# OPTIMAL PLACEMENT OF HTSFCL CONSIDERING OF POWER SYSTEM SECURITY AND STABILITY INDICES BY USING DIFFERENTIAL EVOLUTION

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**ABSTERACT:** *The limiting ability of the fault current of the high-temperature superconducting fault current limiter (HTSFCL) is based on the relation of the resistance and the temperature of the superconductor.* $YBa_2Cu_3O_7$ *(YBCO) can be included in the second generation superconductors having a low resistance at temperature lower than the threshold temperature and with increase in temperature due to the increase in current, there is an increase in its resistance which leads to the limitation of the fault current. The optimal positioning of HTS-FCL is important because HTSFCL is high in cost and also because of the maximization of its usage. In this paper the application of HTSFCL in a single machine system to infinite bus bar has been studied using the PSCAD/EMTDC. The optimal placement of HTSFCL has been developed keeping in mind the enhancement related to the power system security, voltage stability and rotor angle stability .The optimal HTSFCL size and location is determined for a 39 bus New-England test system using differential evolution algorithm using MATLAB which guarantees the indices related to the security, the voltage stability and the rotor angle stability.*

**Key Words:** *Fault current limiter, HTSFCL (High Temperature Superconductor Fault Current Limiter), Security, Voltage and rotor angle stability, DE (Differential evolution).*

## 1. INTRODUCTION

Short circuit current level is one of the most important issues as far as designing, utilization and power system protection is concerned. With the spread of interconnected grids, increase in the demand level and increase in the distributed generation, the short circuit current level also increases and becomes few times the rated current of the system; this can cause heavy damage to the equipment of the power system. Since the power system equipments are expensive and because of the replacement problems, occurrence of damage must be prevented. Therefore, instruments for the limitation of fault current are used. Power system operators are interested in the use and installation of those FCLs which in the normal functioning of the system have low impedance (voltage drop and power losses) and limit the fault current in the first peak and also have a low repair and maintenance cost. This is the reason why HTSFCLs got noticed.

Materials made with the HTS technology(less than 1ms) have the fast transition between their resistive and superconducting state and have the ability to limit the short circuit current of the first peak in the low resistance superconducting state and in the resistive state. HTSFCLs are of inductive, resistive and inductive-resistive types which are noteworthy because of their resistive characteristics [3].Unlike the inductive type this particular type doesn't cause any sort of problems as far as the voltage stability is concerned[4,5]. Recent advances in the HTS technology the cause of increase in the quality, fast performance and the resistance of the resistive condition of the HTSFCL and has reduced the cost of cooling of the superconductor [4, 6].

Specification of the optimum size and location of HTSFCLs using the optimization algorithm such as GA and PSO has been the subject of several papers. As mentioned in [8] the feasibility analysis of the superconductors was performed and the optimum location of SFCL was found by fault analysis. References [11, 14] have performed the optimal placement with the aim of coordination of the protective equipment. Previous papers for the determination of the optimum size, location and value of FCL have always focussed on the main goals of stability [7, 10] or security [4, 9, 15].While a compromise must happen between these two. The proposed method is a complete solution for this problem.

This paper shows the HTSFCL capabilities for limiting the fault current and improving the enhancements of voltage and rotor angle stability. A placement problem of HTSFCL has been formulated for the reduction of fault current and the improvement of the indices of voltage, rotor angle stability and the optimum values have been calculated using the differential evolution algorithm. This method has tested on a 39 bus New England test system and the results have been validated using single objective approaches.

