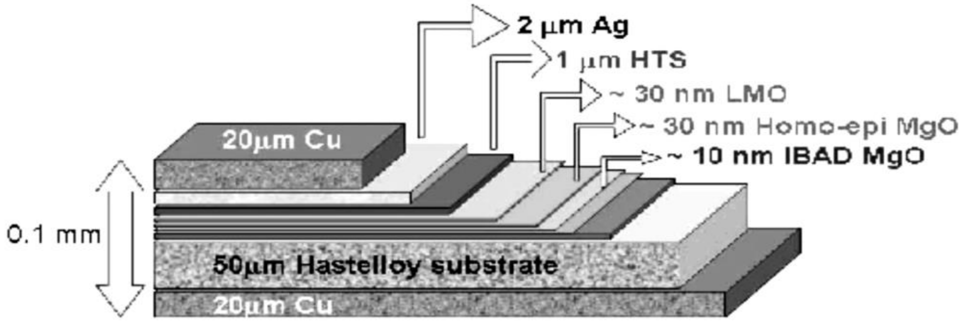

Fig 7: Configuration of a Super Power 2G HTS wire (www.superpower-inc.com)

The coated BSCCO HTS tape is made of three layers. The High Temperature Superconductor (HTS) Bi-2223 is used in this CC. It also comprises of a thick conductive substrate layer made of Hastelloy-C276, which is usually electrically isolated from the HTS, a very thin layer of MgO used as a buffer between Hastelloy-C276 and the High Temperature Superconductor (HTS), and Silver (Ag) stabilizer as the electrical contact with the HTS. The Ag layer mainly removes the excessive heat produced in the HTS tape during fault and protects from damage. The thin layer of MgO was neglected to reduce the computation time.

The YBCO coated tapes produced by Super Power Inc. (SP SCS12050—copper stabilized and SF12100—stabilizer free) consist of YBCO and the surface of YBCO is covered by a stabilization silver layer and buffer layers are deposited on a non-magnetic substrate Hastelloy-C276 with high resistivity. SCS12050 is surrounded by copper stabilizer on both sides. The copper stabilizer was attached by electroplating. Table II shows the specifications of the coated conductors mainly used in this work.

TABLE II. PHYSICAL PARAMETERS OF THE COATED CONDUCTORS

Parameters	***BSCCO-2223***	***SF12100***	***SCS12050***
Minimum Critical Current Ic (A) @77K,Self field	73	200	240
Critical Temperature Tc (K)	108	92	92
Width(mm)	2	12	12
Thickness(mm)	0.4	0.095	0.1
Substrate	Hastelloy C-276	Hastelloy C-276	Hastelloy C-276
Stabilzer	N/A	N/A	Copper
Index Number	8	30	36

2.5 ALGORITHM

The schematic diagram of the operation and the current limiting behavior of the SFCL is shown if Fig. 8 below.

