Investigation of shunt resistor's connection for a DC Resistive SFCL

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Abstract. A DC-operating resistive-type superconducting fault current limiter for AC applications (in short a DC Resistive SFCL) is based on the synergistic use of the “resistive” and the “rectifier” fault current limiter concepts, and allows the superconductor to operate in nearly DC current conditions. This regime of operation drastically reduces AC losses thus opening new perspectives with regard to materials, architecture of the cable, lay out of windings and cryogenics. In this paper the concept of DC resistive SFCL is resumed and a case study about its possible application in the distribution electrical system is reported. Two possible connections of external shunt resistor in order to reduce the Joule heating during the limiting phase are analysed.

1. Introduction
A fault current limiter is a fundamental component for modern electric power system, both at the medium and the high voltage level [1]. In last years a great research effort was carried out in order to develop superconducting fault current limiters (SFCL) based on different concepts [2]. Among all possible devices, those that directly exploit the resistive transition of the superconductor in order to add a impedance to the protected circuit in case of fault (resistive SFCL) seem to have the best perspectives. The main drawbacks of this device are the AC losses occurring in the superconductor, which becomes particularly important for high voltage applications where a long length of superconductor is required [3]. Significant progress can be achieved when low loss superconducting tapes of second generation (YBCO coated conductors) will become available at the industrial level and cheaper cost [4]. However, the demanding cryogenics related to currently available HTS conductors of first generation (BSCCO tapes or wires) still hinders the penetration of these device in the market place. In order to reduce this problem the feasibility of DC-operating resistive-type superconducting fault current limiter for AC applications (in short a DC Resistive SFCL) was recently investigated [5]. This device exploits a diode bridge which allows the superconductor to operate in nearly DC conditions. This regime of operation drastically reduces the AC losses and therefore opens up interesting perspectives with regard to the materials and the cryogenics. In particular, it allows the convenient exploitation of the MgB$_2$, a superconductor with promising limiting properties [6] that can be produced at competitive quantities and costs [7]. Moreover, due to the DC operation, matrix and sheath material with a high electrical and thermal conductivity, which enhances the performance of the device in terms of stability and recovery time, may be used in order to produce the SC wire or tape to be used.
In this paper the concept of DC resistive SFCL is first resumed in session 2. In session 3 a possible application of this limiter in the distribution network is considered and the design parameter of the device are set. Finally, in session 4 two possible connections of external shunt resistor in order to reduce the Joule heating during the limiting phase are investigated.

2. The concept of DC resistive SFCL

The DC resistive SFCL consists of a superconducting coil embedded in diode bridge. A detailed description of this device can be found in [5].

The SC coil is designed in order to have a proper inductance and quenches when the current exceeds a given value. In Figure 1 a circuit scheme of the device is shown. In normal operation the SC coil carries a DC current with an AC ripple superimposed due to the joule losses on the diodes. An as high as possible value of the inductance is desirable in order to reduce the AC ripple. However this inductance affects the circuit during normal (non fault) current increase, therefore its value must not exceed a proper limit. Due to the low inductance the device is not able to limit the current during a fault, therefore a resistive transition of the coil must occur if the current exceeds a given value in order to provide the device with a proper limiting capacity.

![Figure 1. Circuit scheme of a DC resistive SFCL](image)

3. A case study in the distribution network

The distribution system of Figure 2 was considered for the design of the device. In order to determine the proper values of the inductance L a step load change from 12.5 MVA to 22.5 MVA was considered. Figure 3 shows the time evolution of the rms value voltage of the line for various value of the inductance L. The Electromagnetic Transient Program (EMTP) was used to carry out the simulation. From the figure it can be seen that for an inductance of 5 mH (or lower) the disturbance on the voltage does not overcome the limit of 4% prescribed by the EN 50160 standard [8]. The value L = 5 mH is then chosen as reference value for the design of the coil. Figure 4 shows the time evolution of the current through the superconducting coil corresponding to a load of 12.5 MVA for various value of the inductance L. This current is given by the envelop of the peaks of the sinusoidal current that flows in the protected circuit. For the chosen value of L = 5 mH the current through the superconductor is made of a 459.5 A DC component with a ± 1.4 A ripple (about 0.3%) superimposed.

In order to determine the value of the quenched resistance $R_q$ (i.e. the resistance of the coil after the complete transition of the superconductor), the behavior of the device during the fault was modeled by means of the E-J power law [9]. In Figure 5 the fault current following a net three phase to ground short circuit happening at the beginning of the line (point F of Figure 2) is shown for various values of the quenched resistance $R_q$. The considered fault happens at the most onerous instant and lasts for 80 ms (the opening time of circuit breakers). It can be seen that without the transition of the superconducting coil (as in the case of pure rectifier type SFCL) an weak limiting effect is obtained. A satisfactory limiting effect is obtained with the transition of the superconducting coil to a quenched resistance $R_q$ of 4 Ω, which is chosen as reference value for the design of the coil. The main
characteristics of the device for the considered application are resumed in Table 1. The quenching current of 1225 A allows an overload of 20 % for the transformer.

