Optimal Location of Resistive SFCL for protecting electrical equipment in Indian Power Grid: a case study

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Abstract. Due to integration of state power grids with the national grid there is a significant rise in the short circuit fault current levels in Indian power transmission networks. The safety of protection devices in existing power system is essential. One of the possible solutions for safe guarding protection devices against high short-circuit fault currents is the integration of Superconducting Fault Current Limiters (SFCLs) in the power grid. Optimal location of minimum number of SFCLs in a power grid is a challenging job. In this paper, a simulated case study is presented on the optimal locations of SFCLs in a typical network operating at various voltage levels using resistive type SFCLs (R-SFCLs). The R-SFCL is modeled by incorporating E - J characteristics of HTS tape for the 3-phase short circuit fault simulations in MATLAB Simulink. The fault currents obtained from the simulation results, with and without R-SFCLs were then compared and analyzed.

1. Introduction

Electrical power consumption in India has increased in past 5 years due to various industrial and city developments. This increase in power consumption had given a significant rise to fault currents in the existing power grids. The stability of existing power system gets affected due to the integration of various grids, hence giving rise to fault current levels. Use of conventional power system protection devices such as split-bus bars, transformers with higher impedance and fuses are commonly used. Increase in power consumption levels calls for the higher rating of protection devices for safe operation [1]. A high temperature Resistive Superconducting Fault Current Limiter (R-SFCL) can be an alternative to the above conventional power system protection devices. In addition, the SFCL also improves their transient stability of the power system by reducing the level of fault currents in a short duration. The power oscillation in the grid caused due to faults can be easily damped by the SFCL because of its fast dynamic response when compared with the conventional fault current limiters. The energy dissipation in SFCLs is very minimal as compared to that of existing fault current limiters because SFCLs offer negligible impedance during normal operation and introduces high impedance quickly to the power line as and when fault occurs. This quick operation of SFCL compensates for the time delay caused in the operation of circuit breakers. This results in safe guarding of circuit breakers and other power system equipments by reducing the fault current in minimum time [2].

In this paper we have considered a part of a typical Indian power grid for our simulation [3] in which 3 φ short circuit faults were created at two different locations. Current levels under
fault conditions were considered for the specifications of R-SFCL. R-SFCLs were then located at 5 different places and the corresponding effects on fault current were observed. These R-SFCLs were modeled using E-J characteristics of HTS tapes. In the later section, fault currents with and without R-SFCLs were compared for different combinations (62 nos.) and the simulated results are used to find the optimal location with minimum number of R-SFCLs required for safety of the selected grid.

2. Grid Configuration

The grid used for simulation consists of two Hydro Power Plants HPP1 and HPP2, operating at 25 kV, 50 Hz with a capacity of 450 MW and 400 MW which are situated 250 km and 300 km respectively away from the common power grid Figure 1. The voltages generated in both the power plants were stepped up to 400 kV using power transformers (TX1 and TX2). These transformers are connected to a common grid with transformers TX3 (400kV/400kV), TX8 (400kV/220kV) and TX9 (400kV/132kV) via transmission line TL1, TL2 and TL29 respectively as shown in Figure 1.

Power transformer TX3 is fed by the power lines coming from HPP1 and HPP2 at 400kV. This parallel input to TX3 interconnects the two power plants in order to supply the power to the industrial load L10 at 132 kV through TX5 and TX10. On the other hand metro city load L9 and domestic load L8 are connected via TX4, TX6, TX11 and TX4, TX7 and TX12 respectively. The details about transformer voltages and transmission line lengths are specified in Table 1 and Table 2 respectively. Industrial load 6 and Metro city load 5 are connected via parallel feeders that are TX16, TX17 and TX18, TX19 respectively. These parallel feeders are required for supplying the powers to the loads even when one of the feeders is out for maintenance. Such system provides redundancy of power supply to loads. This redundancy causes strong interaction between two different feeders, which results in high power flow oscillation in the network during faults.