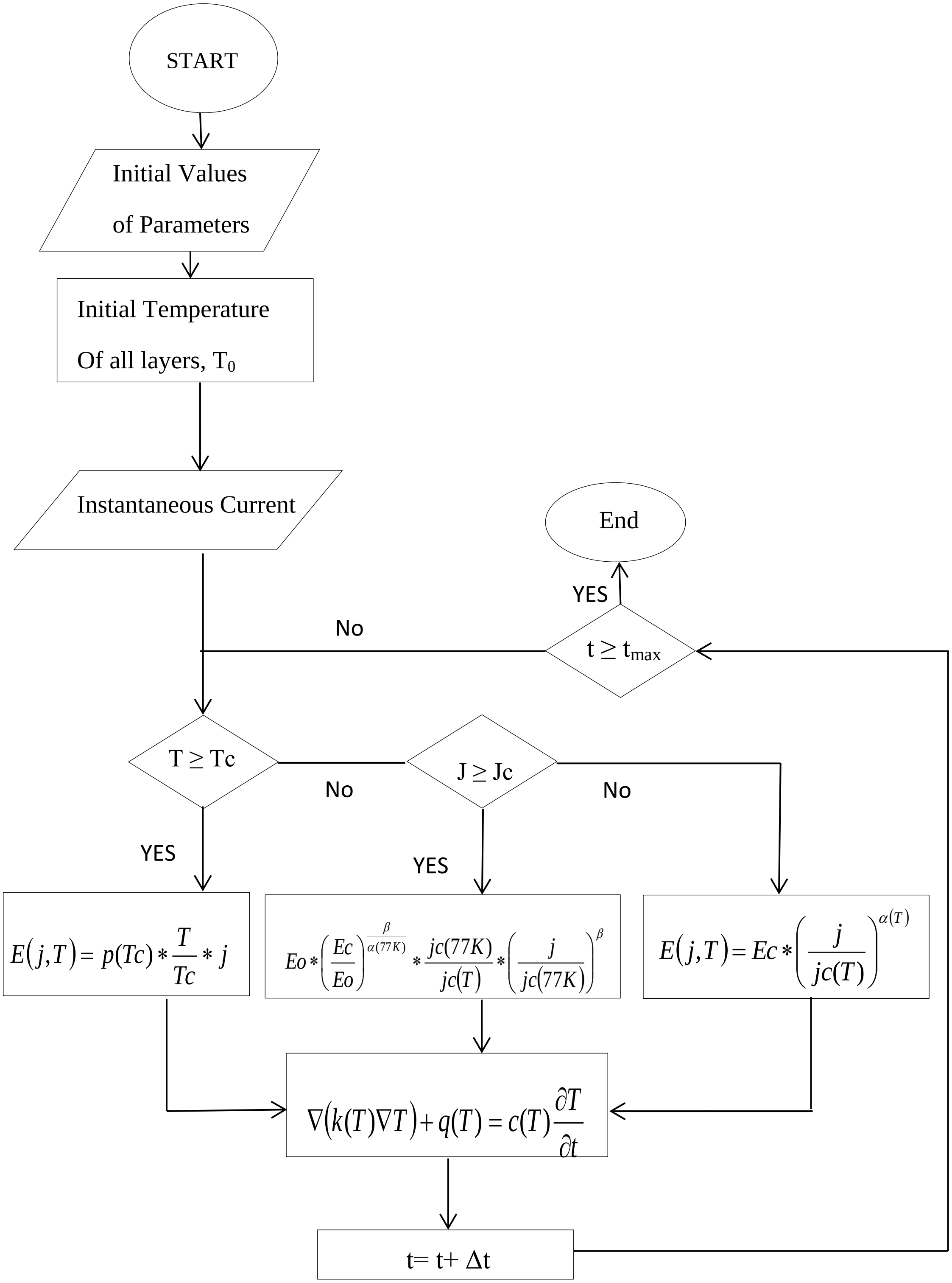

Fig 8. Flowchart of Current limiting characteristics

CHAPTER 3

SIMULATION RESULTS AND DISCUSSION

3.1 NORMAL OPERATION

In the circuit shown in Fig.6 SFCL is connected in series with a resistance (R_{load}) and an inductor (L) in the 110kV/9kA network. During the normal operation the switch S is open. The initial current in the circuit at starting time is assumed to be as zero. The electrical parameters used in the system are given in Table III. In order to have an acceptable tolerance during normal operation it is assumed that the current density should not exceed k % of J_C which is assumed as k=0.8. A sinusoidal waveform with amplitude 9000*√2A flows in the circuit as shown in Fig.9. The temperature of the superconductor during the normal operation remains constant at 77K which is the temperature of LN2. The SFCL retains its state in the Superconducting region without any change of resistance during the normal operation.