## 2. HTSFCL Model

HTS materials have two states one being the superconducting state and the other one is the normal (highly resistive) state and the transition between these two stats (known as a quench), according to the figure (1) is specified by current, magnetic field and temperature. The use of second generation HTS products (such as YBCO) instead of the first generation ones (such as BSCCO) has been the cause of increase in reliability and quality in FCLs as well as it has been able to reduce the production costs [17, 18,19].YBCO acts as a superconductor when the temperature is less than 77 K due to this reason liquid nitrogen is the most ideal substance to be used in the cooling system. With the passage of fault current, the cooling system no longer is able reduce the temperature of HTSFCL rapidly and with the increase in temperature HTSFCL enters the highly resistive region. After the occurrence of fault, a specific amount of time is required for the HTSFCL to return to its superconducting condition, this time period is known as "recovery time". Decrease in recovery time requires an efficient cooling system.

Figure (2) illustrates the (E-I) characteristic curve of the HTS material and this curve is expressed using relation (1), where E represents the voltage drop across a unit length, I represents the current through the superconductor and n is a constant number. For controlling the steepness of the characteristic curve of the fast quenching superconductors, value of "n" should be about 20.

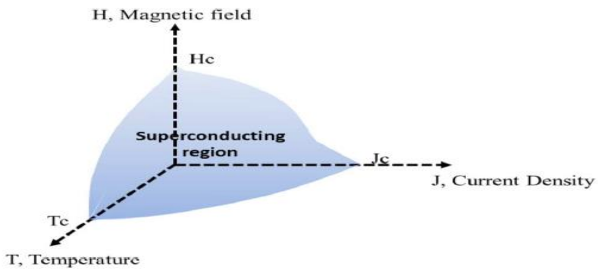


**Figure (1) - HTS superconducting state**

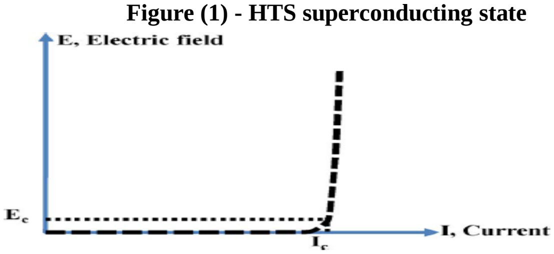


**Figure (2) - Voltage-Current Characteristic curve of the HTS**

$$E = E_c\left(\frac{I}{I_c}\right)^n \qquad (1)$$

Resistive HTSFCLs are usually modeled as variable resistors. Some of the references (such as[7,20]) use time dependent variable resistors and some other (such as[21,22]) use current dependent variable resistors for utilization of the stated process both the models have a suitable performance[25].The current dependent resistance of HTSFCL can be expressed using relation no. (2), where I is the current, ($R_{max}$) is the resistance in the normal state, ($R_{sc}$) is the resistance in the superconducting state, ($I_Q$) is the critical quenching current (app. 2 pu) and n is a constant whose value is equal to 24.

$$R_{\mathrm{HTSFCl}}(i) = R_{max}\frac{\left(\frac{i}{I_Q}\right)^n}{1+\left(\frac{i}{I_Q}\right)^n} + R_{sc} \qquad (2)$$

## 2.1. Performance of the HTSFCL model

In order to analyze the performance of the resistive HTS-FCL, its operation was tested on a single machine infinite bus(SMIB)system as shown in figure (3).The stated system has a synchronous machine rated 120 MVA, 13.8kV connected to an infinite bus of 230kV with a frequency of 50 Hz and X/R=9 through a (Δ/Y) transformer rated at 13.8kV/230kV, 120MVA and the resistive HTSFCL has the following specifications n=24، $I_Q$=2pu ، $R_{max}$=50Ω و $R_{sc}$=0.02Ω and the recovery time from the superconducting state to the resistive state is 1ms [7,10,24,26], this whole setup has been simulated in PSCAD/EMTDC.