![Figure 1. Power system model based on Indian grid standard for two prospective fault positions and five prospective SFCL locations.](image-url)
The details about other transformers, transmission lines and loads are listed in Table 1, Table 2 and Table 3 respectively. Current and voltages were monitored at different measurement points as indicated in Figure 1.

### Table 1. Power and voltage ratings of transformers used for simulation.

| Transformer | Primary Voltage | Secondary Voltage |
|-------------|----------------|------------------|
| TX1         | 25 kV          | 400 kV           |
| TX2         | 400 kV         | 220 & 132 kV     |
| TX3         | 400 kV         | 220 kV           |
| TX4         | 400 kV         | 220 kV           |
| TX5         | 400 kV         | 220 kV           |
| TX6         | 400 kV         | 220 kV           |
| TX7         | 400 kV         | 220 kV           |
| TX8         | 400 kV         | 220 kV           |
| TX9         | 400 kV         | 132 kV           |
| TX10        | 220 kV         | 132 kV           |
| TX11        | 400 kV         | 132 kV           |
| TX12        | 220 kV         | 132 kV           |
| TX13        | 220 kV         | 132 kV           |
| TX14        | 220 kV         | 132 kV           |
| TX15        | 220 kV         | 132 kV           |
| TX16        | 220 kV         | 132 kV           |
| TX17        | 220 kV         | 132 kV           |
| TX18        | 132 kV         | 66 kV            |
| TX19        | 132 kV         | 66 kV            |
| TX20        | 132 kV         | 66 kV            |

### Table 2. Length of transmission lines used for simulation.

| Transmission Line | Length (km) | Transmission Line | Length (km) | Transmission Line | Length (km) |
|-------------------|-------------|-------------------|-------------|-------------------|-------------|
| TL1               | 250         | TL11              | 50          | TL12              | 45          |
| TL2               | 300         | TL11              | 50          | TL12              | 45          |
| TL3               | 120         | TL13              | 110         | TL14              | 150         |
| TL4               | 150         | TL14              | 150         | TL15              | 110         |
| TL5               | 60          | TL15              | 110         | TL16              | 90          |
| TL6               | 90          | TL16              | 90          | TL17              | 150         |
| TL7               | 80          | TL17              | 150         | TL18              | 55          |
| TL8               | 100         | TL18              | 55          | TL19              | 60          |
| TL9               | 110         | TL19              | 60          | TL20              | 40          |
| TL10              | 70          | TL20              | 40          |

### Table 3. Power and voltage ratings of loads used for simulation.

| Load | kV | MW |
|------|----|----|
| L1   | 132| 60 |
| L2   | 132| 50 |
| L3   | 132| 50 |
| L4   | 132| 50 |
| L5   | 66 | 100|

In order to compare the effect of fault on single feeder and parallel feeders in the power grid, 3-phase short circuit (L-L-L) faults F1, F2 were considered for simulation (one at a time) near...
to an industrial load L10 and industrial load L6 respectively. In order to limit the fault current, SFCLs were introduced at 5 different locations (S1, S2, S3, S4 and S5) as indicated in Figure 1. This results into 31 combinations (Combinations = 2^5 – 1, for x = 5, combinations = 31) of SFCL locations corresponding to a single fault. Henceforth, 62 simulations with SFCL for two faults are considered. In addition, two simulations without SFCL for faults F1 or F2 and one simulation without fault & SFCL were carried out to find the minimum numbers of SFCLs and their optimal locations to limit the fault currents. The details about the simulation and the results are discussed in the later sections.

