Comparison of the Performances of Three Different Types of Fault Current Limiter in the Distribution Network

A. Morandi1, M. Bocchi2, M. Fabbri1, L. Martini2, F. Negrini1, P. L. Ribani1
1 Department of Electrical Engineering, University of Bologna, Italy
2 Renewable Energies & Superconductivity, CESI, Milan, Italy
Corresponding author: antonio.morandi@mail.ing.unibo.it

Abstract. In this paper the comparison of three different types of SFCL, the resistive, the inductive and the rectifier type, with reference to a significant position in the distribution network, is carried out. The design of the SFCL devices is developed and size, losses and refrigeration power are evaluated. An equivalent circuit model of each device is then derived and implemented, along with the scheme of the considered distribution network, in the EMTP program. The limiting effect, joule integral, recovery time and influence of SFCL devices on the healthy part of the system are studied and compared.

1. Introduction
Superconducting fault current limiters (SFCLs) are expected to bring considerable technical and economical benefits to electric power systems. The feasibility of different concepts of SFCL has been widely demonstrated during the last decades by means of several laboratory scale prototypes. Extensive work to model SFCLs has also been carried out in parallel, in order to assist and optimize the design and to investigate the reciprocal interaction of SFCLs with power networks [1]-[4]. Some SFCL prototypes have nowadays reached a pre-industrial stage of development and have been successfully submitted to long term field test [5]-[7].

At the present state of the art it seems questionable for the inductive type SFCL to find a short term application in power systems due to its difficult scalability from the prototype stage to the medium or high voltage rating. Conversely, a general optimism exists about the scalability of the resistive and the rectifier type SFCL [6], [8]-[10]. However the choice of the most suitable type of SFCL is not a trivial task since it involves many technical and economical aspects including effectiveness of its limiting effect, recovery time, joule integral, running costs and size and moreover it is strictly related to the position within the power network and therefore to the voltage level and the existing protection scheme and apparatus.

In this paper a comparison of the performance of three different types of SFCL, the resistive, the inductive (magnetic shield) and the rectifier type, with reference to the bus-tie position within the distribution grid shown in figure 1, is presented. The grid, whose main characteristics are listed in table 1, is connected to the transmission network operating at the voltage of 132 kV, that is supposed to have an infinite power. The values of fault current of table 1 refer to the current through the circuit breaker after a three-phase to ground short circuit, occurring at the beginning of the distribution line 1. Since the two loads are equal no current flows through the interconnection bus in nominal condition. In addition it is supposed that for service reasons, one transformer can supply both the loads; the nominal current through the interconnection bus during this condition is equal to 360 A.

In order to carry out the comparison, first the design of the three different types of SFCL having the appropriate characteristic for the considered application is carried out and size, losses and refrigeration power are evaluated. An equivalent circuit model of each device is then derived and implemented in the Electromagnetic Transient Program (EMTP), along with the scheme of the distribution network. A distributed parameters model is used for the distribution lines. The performances of the three devices in terms of limiting effect, joule integral,
recovery time and influence on the healthy part of the system, are evaluated with reference to the case of a three-phase to ground short circuit occurring at the beginning of the distribution line 1 (point F of figure 1).

| Table 1: data of the distribution network |
| Nominal Voltage | 20 kV |
| frequency       | 50 Hz |
| Opening time of circuit breakers | 80 ms |
| Reclosing time of circuit breakers | 300 ms |
| Asymmetric peak fault current | 28.7 kA |
| Symmetric peak fault current | 15 kA |

2. Design aspects and modeling

All the considered SFCLs are based on the Bi2223 material. Their design has been carried out by assuming that they can supply permanently, through the interconnection bus, one of the two loads when one of the transformers is disconnected, with a 100% overload admitted. The design parameters are reported in table 2, where the current indicates the value that starts the transition of the device to a high impedance state. The design procedure, the layout and the modeling of any of the SFCLs are described in the following.

2.1.1. Resistive type SFCL. The main characteristic of the resistive type SFCL are reported in table 3. The final layout is arrived at by fitting the parameters specified in table 2 by means of a trial and error procedure. The device is made of several parallel connected Bi-2223/Ag multifilamentary tape wound in non inductive way. The considered HTS tape has a critical current in self field at 65 K of 140 A [11]. The model of the device is obtained by calculating, based on the E-J characteristics of the tape, the temperature dependent value of the parallel connected resistances that schematizes the sharing of current between the HTS filaments and the silver matrix. The temperature is assumed uniform over the SC winding, and is calculated by means of the coupled heat exchange equation with convective boundary condition. This model allows a good agreement with the experimental results in [1]. The AC losses are calculated by means of the Norris formula.