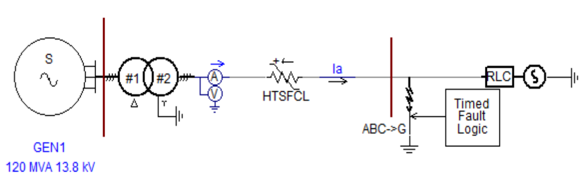


**Figure (3) - Single machine infinite bus system in PSCAD/EMTDC**

According to figure (3) the given system was subjected to a three phase-to-ground fault at t=15 sec for the time = 0.1 sec. Active and reactive power changes, generator rotation speed, rotor angle, current and voltage were observed during the fault as shown in the figures 4A and 4B (in order from top to bottom), 4A shows the state when FCL hasn't been used and 4B shows the state when FCL has been used.

It is obvious from figure (4) that the number and domain of the reactive power fluctuations have reduced. It is obvious that the changes in the active power are the cause of the changes in the rotor angle and lesser these changes are lesser would be the rotor angle fluctuations. Also it is seen in figure (4) that by using HTSFCL the changes in power and also in speed have reduced which in itself is a sign of higher angle stability. As it was stated earlier that the aim of using HTSFCL is to reduce the fault current, in this system when HTSFCL was used the fault current was reduced by 35% as compared to the situation when HTSFCL was not used.

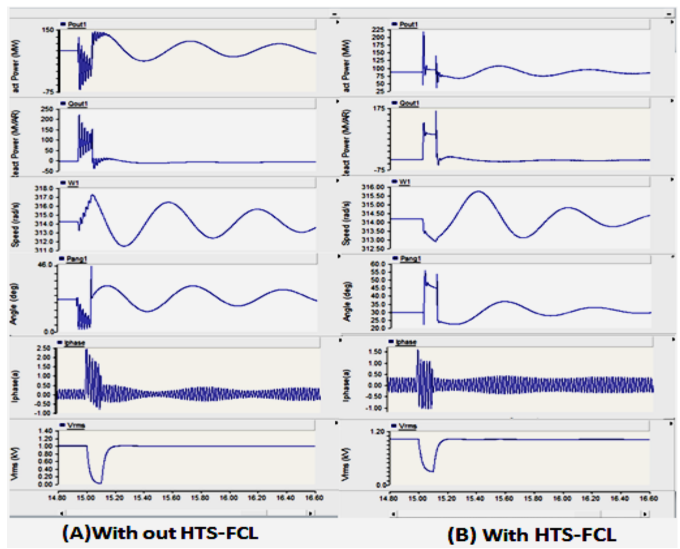


**Figure (4) – illustrations of the changes in the system parameters**

Voltage changes in the first fault occurrence have reduced when HTSFCL was used and the effective value of the stator voltage has also reduced by 33% of the amount it was when HTFSCL was not installed, which confirms the higher voltage stability circumstances.

## 3. Problem formulation

For obtaining the optimum size and location for the usage and installation of the HTSFCL, intelligent methods can be used, some of the studies have used genetic algorithm for the optimum placement of FCL. It is obvious that the main aim of the installation of HTSFCL is the reduction of the short circuit current level. A system's security and protection parameters are improved if short circuit current level is reduced. Short circuit current of every bus can be calculated using equation (3) and also by updating the values of the matrix $Z_{Bus}$.

$$I_{sc}^K = \frac{E_{pre-fault}^K}{Z_{KK}} \qquad (3)$$

Where $Z_{KK}$ represents the diagonal elements of the matrix $Z_{Bus}$ and $E_{pri\text{-}fault}^{K}$ is the voltage of the k th bus before the fault , k = 1,2,3…..n and n is the number of buses. Therefore first expression that must be optimized is shown in th equation (4):

$$\text{Minimum } (J_1) = \sum_{K=1}^{n} I_{sc}^{K} \quad (4)$$

Increase in the critical clearing time leads to the increase in the angular stability of the rotor of the synchronous machine. The swing equation for the $i^{th}$ synchronous machine can be written according to equation (5) it is observed that with the reduction in reactive power changes during fault occurrence the angular stability increasing is available.