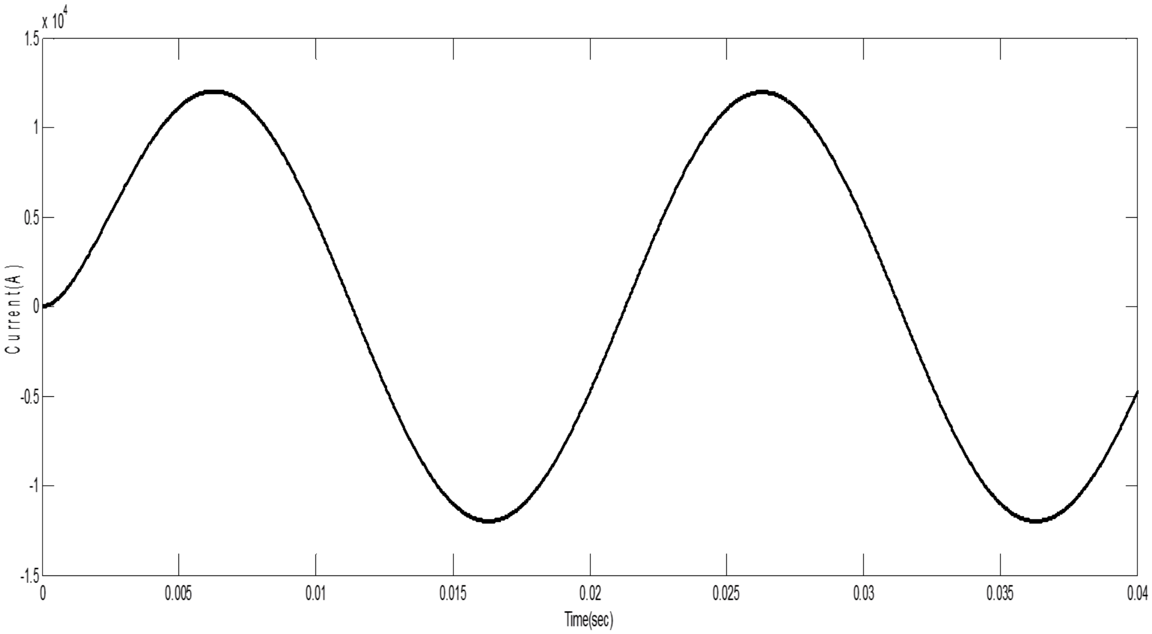

Fig.9: Current waveform of SFCL during normal operation

TABLE III. ELECTRICAL PARAMETERS OF SFCL

Parameters	**Values**
Initial Electric Field (E_o)	0.05V/m
Critical Electric Field (E_c)	1e-4V/m
Nominal Current (I_n)	9000* √2
Load Resistance (R_{load})	9Ω
Inductor (L)	0.165H
Critical Current Density(J_c)	2e+7A/m^2

3.2 SHORT CIRCUIT TEST

Under severe fault conditions the SFCL shows a very high current limitation capacity. Circuit Breakers cuts faults in 0.2 s in power system network, so here we applied a constant AC voltage to CCs for duration of 0.1 sec. Short circuit test were performed for investigating the current limiting characteristics of the different CCs. In order to see the operation of the SFCL under fault, the switch S in Fig.1 is closed after two cycles (at 0.04 sec). Fig.10 shows the circuit during fault. The maximum fault current reaches the value of more than 40kA, 36kA and 29kA in case of BSCCO-2223, SCS12050 and SF12100 respectively as shown in Fig.11.