2.1.2. Magnetic shield type SFCL. The main characteristic of the inductive type SFCL are reported in table 4. The three phase inductive type SFCL is made of three distinct single phase devices made of a normal coil and a Bi2223 tube coupled together via a closed ferromagnetic core made of laminated 2V-permendur material. The characteristics of the considered tube can be found in [12]. A direct three phase configuration can be achieved by assembling three single phase device with a shared central magnetic yoke. The design has been accomplished by means of a stochastic multi-objective optimization algorithm. The degrees of freedom were the inner radius, the thickness of the SC tube, the number of turns and the height of the HTS coil. The objectives were the maximum inductance in non limiting phase and the maximum inductance under limiting condition; since these quantities increase with the increase of the leakage inductance in air between the coil and the SC tube and the self inductance in air of the coil respectively, for simplicity their extremes were determined by considering the latter as objective functions. It was assumed that when the quenching current circulates through the normal coil, the critical current density penetrates the whole cross section of the SC tube. Moreover, it was assumed that a three phase short circuit that causes the complete transition of the SC tube can occur and persist at the FCL busbar without causing the saturation of the magnetic core. Among the set of solution found, the most compact has been chosen. The numerical model of the device has been obtained starting from an integral formulation of the coupled electro-magnetic-thermal problem at the interior. It consists of three coupled electric, magnetic and thermal networks whose topology depends on the discretization that is needed to reach the convergence of the numerical solution for the distribution of current, losses, magnetic flux density and temperature inside the device [3]. For what concern the calculation of the AC losses in nominal condition a very fine discretization of the SC volume was needed. Conversely, for the investigation of the interaction of the device with the power system, only the convergence of the solution with respect to the current and the voltage across the limiter, that is attainable with a relatively coarse discretization, was required, therefore a simple equivalent circuit, has been used without a significant loss of accuracy.

2.1.3. Rectifier type SFCL. The main characteristic of the rectifier type SFCL are reported in table 5. The SC coil is made of several parallel connected Bi-2223/Ag multifilamentary tapes [11]; its final layout has been obtained by minimizing, through a deterministic optimization algorithm, the volume of the superconductor [13]. The value of the inductance, that is series connected to the protected circuit when the quenching current of the device (coinciding with the bias current of the coil) is exceeded, has been chosen by imposing that 80 ms after
the fault (the time required by the switchgear to open the circuit) the current does not overcome the allowed peak value of 4 kA. Since this device operates with DC current in nominal condition it does not produce any AC losses. The only heat load for the cooling system is given by the thermal input of the current leads. The simulations have shown that this limiter does not affect the system during nominal condition or ordinary load variation.

### Table 2: design parameters of the SFCLs

| Parameter                        | Value          |
|----------------------------------|----------------|
| Nominal current                  | 360 A rms      |
| Critical current                 | 1015 A         |
| Operating temperature            | 65 K           |
| Maximum allowed peak current     | 4 kA           |
| Recovery time                    | 220 ms         |

### Table 3: resistive type SFCL (single phase)

| Parameter                        | Value          |
|----------------------------------|----------------|
| Number of parallel connected SC tapes | 9              |
| Inner Radius of the SC winding     | 50 mm          |
| Thickness of the SC winding       | 100 mm         |
| Height of the SC winding          | 1200 mm        |
| Length of the SC tapes            | 8 km           |
| AC losses in nominal condition    | 390 W          |
| Thermal input from the current leads | 32.4 W        |

### Table 4: inductive type SFCL (single phase)

| Parameter                        | Value          |
|----------------------------------|----------------|
| Inner Radius of the SC tube      | 213 mm         |
| Thickness of the SC tube         | 8 mm           |
| Height of the SC tube            | 839 mm         |
| Inner Radius of the normal coil  | 273 mm         |
| Thickness of the normal coil     | 22 mm          |
| Height of the normal coil        | 1000 mm        |
| Number of turns                  | 200            |
| Radius of the magnetic column    | 195 mm         |
| Height of the magnetic column    | 1020 mm        |
| Inductance in non-limiting phase | 2.1 mH         |
| Resistance of the normal coil    | 56 mΩ          |
| AC losses in nominal condition   | 220 W          |

### Table 5: rectifier type SFCL (single phase)

| Parameter                        | Value          |
|----------------------------------|----------------|
| Nominal current                  | 1015 A         |
| Quenching current                | 4 kA           |
| Number of parallel connected SC tapes | 40             |
| Inner Radius of the SC coil      | 190 mm         |
| Thickness of the SC coil         | 104 mm         |
| Height of the SC coil            | 380 mm         |
| Number of turns of the SC coil   | 988            |
| Length of the SC tapes           | 1.5 km         |
| Thermal input from the current leads | 90 W          |

