Short-Circuit Testing of Monofilar Bi-2212 Coils Connected in Series and in Parallel

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Abstract. Superconducting Fault Current Limiters (SCFCL’s) are among the most promising technologies for fault current limitation. In the present work, resistive SCFCL components based on Bi-2212 monofilar coils are subjected to short-circuit testing. These SCFCL components can be easily connected in series and/or in parallel by using joints and clamps. This allows a considerable flexibility to developing larger SCFCL devices, since the configuration and size of the whole device can be easily adapted to the operational conditions. The single components presented critical current (Ic) values of 240-260 A, at 77 K. Short-circuits during 40-120 ms were applied. A single component can withstand a voltage drop of 126-252 V (0.3-0.6 V/cm). Components connected in series withstand higher voltage levels, whereas parallel connection allows higher rated currents during normal operation, but the limited current is also higher. Prospective currents as high as 10-40 kA (peak value) were limited to 3-9 kA (peak value) in the first half cycle.

1. Introduction

Superconducting Fault Current Limiters (SCFCL’s) are among the most promising fault current limiter devices under development [1]. SCFCL’s for application on power distribution are approaching the commercial level and prototypes for power transmission are being developed [1-4]. There are several types of SCFCL devices. However, most of the current efforts have been focused on the development of resistive SCFCL’s, because of its simple design, compact size, cost effectiveness and minimal interference in the “load-flow” during fault limiting and during recovery to the superconducting state. The resistive type is based on the fast transition from the superconducting to the normal state, when the device faces a surge current well above the critical current (Ic) of the superconductor material.

Resistive SCFCL components based on bulk Bi-2212 superconducting coils have been successfully tested [5-8] and used in a 10 kV/10 MVA prototype [9]. Such bulk Bi-2212 coils were produced with a bifilar geometry, in order to minimize self-field and inductance. Further development led to the production of bulk Bi-2212 components that are based on a monofilar coil. The monofilar design allows higher voltage drops, especially in the case of lightning, when extremely high overvoltages may develop between the first turns of a bifilar coil [3]. A superconducting compensation tube consisting of bulk Bi-2212 may be used to minimize self-field and inductance of Bi-2212
monofilar coils. The coil is introduced into the compensation tube, which generates a magnetic field opposing the self-field of the coil. In addition, the monofilar components can be easily connected in series and/or in parallel by using joints and clamps. This allows a considerable flexibility to developing SCFCL devices, since the configuration and size of the whole equipment can be easily adapted to the operational conditions. In the present work, Bi-2212 monofilar components without compensation tubes are connected in series and in parallel and submitted to short-circuit testing.

2. Experimental

Two SCFCL components (NEXANS SuperConductors, 2008) were used in the present work. Each single component consists of a bulk Bi-2212 (MCP BSCCO 2212) monofilar coil with two copper terminals, as shown in Figure 1. A shunt alloy with $\rho = 77 \mu\Omega\cdot\text{cm}$ is continuously soldered over the whole superconductor. The shunt layer was designed to withstand $E = 0.3-0.6 \text{ V/cm}$ for $t = 40-120 \text{ ms}$. Table 1 lists the dimensions of the single components.

![Figure 1. A single bulk Bi-2212 monofilar component.](image)

| Table 1. Dimensions of each single component |
|---------------------------------------------|
| Length (including copper terminals)         | 310 mm |
| Active length                               | 270 mm |
| Whole coil length – current pathway         | 4200 mm|
| External diameter                           | 54 mm  |
| Internal diameter                           | 35 mm  |

The components were connected in series and submitted to short-circuit testing in an open bath of liquid nitrogen (77 K). The components were then taken out of the liquid nitrogen and reconnected in parallel for further short-circuit testing. Series and parallel connection were made by means of copper clamps, as can be seen in Figures 2 and 3.
All short-circuit tests were carried out in the High Current Lab of the High Power/High Voltage facilities of CEPEL. The High Current Lab can achieve source voltages as high as 6 kV_{rms} (single-phase) or 3.5 kV_{rms} (three-phase) and currents up to 50 kA_{rms} (steady state) and up to 200 kA_{rms} / 500 kA_{peak} (maximum short-circuit times of 5 s). Figure 4 depicts the test circuit used in the present work. In order to avoid damages due to high E values along the shunt coil, the lowest source voltage attainable by the experimental set-up was used (138 V_{rms}). On the other hand, short-circuit tests with the maximum specified time (120ms) were undertaken. The resistance R was varied in order to control the value of the prospective current (I_p). Following the manufacturer specifications, the minimum interval between successive single short-circuit tests was 10-15 minutes, in order to allow full recovery of the superconducting state.