$$\frac{d\omega_i}{dt} = \frac{1}{M_i}\left(P_m^i - P_e^i\right) \quad (5)$$

$$\omega_i = \frac{d\delta_i}{dt} \quad (6)$$

$$P_e^i = \sum_{j=1, j\neq i}^{n} E_i E_j\left(G_{ij}\cos(\delta_{ij}) + B_{ij}\sin(\delta_{ij})\right) \quad i = 1,2,\dots,N \quad (7)$$

Where Mi is the inertia constant, $\boldsymbol{\omega_i}$ is the rotor speed, $\boldsymbol{\delta_i}$ is the rotor angle, $P_e^i$ is the output electrical power, $P_m^i$ is the mechanical power, $E_i$ is the internal voltage of the synchronous generator i,$G_{ij}$ and $B_{ij}$ are the elements from the matrix $Y_{Bus}$ and N is the number of the synchronous machines. Finally the swing equation can be represented using the equation (8).

$$\frac{2H_i}{\omega_o}\frac{d^2\delta_i}{dt^2} = P_m^i - P_e^i \quad (8)$$

Where $H_i=\omega_0/2M_i$ is the per unit amount of the energy stored in the rotor. $P_m^i$ is the pre-fault mechanical power and $P_e^i$ is the electrical power during the fault which can be calculated using the transient equations mentioned below.

$$E_i^K = E_i\left(1 - \frac{Z_{iK}}{Z_{ii}}\right) \quad (9)$$

$$I_{ij} = Y_{ij}\left(E_i - E_j\right) \quad (10)$$

$$P_e^{iK} = Re\left[E_i^K I_{ij}\right] \quad (11)$$

$$\frac{2}{\omega_o}\frac{d^2\delta_i}{dt^2} = \frac{P_m^i - P_e^{iK}}{H_i} = \frac{\Delta P}{H_i} \quad (12)$$

Where $2/\omega_0$ is a constant term and the angular stability index of the machine i during the fault at the bus K has been shown by equation (13) and equation (14) is second equation that must be optimized.

$$ASI_K^i = \frac{d^2\delta_i}{dt^2} = \frac{\Delta P}{H_i} \quad (13)$$

$$\text{Minimum } (J_2) = \sum_{K=1}^{n}\sum_{i=1}^{N} ASI_K^i \quad (14)$$

As it was seen in the single machine system, using the resistance limiter which was made using high temperature superconductors reduces the amount of voltage drop at the time of the fault. Thus the other problem which needs to be optimized is the level of voltage drop at the time of the fault or in other words the level of the voltage change. Voltage stability index for the bus I during the fault at the bus K is calculated using the equation (15) and equation (16) is the third expression which must be optimized.

$$VSI_K^i = E_i - E_i^K \quad (15)$$

$$\text{Minimum } (J_3) = \sum_{K=1}^{n}\sum_{i=1}^{N} VSI_K^i \quad (16)$$

Where $E_i$ is the voltage of the bus I obtained from the load flow and $E_i^k$ is the voltage of the same bus during the fault at bus K. Therefore everything that must be optimized has been mentioned in the equation (17).

$$\text{Minimum } (J) = \omega_1 \sum_{K=1}^{n} I_{sc}^{K} + \omega_2 \sum_{K=1}^{n}\sum_{i=1}^{N} ASI_K^i + \omega_3 \sum_{K=1}^{n}\sum_{i=1}^{N} VSI_K^i \quad (17)$$

So that :

$$I_{sc}^{n} \le I_{sc}^{\max}, \; Z_{FCL} \le Z_{max}, \; n_{FCL} \le n_{max}$$

## 4. The studied system description

This paper uses the New-England (IEEE) 39-bus system for the validation and credibility of the optimization results. The system shown in the figure (5) consists of 10 generators, 39 buses and 46 lines, the details of the system has been taken from [2] (T.Athay's research paper) and the appendix B taken from [1](PhD thesis of A.K.Behera).