### Table 6: comparison of the three SFCL

| SFCL Type                  | Nominal current | Critical current | Operating temperature | Maximum allowed peak current | Recovery time |
|----------------------------|-----------------|------------------|------------------------|------------------------------|---------------|
| Resistive type             | 4 kA            | 1015 A           | 65 K                   | 4 kA                         | 220 ms        |
| Inductive type             | 2.1 mH          | 56 mΩ            | 213 mm                 | 8 mm                         |
| Rectifier type             | 220 W           | 220 W            | 1015 A                 | 4 kA                         |

### 3. Results and discussion

Figure 2 shows the current through circuit breaker CB1 during a three-phase to ground short circuit occurring at the beginning of the distribution line L1 at the zero crossing of the voltage (most onerous case) for the three types of SFCL. The circuit breaker is supposed to interrupt the current after 80 ms from the fault occurrence. The fault currents without any limiter and without the interconnection bus are also shown in the figure. As it can be seen from the figure a 40% reduction of the peak current is achieved by means of all the three types of SFCL. The limited current is only slightly greater than the fault current without interconnection bus, that is the minimum possible value. Figure 3 shows the voltage of line 2 during the fault of line 1. It can be seen that, thanks to the disconnecting action of the SFCLs, line 2 remains in operation even though with a perturbed voltage waveform. Moreover, simulations show that in nominal condition no harmonics are produced by the SFCLs in the power system.

In order to carry out a thorough comparison of the limiting action, the Joule integral of the fault current (i.e. the integral over the time of the square of the current) has been calculated for the three SFCL and plotted in figure 4. Being proportional to the thermal power allowed to flow through the upstream components (transformer T2), the joule integral is a significant figure of merit of the SFCL. It can be seen from the figure that, compared with the other two, the resistive type SFCL admit an higher joule integral; this means that this limiter cause a greater stress of the upstream components after a fault.

Figure 5 shows the average temperature inside the resistive and the inductive SFCL during the fault event and in the following recovery phase. In this simulation circuit breaker CB1 open the circuit 80 ms after the fault occurrence and re-closes 220 ms later, when the fault is cleared. At reclosing time we assume that one of the transformers (T1) is disconnected; due to the fact that a current circulates through the SFCL, this represents a more onerous condition for the recovery. It can be seen from the figure that the temperature of both the devices is well below Tc at the reclosing, therefore their recovery is successfully accomplished. Moreover, since no change is observed in the derivative of the temperature at the reclosing, the cooling of both SFCLs down to the nominal temperature of 65 K is not slowed down if the limiters supply their nominal load immediately after the reclosing.

Table 6 shows a comparison of the three considered SFCL that takes into account all the relevant elements concerning the device layout, and the behavior under nominal and limiting condition. A cooling penalty of 20 has bee used for the calculation of the refrigeration power. The AC losses are not considered in the active power losses. It can be seen from table 6 that, even though all the devices turn out effective for what concern the limit-
ing effect, the protection of the healthy part of the system and the recovery time, the diode bridge type is favorable in terms of losses and refrigeration power, that are proportional to the running costs.

![Figure 2: current through circuit breaker CBI during the fault](image)

![Figure 3: voltage of line 2 during the fault of line 1](image)

![Figure 4: Joule integral of the SFCLs during the fault](image)

![Figure 5: average temperature of the resistive and inductive SFCL](image)

**Table 6 - Comparison of the three considered SFCL**

|                     | Limiting effect | Disconnecting effect | Joule integral | Recovery | Active Power | Reactive Power | Thermal load | Cooling power | Size (estimated) |
|---------------------|-----------------|----------------------|----------------|----------|--------------|---------------|--------------|---------------|------------------|
| Resistive           | effective       | effective            | high           | immediate| 0            | 0             | 1267 W       | 25.3 kW       | 0.3 × 0.9 × 1.2 m³ |
| Inductive           | effective       | effective            | low            | immediate| 7 kW         | 85 kVAR        | 660 W        | 13.2 kW       | 0.8 × 1.8 × 1.2 m³ |
| Rectifier           | effective       | effective            | medium         | immediate| 0            | 0             | 270 W        | 5.4 kW        | 0.6 × 1.8 × 0.4 m³ |

4. Conclusion

In this paper the comparison of three different types of SFCL (resistive, inductive and rectifier type), with reference to a significant position in the distribution network, has been carried out. The devices with appropriate characteristics for the specific application have first been designed and then modeled in EMTP along with the scheme of the distribution network. Even though all the devices have turned out effective for what concern the limiting effect, the protection of the healthy part of the system and the recovery time, the diode bridge type seems favorable, for the considered application, in terms of losses and refrigeration power.

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