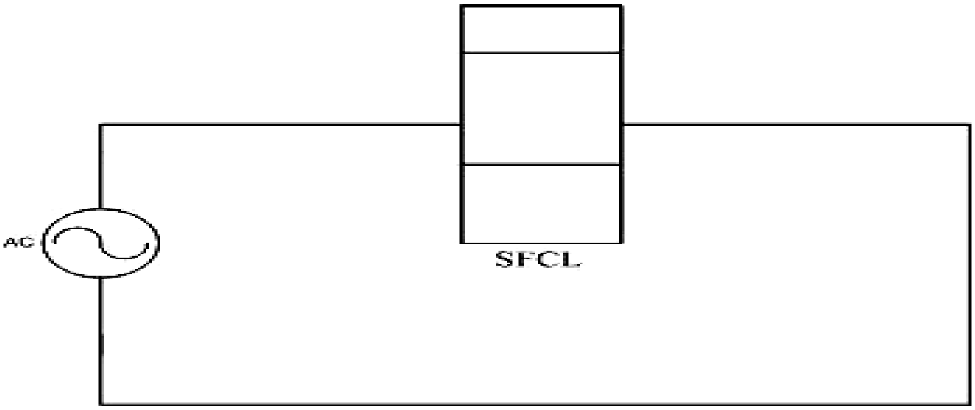

Fig.10: Circuit during fault conditions

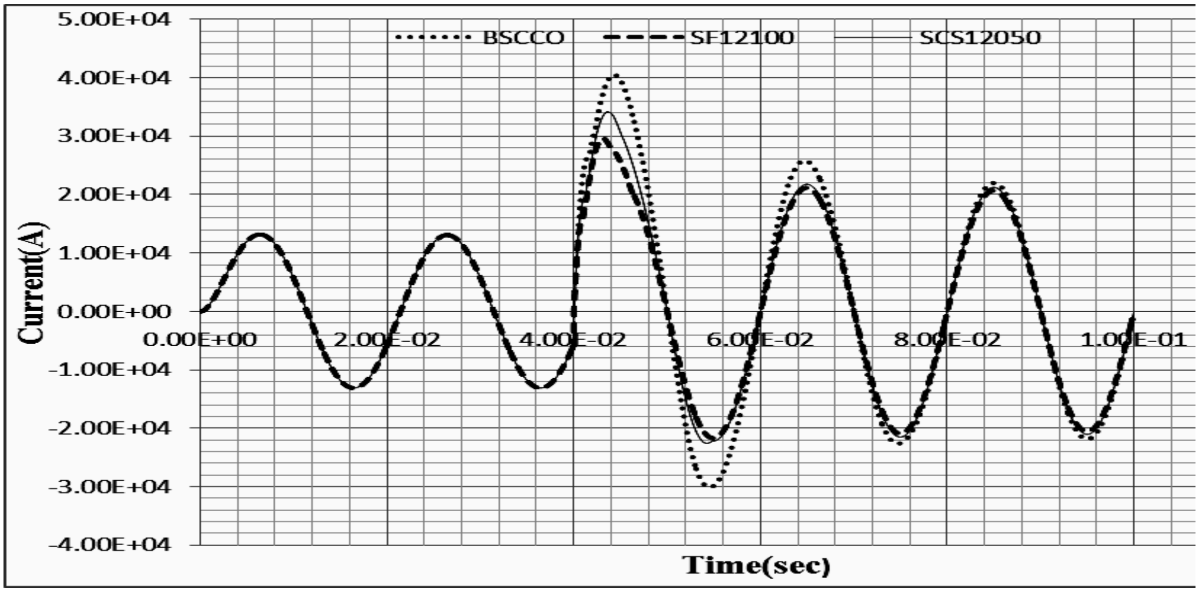

Fig.11: Current waveform of the CCs during fault

The fault current results in quenching of the Superconductor changing its state from Superconducting state to Normal state. A high resistance is generated instantaneously which limits the fault current in a fraction of second. The comparison of the Current limiting characteristics of the 3 different CCs have been shown in the Table IV.

The results from Table IV illustrate that YBCO CCs shows exceptional performance due to their high critical current density linked to their high index value (n).

These tapes has a much better response time, when Superconducting-to-Normal (S/N) transition occurs_compared with the BSCCO CC. From variation of the quenching characteristics of the CCs the thermal stability can be conveniently studied as the increase in the resistance results in temperature rise. Fig.12 shows the Superconducting-to-Normal (S/N) transition for the different Coated Conductors.