3. R-SFCL model with E-J Power law characteristics

On quenching, R-SFCLs are known to introduce high resistance in the network. This quenching is mainly due to current crossing its critical values. The variation in electric field in the superconductor due to change in current density is known as E-J power law curve. In this paper, Bi – 2212 based SFCL is considered for simulation. This curve is highly non-linear for the given HTS tape. The non-linear response of the E-J curve is divided into three regions i.e. superconducting region, flux flow region and normal conducting zone. Following are the governing equations for the E-J power law used for modeling R-SFCL in simulation eq.( 1).

\[
E(T, t) = \begin{cases} 
E_c \left( \frac{J(t)}{J_c(T(t))} \right)^n & \text{for } E(T, t) < E_0 \text{ and } T(t) < T_c \\
E_0 \left( \frac{E_c}{E_0} \right)^{m/n} \left( \frac{J_c(77K)}{J_c(T(t))} \right) \left( \frac{J(t)}{J_c(77K)} \right)^m & \text{for } E(T, t) > E_0 \text{ and } T(t) < T_c \\
\rho(T_c) \frac{T(t)}{T_c} J(t) & \text{for } T(t) > T_c 
\end{cases} (1)
\]

Where,

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

For modeling m = 3 and n = 9 are taken for power indices based on the references [4]. Higher the value of index n, faster will be the response of R-SFCL, whereas power index m determines the current capacity during flux flow state which includes the effect of self induced magnetic field. \( \rho(T_c) = 5 \mu \text{ohm} \) was used for the computation of equivalent resistance value of R-SFCL. A MATLAB program was developed as a sub-routine which was called in the Simulink to operate as a R-SFCL in accordance with the fault current levels. This R-SFCL sub-routine works only for a single phase, hence 3 R-SFCL sub-routines were clubbed together to form 3 – φ R-SFCL.

4. Optimal location of R-SFCL

The grid shown in Figure 1 was modeled in MATLAB Simulink software using Powersim module. Initially the grid is simulated for normal condition i.e. without any SFCL or faults. Voltages and currents are measured at various locations and were recorded for the modeled grid using measurements module as shown in Figure 1. These measurements help in understanding the dynamics of the grid under various conditions.

After modeling the grid two faults were created at F1 and F2 locations and the corresponding fault currents were recorded and analyzed separately. Based on the analysis of a fault currents with and without faults, five different locations of SFCL were identified to safeguard the power system from a severe 3 - phase short circuit fault. 31 simulations were carried out for different combinations of SFCLs location corresponding to each fault location. Thus, overall 65 simulations were carried out. The current from all 16 measurement locations for all R-SFCL simulations were compared to obtain the optimal location of R-SFCLs along with minimum number of R-SFCLs (discussed in next section).
5. Results and discussions
It was observed that the fault current values at some locations (S1 closure to HPP1) with R-SFCLs were higher than those without R-SFCLs after fault clearance due to sudden change in load. It was also observed that at some R-SFCLs locations (S2 closure to HPP2), there was insignificant effect on current limitations. R-SFCLs at various location combinations such as (S3), (S2 and S4), (S2 and S5), and (S2, S3 and S5) are capable of limiting the fault currents within 47% to 89% for the faults F1 and F2 only occurring independently in the first cycle of fault in the modeled grid. It is also visible that faults occurring closer to the load (L5) cannot be attenuated by R-SFCL at location S3 alone; Similarly, the locations combinations (S2 and S4) and (S2 and S5) cannot limit the fault currents for fault location F1 significantly. Hence, the location combinations (S2, S3 and S5) is the most suitable location to safeguard the power equipments from any of the faults occurring at any load locations. Figure 2 shows the bar graph for comparison of current levels under no faults and fault (F1 and F2) conditions at different measurement locations for R-SFCLs location combinations (S2, S3 and S5).

6. Conclusions
A part of typical Indian power grid was modeled and simulated for two fault locations (one at a time) and five R-SFCL location combinations. The R-SFCLs were modeled using E - J power law having an ‘n’ factor of 9. Out of 62 possible location combinations presently studied, it is observed that 4 location combinations viz (S3), (S2 and S4), (S2 and S5), and (S2, S3 and S5) are capable of limiting the fault currents within 47% to 89% of its peak value. Moreover, the location combination (S2, S3 and S5) is the optimal location, as it can limit the fault current occurring from any load located in the grid considered.

References
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