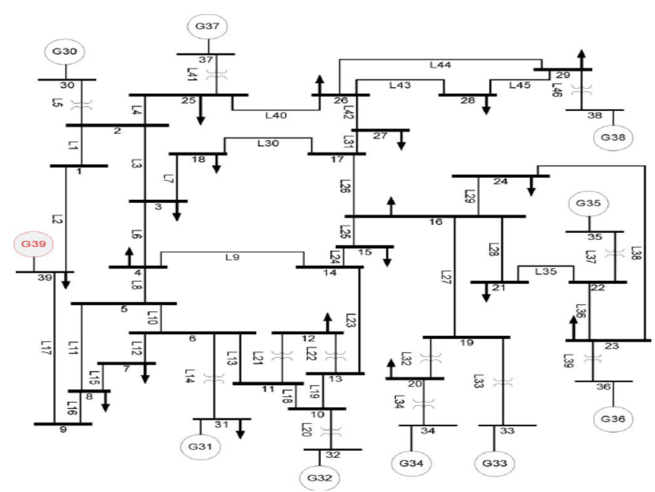


**Figure (5) - 39 bus IEEE test system**

## 5. Optimum placement steps of HTSFCL

Figure (6) shows a flowchart showing the steps of determining the optimum values and location of the installation of HTSFCL in the grid.

## 6. Studying the results

The differential evolution method (DE) was presented by R.M. Storn and K.V. Price in 1995, this method is about optimization evolution based on population. This method was used for optimization and it took this method with 1000 iterations to obtain the results of the optimized placement, the initialization of the superconducting fault current limiters.

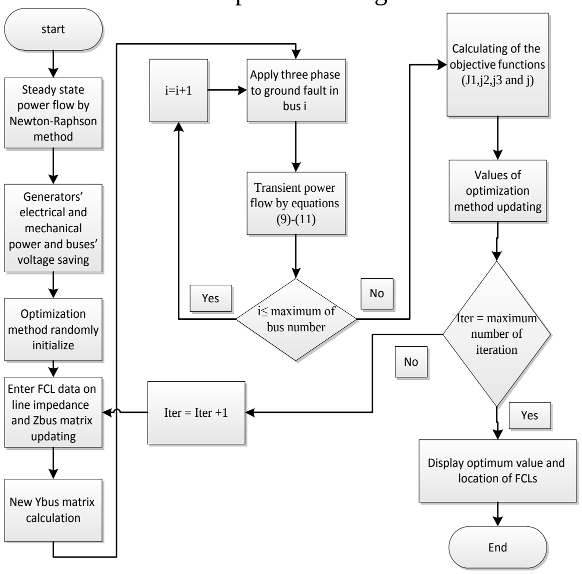


**Figure (6) - flowchart showing the steps of optimal placement of HTSFCL**

**Table (1) shows the optimization results for all conditions. Coefficient values of multi objective optimization mode (equation (17)) are equal to below:**
**w1 = 0.4, w2 = 0.4, w3 = 0.2**

| Indices | Optimum place & Optimum value | | | |
|---|---|---|---|---|
| J1- $I_{sc}$ | 3<br>0.917239 | 14<br>1 | 26<br>1 | Line No.<br>value (pu) |
| J2- ASI | 3<br>1 | 14<br>1 | 21<br>1 | Line No.<br>value (pu) |
| J3- VSI | 3<br>1 | 14<br>1 | 26<br>1 | Line No.<br>value (pu) |
| *J-MO* | *5*<br>0.982 | *15*<br>*1* | *21*<br>0.99337 | Line No.<br>value (pu) |

Table (1) - Optimization results

The 5 conditions (Mode=1:5) include:
1-Non-use of fault current limiters
Optimized use of fault current limiters
2-With fault current indices
3-With voltage stability indices
4-With angular stability indices
5- With multi objective indices

By using the values obtained from the optimization and simulation of fault of the three phase-to-ground, the amount of fault current in every bus has been shown in the figure(7). It is evident from the figure (7) that usage of multiple target functions (Mode 5) has better results. As a result it is obtained that the amount of fault current has reduced in comparison to other conditions, therefore in terms of security and protection better conditions would be obtained.