Figure 2. Scheme of the distribution system

Figure 3. Line voltage during load increase

Figure 4. Current of the SC coil during normal operation
4. Shunt Resistor

The limiting mechanism of the proposed device is resistive, this means that the energy flowing during a fault is converted in heat inside the superconductor rather than being stored in the magnetic field as in the case of the inductive mechanism.

The resistive behavior makes the recovery of the device a concern. As for the AC resistive SFCL, a conventional shunt resistor can be connected in parallel to the non linear superconducting one in order to offer an alternative path to the current during a fault and reduce the Joule heating and consequently the recovery time [10]. A possible connection is shown in Figure 6.a. In normal conditions the shunt resistor is short circuited by the superconductor, therefore it does not carry any current. However, this connection requires the physical separation between the inductance and the resistance (they cannot be manufactured as an unique coil) and moreover requires one additional current leader thus increasing the thermal income in the cryostat. An alternative connection that avoids the need for an additional current leader is shown in Figure 6.b. In this case the shunt resistor is short circuited by the diodes in normal operating conditions (indeed it is exposed to a small voltage each half a cycle during the recharge the inductance) and becomes parallel connected to the inductance and the superconducting resistance during a fault. The comparison of the performance of the two connections is discussed in the following.

In section 3 we found that a total resistance of 4 Ω is needed in order to obtain the required limiting effect. This value should be secured also in presence of the shunt resistor, therefore the equivalent resistance of the parallel between the quenched resistance $R_q$ and the shunt resistance $R_{\text{shunt}}$ should be 4 Ω (or greater). Moreover, in order to reduce the current through the superconductor the resistance $R_q$ should be as high as possible compared to the resistance $R_{\text{shunt}}$. In order to satisfy both these conditions

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**Table 1. main characteristics of the DC resistive SFCL**

| Characteristics                  | Value   |
|----------------------------------|---------|
| Nominal Rating                   | 25 MVA  |
| Nominal Voltage, rms             | 20 kV   |
| Nominal Current, rms             | 725 A   |
| Quenching current                | 1225 A  |

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*Figure 5. Fault current*
we chose as design values $R_q = 20 \, \Omega$ and $R_{\text{shunt}} = 5 \, \Omega$. In Figure 7 the fault current occurring with these values for both the connections of the shunt is shown. Figure 8 shows the current circulating in the superconductor during the fault. In Figure 9 the corresponding Joule heating of the coil is shown. It can be seen that for both the connections the shunt does not affect the operation of the device in normal conditions. The calculated power consumption occurring on the shunt parallel to the bridge during the recharge of the inductance was negligible (less than 90 mJ each half a cycle, corresponding to an average power of about 8 W). However, the shunt parallel to the superconducting resistance does not affect the limiting performance of the device, while a reduction of the limiting effect (4.6 kA peak compared to 3.4 kA, see Figure 7) is achieved with the shunt parallel to the bridge. Furthermore, the shunt parallel to the SC resistance allows significantly reduced current (see Figure 8) and joule heating of the superconductor at the end of the fault (about 365 kJ compared to 950 kJ, see Figure 9), thus allowing a shorter recovery of the device. It is worth to notice that by increasing the values of the resistances $R_q$ and $R_{\text{shunt}}$ it is possible to increase the limiting effect also in case of shunt parallel to the bridge. As an example with $R_q = 40 \, \Omega$ and $R_{\text{shunt}} = 10 \, \Omega$ a peak fault current of 3.4 kA (the same as for the shunt parallel to the superconducting resistance), is obtained. However the current through the superconductor and the Joule heating are quite unaffected by the values of the resistances. In conclusion, even though a satisfactory limiting effect can be achieved, the recovery may be a greater concern if the shunt is connected in parallel to the bridge. Nonetheless, it must be considered that this configuration allows one current leader less and a greater flexibility in the design of the coil.

![Diagram](image1.png)

**Figure 6.** Possible connections of the shunt resistor

![Diagram](image2.png)

**Figure 7.** Fault current for different connections of the shunt resistor
5. Conclusion
A case study of a DC resistive SFCL for application to the distribution network was reported. Two possible connections of the shunt resistor were considered in order to reduce the joule heating of the superconductor during the fault and assure a quick recovery of the device. Both the connections were found to allow a satisfactory limiting behaviour. The connection of the shunt parallel to the superconducting resistor allowed a lower joule heating but requires the physical separation between the inductance and the resistance (they cannot be manufactured as an unique coil) and moreover requires one additional current leader. The connection of the shunt parallel to the bridge must be preferred. The drawback of the greater joule heating can be overcome by increasing the length of superconducting wires, which in the considered design can be carried out without an appreciable rise of the AC losses. The increased length implies an increased thermal capacity, which limit the temperature rise of the superconductor during a fault thus allowing a quick recovery of the device.
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