The critical current (Ic) of each single component was measured before and after testing by using the four points method (1 \mu V/cm). A dc current source and a digital multimeter were used. The obtained VxI curves were corrected by subtracting the voltage signal of all contact resistances introduced by electric connections like clamps and cable connections. ExI curves were generated by dividing voltage values by the whole current pathway of each single component (4200 mm).
Figure 4. Schematic diagram of the test circuit used in the present work. Measuring system components: Capacitive voltage dividers for voltage measurement and current transformer for current measurement, fiber optical for signal transmission and a digital scope 1 GS/s.

The short-circuit limiting tests described above were simulated by NEXANS SuperConductors [10]. Such simulations are based on the E(j) characteristics of the superconductor as well as all thermal and electrical properties of the materials involved [11].

3. Results and Discussion

3.1. Critical Current (Ic)

The ExJ curves of the single components indicates Ic = 245 A for component A and Ic = 253 A for component B, at 77 K (Figure. 5). Both curves exhibit the same behavior, but with a noticeable difference in E values in the flux flow region (I > Ic) due to the small difference between the Ic values of the components.

Figure 5 ExJ curves of the bulk Bi-2212 components (77 K, 1 μV/cm)
After all short-circuit tests described below, ExI measurements showed the same behavior and the same Ic values of the curves displayed in Figure 5, indicating that the components were not damaged (Figure 6).

3.2 Series Connection

Table 2 shows the main results of simulation for different prospective currents, whereas Figure 7 depicts the simulated limitation behavior for a symmetric prospective current of 37 kA. The simulation agrees well with the experimental results shown in Table 3 and in Figures 8 and 9. The measured voltage curve behaves differently from the simulated one because of the output impedance of the real voltage source of the test circuit (non-infinite bus).

Symmetric prospective currents of 5-37 kA (peak value) were limited to 2.8 – 3.8 kA (first peak) by the components connected in series. Two single-shots were applied for each prospective current value: a first one with t = 40 ms and a second one with t = 120 ms. The value of the first limited peak was practically the same in two successive single-shots with a given prospective current. A total of 8 single shots were applied. Voltage appears along the superconductor because of flux flow and/or the formation of hot-spots during quenching [3]. It can be seen that the total voltage drop along the components was only 120-140 Vrms, corresponding to E < 0.20 V/cm (V/840cm). Since these E values are well below the specified limit and the maximum duration of each single-shot was 120ms, those tests were undertaken at safe conditions.

Table 2. Simulation of limiting behavior of series connected components (t = 120 ms).

| Prospective Current (kA) | First peak (kA) | Current (kA_m) | Voltage (V_m) | E (V/cm) |
|-------------------------|----------------|---------------|---------------|---------|
| 5.4                     | 3.25           | 0.53          | 121.6         | 0.145   |
| 10                      | 3.68           | 0.59          | 136.3         | 0.162   |
| 20                      | 3.54           | 0.58          | 133.6         | 0.159   |
| 37                      | 3.76           | 0.60          | 137.9         | 0.164   |
Table 3. Main data of limitation tests made with series connected components (t = 120 ms).

| Prospective Current (kA) | First peak (kA) | Current (kA rms) | Voltage (V rms) | E (V/cm) |
|-------------------------|----------------|-----------------|-----------------|----------|
| 5.4                     | 2.79           | 0.53            | 121.9           | 0.145    |
| 10                      | 3.25           | 0.57            | 129.7           | 0.154    |
| 20                      | 3.45           | 0.54            | 136.0           | 0.162    |
| 37                      | 3.82           | 0.54            | 138.9           | 0.165    |

\* measured in the last half-cycle
\* t = 80 ms

The voltage drop was weakly dependent on the prospective current, but it is a strong function of voltage source power. For a given I\(p\) value, higher source voltage (V\(o\)) values can lead to much higher voltage drops along the component [12]. For all prospective current values the rms current is practically the same, since it is measured after full quenching of the superconducting coil, when all current is passing through the shunt. A slight higher value was observed for I\(p\) = 10 kA, since this short-circuit lasted 80ms instead of 120ms.