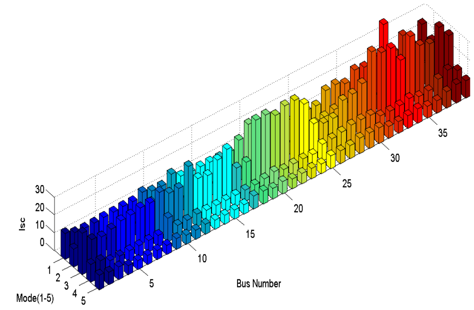


**Figure (7) – comparison of the fault currents in our bus for the 5 modes**

In the same way for the five mentioned modes, the indices of voltage stability have been shown in the figure (8) which shows that the use of multiple target indices (Mode=5) has caused the enhancement of the final results and is the cause of the reduction of the amount of voltage changes during the fault in comparison to other modes.

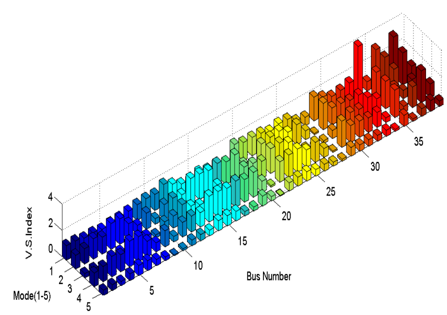


**Figure (8) – The Comparison of voltage stability functions for all the 5 mentioned modes**

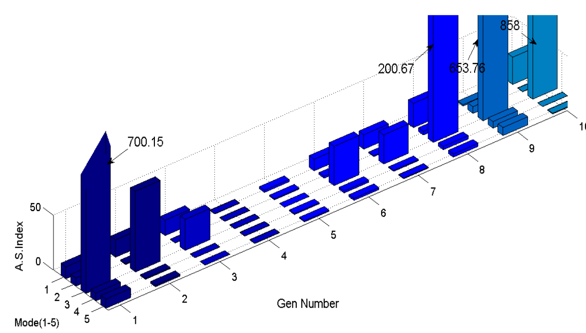


**Figure (9) – The comparison of the angular stability functions in the generator buses for all the 5 modes**

And also in the 5 mentioned conditions, with the application of the obtained values from the optimization and simulation of the three phase-to- ground, the indices of angular stability in the productive buses has been shown in the figure(9). Figure (9) shows the advantage of the use of multiple target method in this case and also explains the use of voltage stability indices in the worst possible situation for the provision of angular stability is in the buses connected to the generator.

## CONCLUSION

Superconducting materials have different uses and some of its uses are linked and mixed with the electrical industry. One of these uses is in fault current limiters. Superconductors which are manufactured by HTS technology, have the suitable properties to be used in FCLs. HTSFCL are used in the electrical transmission and distribution grids for the reduction of fault current.

The optimization of amount and location of FCLs has been a topic of several papers. In this paper, a type of resistive type FCL made by HTS technology has been considered and its modeling in a single machine system, first of all the performance of this type of FCL for the reduction of fault current, reduction of voltage changes and the fluctuation of the rotor angle of the machine was studied. Then with the use of the differential evolution the optimum values of this type of FCL in a test system with stability and security functions under consideration. Results in the Table (1) are the proof of the superiority of this type of FCL with the use of multi objective indices as compared to the single ones. According to figure (7) the amount fault current in this mode has been reduced which itself is the expresser of the enhancement of the conditions as far as protection and security is concerned. And the graph in figure(8) explains the increase in voltage stability also figure (9) explains the increase in angular stability in the condition of HTSFCL placement using multi objective optimization.

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