At the fault condition, the resistance of the SFCL increases instantaneously and rapidly. When the inflowing current in CC was above its critical current, quenching occurs and the current is shared between HTS layer and stabilizer. From the above graph we can see that the recovery time for transition from the Superconductor state to Normal state on fault condition is around 6.2ms for SF12100, 14.3ms for SCS12050 and 35.7ms for BSCCO-2223 CC. YBCO CCs have a high index number, so the resistance of the SFCL increases very rapidly at the moment of fault. BSCCO CCs has low resistance in its normal conducting state and it takes a longer time for the quenching of the High Temperature Superconductor (HTS) Bi-2223. In SCS12050, the copper acts as a parallel resistance to the substrate resulting in decrease of the total resistance of this CC so this YBCO CC shows low resistivity in Normal conducting state. Here, the SF12100 CC shows a superior performance over the other CCs.

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TABLE IV. CURRENT LIMITATION OF CCS AT DIFFERENT LENGTHS

Length (m)	**Electric Field (V/m)**	**CCs**	**Peak Fault Current (A)**	**Fault Current - Cycle 1 (A)**	**Fault Current - Cycle 2 (A)**
70	2222	BSCCO	4.054e+4	2.582e+4	2.2e+4
		SCS12050	3.416e+4	2.176e+4	2.123e+4
		SF12100	2.962e+4	2.176e+4	2.116e+4
80	1944	BSCCO	3.667e+4	2.457e+4	2.007e+4
		SCS12050	3.156e+4	1.926e+4	1.886e+4
		SF12100	2.767e+4	1.881e+4	1.833e+4
100	1555	BSCCO	3.068e+4	2.259e+4	1.898e+4
		SCS12050	2.727e+4	1.751e+4	1.539e+4
		SF12100	2.447e+4	1.535e+4	1.502e+4
120	1296	BSCCO	2.629e+4	2.096e+4	1.756e+4
		SCS12050	2.394e+4	1.638e+4	1.388e+4
		SF12100	2.186e+4	1.364e+4	1.274e+4