Figure 8 shows that a prospective current of 37 kA was limited to only 3.8 kA in the first half-cycle. The voltage drop along each component was measured (figure 9). First voltage and current peaks are considerably higher than the following ones, because the transition from superconductor to normal state is taking place. Full transition of the superconductor coil is almost completed after the first cycle, when most of the current passes through the metallic shunt. This explains why the following limited current and voltage peaks have practically the same value. Shunt heating provokes a slow decay in current value.

The voltage drop along each single component can be seen in Figure 9. The considerable difference between voltage curves in the first peaks indicates that the components quench at different times. The ExI curves suggest that quenching initiates first in component A, so that a higher voltage develops along the superconductor coil of this component (Figure 5). However, both components present the same voltage drop after full quenching of the Bi-2212 coil. The shunt worked well, since no degradation was observed after short-circuit testing.

Figure 7 Simulation of the limiting behavior of two components connected in series for a prospective current of 37 kA and t = 120 ms. Solid line: current; dashed line: voltage.
Full quenching was relatively slow because of low short-circuit power. In other words, the higher is \( E \) and/or \( I_p \), the faster is the superconductor heating. In the present work, full quenching required over 1 cycle even for \( I_p \) values as high as 20-37 kA. This can be attributed to the low \( V_0 \) and consequent low electrical field along the components. Suitable \( I_p \) and \( E \) values can promote faster limitation with full quenching in the first half cycle [3, 5-8].
3.3 Parallel Connection

Parallel connection may be needed for increasing the rated current of an SCFCL device. However, the total resistance decreases, which mean that the limited current will be higher than in series connected components. The simulation of the limiting behavior (table 4 and figure 10) is in good agreement with the experimental results (table 5 and figure 11).

A total of 3 single shots were applied. The first one with $t = 40$ ms and the following ones with $t = 120$ ms. Table 5 shows the high reproducibility of successive single shots with $t = 120$ms. A prospective peak of 37.4 kA was limited to 9.4 kA in the first half-cycle and to 1.67 kA in the shunt (Figure 11). Besides, the electrical field along the shunt was 0.32 V/cm, the double of the E value along the series connected components submitted to the same source voltage and almost the same prospective current. For given $V_0$ and $I_p$ values, the voltage along the shunt of parallel connected components was practically the same voltage along the two components in series. Since this voltage is divided by 420 cm (one coil length) in the parallel connection and by 840cm (two coils length) in the series connection, the electrical field of parallel connection was the double of the electrical field of the series connection. It is worth of noticing that the present comparison between series and parallel connection was made using the same source voltage value. The series connected components can be submitted to higher source voltages than parallel connected components. Therefore, series connection is needed for increasing the rated voltage of a SCFCL device. The number of components connected in series will be proportional to the rated voltage of the device. On the other hand, parallel connection may be needed for increasing the rated current. Normally, a SCFCL device needs both parallel and series connected components.

Table 4. Simulation of limiting behavior of parallel connected components ($t = 120$ ms).

| Prospective Current (kA) | First peak (kA) | Current (kA RMS) | Voltage (V RMS) | E (V/cm) |
|-------------------------|----------------|----------------|----------------|---------|
| 37.4                    | 9.59           | 2.22           | 136.2          | 0.32    |

Table 5. Main data of limitation tests with parallel connection ($t = 120$ ms).

| Prospective Current (kA) | First peak (kA) | Current (kA RMS)$^*$ | Voltage (V RMS)$^*$ | E (V/cm) |
|-------------------------|----------------|---------------------|---------------------|---------|
| 37.4                    | 9.44           | 1.67                | 135.1               | 0.32    |
| 37.4                    | 9.34           | 1.67                | 136.1               | 0.32    |
Figure 10  Simulation of the limiting behavior of two components connected in parallel for a prospective current of 37.4 kA and $t = 120$ ms. Solid line: current; dashed line: voltage.

Figure 11. Short circuit limitation with two components connected in parallel for a prospective current of 37.4 kA and $t = 120$ ms.
4. Conclusions

Both series and parallel connection of Bi-2212 monofilar components presented optimum fault current limiting performances, with high reproducibility. The same source voltage was used in both cases. All simulations agreed well with the experimental results, indicating that the SCFCL components behaved as expected. Series connection allows higher voltage levels (total voltage along the components), whereas parallel connection allows higher rated currents, but the limited current and the electrical field along each component are also higher. The design of an SCFCL device may need both series and parallel connected components. The number of components will depend on factors like the rated and prospective currents, as well as the maximum allowable electrical field and short-circuit time duration.

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