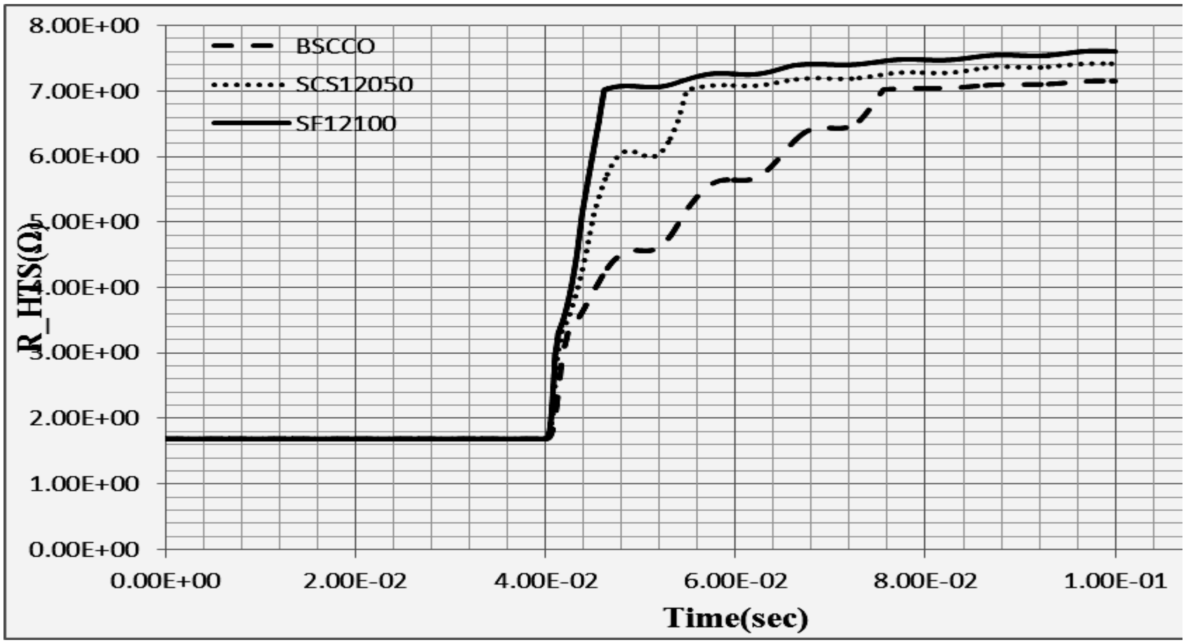

Fig.12: Non-linear Resistance change of the CCs at conductor length of 70m

A very large amount of heat is produced due to the rapid increase in resistance of the superconductor under fault which may damage the SFCL. The shunted tape acts as a parallel resistance which lowers the overall resistance of the tape and also the excess heat is dissipated from the HTS layer to the shunt layer. So there is no requirement of any attenuation so that greater amount of current can flow in the tape. This decreases the losses occurring in the HTS film and also creates less Joule losses in the conductive parallel paths.

Another important criterion in general design process of Resistive-SFCL is the maximum temperature reached. The electric field intensity is determined by the temperature rise in the SFCL. Generally, SFCL is designed for a maximum temperature of about 300 K because thermal shock can degrade the CC properties. The thermal stability of the CC is also dependent upon the length of the superconductor. Shorter conductor lengths saves expenses but there will be a large electric field distributed over the HTS resulting into overheating. The thermal stabilization of the CCs over different lengths is shown in Table V.

The results obtained from Table V, shows that as the length of the superconductor is increased the temperature decreases gradually. Short length of superconductors is not applicable for application in SFCL due to the large amount of rapid heat produced in the superconductor. If very long conductors are used the amount of electric field distributed over the length is quite less.

TABLE V. THERMAL STABLITY ANALYSIS OF THE CCS OVER DIFFERENT LENGTHS

Length (m)	**Material**	**R_HTS (Ω)**	**Temperature (K)**
70	BSCCO	7.1308	151.71
	SCS12050	7.4182	210.77
	SF12100	7.6056	286.84
80	BSCCO	8.0605	138.15
	SCS12050	8.3537	183.33
	SF12100	8.5658	241.97
100	BSCCO	8.7539	121.75
	SCS12050	10.2135	150.85
	SF12100	10.4791	188.58
120	BSCCO	9.3677	111.43
	SCS12050	12.0726	133.29
	SF12100	12.3268	159.21

The critical current density exceeds slightly and the conductors warm up slowly resulting in high AC loss. BSCCO-2223 has a very low resistance in its Normal Conducting state, so the BSCCO tape is very hard to be utilized in a S/N transition type SFCL. A very long BSCCO wire is required to overcome this shortcoming. This results into increase in cost of the BSCCO-2223 wire as a large amount of silver is to be sheathed onto the BSCCO tape. SCS12050 shows a faster S/N transition than BSCCO with higher increase in resistance during the fault. The Copper stabilizer gives additional thermo-mass and acts as a parallel resistance reducing the total resistance of the CC. But this consequences in higher joule heat dissipation as the power system operates at constant voltage mode. SCS12050 performance is not satisfactory for the application in Resistive SFCL.

SF12100 is the most suitable choice for application of Resistive-SFCL. The stabilizer free CC has a thicker substrate layer of 100 µm for purpose of thermal stability of the CC. A rapid increase in the resistance on fault occurrence results in the fastest S/N transition among the other CCs. Over increasing the length of the SF12100 it shows a better current limiting characteristics and a better thermal stability with increase in temperature due to quenching of superconductor. An external by-pass shunt in parallel with the YBCO tape is necessary for the application in SFCL. During fault, the shunt layer absorbs a fraction of the current avoiding irreversible degradation of the YBCO. Considering the voltage tolerance of YBCO coated conductors, the YBCO tape should be at least 150 m. So for this 11 kV SFCL prototype current limiting characteristic of the optimal choice CC SF12100 is show in Fig.13 and the characteristics are tabulated in Table VI corresponding to different lengths for safe operation.

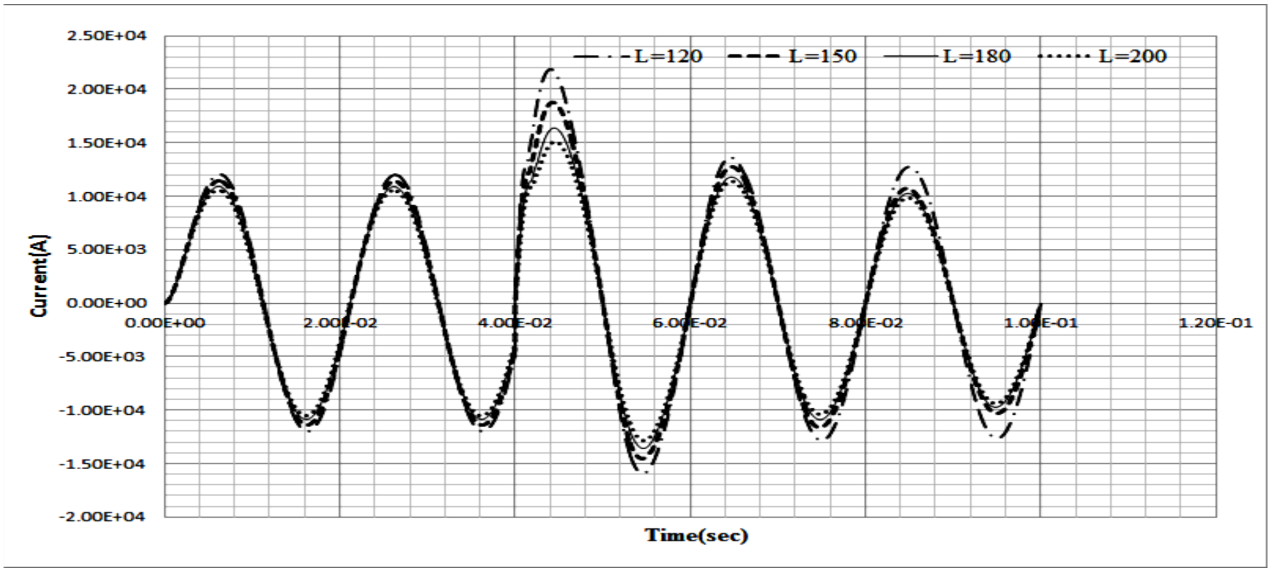

Fig.13: Current waveform of SF12100 over different lengths

TABLE VI. TEMPERATURE AND FAULT CURRENT OF SF12100 OVER DIFFERENT LENGTHS OF SUPERCONDUCTOR

Length (m)	Peak Fault Current (A)	Fault Current - Cycle 1 (A)	Fault Current -Cycle 2 (A)	Temperature (K)
120	2.186e+4	1.364e+4	1.274e+4	159.21
150	1.876e+4	1.274e+4	1.274e+4	135.32
180	1.637e+4	1.177e+4	1.025e+4	122.51
200	1.507e+4	1.139e+4	0.984e+4	116.28

CHAPTER 4

CONCLUSIONS

In this report, an 11kV/9kA Resistive-SFCL prototype studying the electrical and thermal behavior of HTS for CC SFCL applications is presented. The different types of Coated Conductor have different specific characteristics making it ideal for a definite application. The YBCO tapes shows better characteristics for the application as a Superconducting Fault Current Limiter operating at 77 K due to its high critical current density, high normal-state resistance, high index number, low ac losses and quick recovery against thermal instabilities. Among the YBCO CCs it is shown that SCS 12050 is not adequate for application purpose in Resistive-SFCL as Copper stabilizer gives additional thermo-mass resulting in higher joule heat dissipation. SF12100 with highly resistive substrate is the optimal choice of Coated Conductor for application in SFCL. The SF12100 characteristics are studied corresponding to different lengths of superconductor for a thermally stable configuration and showing the current limiting efficacy. SF12100 was successfully applied in the SFCL prototype and the simulation model was done in MATLAB. This model can be tested experimentally for novel and efficient design of SFCL application in the present electrical networks.

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