Simulation and electrical characterization of MgB$_2$ and YBCO tapes for superconducting fault current limiter prototypes

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Abstract. In the past, bismuth-based high temperature superconductors (HTS) was the only commercially available HTS conductors. The recent achievements in the production of MgB$_2$ tapes and YBCO coated conductors (CC) persuaded us to study both these HTS as potential candidates for Superconducting Fault Current Limiter (SFCL) applications. In this work, we report on critical current measurements on MgB$_2$ tapes and windings and YBCO CC at 4.2 K and in the temperature range 65 - 80 K, respectively. Results of electrical characterizations on MgB$_2$ and YBCO specimens having different metallic matrix, are used in a numerical model able to predict the SFCL behaviour in view of their potential applications.

1. Introduction

The main objective of our research activity is to provide innovative and functional solutions, based on new materials and technologies, that can facilitate the increase of efficiency, reliability and safety of the Italian transmission and distribution electrical systems.

The Superconducting Fault Current Limiter (SFCL) is one of the most innovate components from the point of view of functionality; resistive-type SFCL are: i) ‘transparent’ to the grid during the normal operation, ii) do not produce overvoltages at fault inception, iii) self-triggering and self-recovering and iv) efficiently address the problems related to the increasing level of short-circuit currents ($I_{SC}$). Excessive fault current levels can damage expensive equipment located at electrical substations and elsewhere in the grid, whereas the SFCL is able to limit instantaneously large $I_{SC}$ reducing it to an acceptable level before the circuit breaker trips.

The use of HTS of different type (tapes, thin films, bulks) allows the manufacture of SFCL devices with different configurations. However, the selection of the HTS material to employ and of the SFCL design depends on grid operation at nominal, overload and fault conditions (current, electrical insulation level, …), and electro-mechanical stresses [1] [2]. Therefore, it must be found the best compromise between the power device characteristics, reliability and cost-effective compact design. For SFCL applications the HTS material must have suitable mechanical properties and electrical resistance and thermal conductivity values, otherwise would invalidate the SFCL performance and probably would lead to out of service of part of the grid.
In spite of the excellent results obtained on BSCCO-based SFCL prototypes [3], the recent achievements in the production of YBCO coated conductors (CC) and MgB2 tapes induced us to study both these HTS as potential candidates for SFCL applications.

In this work, we report on critical current measurements on Ni-alloy sheathed MgB2 tapes and windings and YBCO CC at 4.2 K and in the temperature range 65 - 80 K, respectively. Results of electrical characterizations on MgB2 and YBCO specimens having different metallic matrix, are used in a numerical model able to predict the SFCL behavior in view of their potential applications.

2. Modelling for SFCL applications

As it has been done in the past for the Ag-sheathed BSCCO-2223 tape conductors [4], the actual electrical and thermal properties of YBCO CC and MgB2 composite conductors (HTS and metallic matrix), as function of temperature and current value, have been measured experimentally and then implemented in an self-developed mathematical model. This model is based on a system of differential equations describing the time evolution of all relevant electrical quantities coupled with the actual temperature of HTS winding. The physical properties of Nitrogen and Neon (for MgB2) as cryogens, in a wide pressure and temperature range, are also included in this programme.

Moreover, the E-J characteristics of YBCO CC up to high electrical fields, i.e., E(J) >5000-Ec with Ec=10^{-4} V/m, have been implemented into the model which is thus able to predict the behaviour of coated conductors and obtained SFCL windings in nominal conditions (I<IC), and in the limiting phase for I>>IC. Tanks to over-current and for T > Tc tests it has been possible to improve the model of YBCO tape also under fault condition.

3. HTS conductors and experimental setup

Electrical characterizations have been performed on YBCO CC and MgB2 conductors obtained from different manufacturers and having different layout, see Table 1. In particular, Y_Cu and Y_SS tapes are from the same supplier and have the same layer configuration (see figure 2) except for the stabilizing material: copper and stainless steel, respectively. Specimen Y_ns has only a 0.5 μm thick silver cap layer and hence has not metal stabilizer. Regarding the MgB2 tapes, all specimens are multifilamentary, have a similar filling factor of about 10% but differ from one another in stabilizer and its position: Ni or Cu sheath and/or Cu core.

| Table 1. Main characteristics of YBCO and MgB2 specimens. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | YBCO Coated Conductors | MgB2 multifilamentary tapes |
| Thickness (mm)  | Y_Cu  | Y_SS  | Y_ns  | MFT  | M_Cu  | M_Coil |
| Width (mm)      | 4.4    | 4.4   | 10    | 3.9  | 2.37  | 3.8   |
| Substrate (μm)  | 75     | 75    | 100   | -    | -     | -     |
| Stabilizer      | Copper | Stainless steel | Ni sheath | Cu sheath | Ni sheath |
|                 | 2 x 50 μm | 2 x 50 μm | - | + Cu core | + Cu core |

Figure 2. SEM images of Y_Cu (sx) and Y_SS (dx) samples cross-section.
Critical current ($I_C$) measurements have been performed on MgB$_2$ tapes and windings and on YBCO CC specimens at 4.2 K and in the temperature range 65 - 80 K in, respectively. In particular, a Stirling close-circuit refrigeration system has been used to stabilize $65 \text{ K} < T < 80 \text{ K}$.

The HTS specimens have been mounted on the sample holder by clamping to avoid possible degradation resulting from soldering, see figure 1; four voltage taps have been placed to evaluate electrical homogeneity, possible HTS degradation, and local overheating.

4. Electrical characterization results

4.1. YBCO Coated Conductor short samples

Figure 3 shows the E-I characteristics for a Y_SS specimen at different temperature values: we can observe the steep transition of E-I curves with $n$-values $n>20$. Similar measurements have been performed for all YBCO samples and the $I_C$ results, normalized by the conductor width, are shown in figure 4. As it can be seen, at 77 K all YBCO samples exhibit identical $I_C$ values; at lower T, owing to its slightly steeper $I_C$ dependence on temperature, the Y_SS specimen shows the highest $I_C$ value.

Overcurrent tests have been performed at 77 K by applying, for short times ($t< 2 \text{ s}$), currents much higher than $I_C$; figure 5 shows the results for a Y_Cu specimen for currents up to 120 A corresponding to $1.65 I_C$ and $E >5000 E_c$. At high currents the E-I curve has been corrected by taking into account the matrix contribution to the current transportation (about 30% at 120 A).

Figure 6 shows the resistance of a Y_Cu sample as function of temperature from 80 K up to 230 K, an indication about the current sharing between HTS and metallic matrix up to $T_C$ is also reported.

Figure 7 shows the resistance of all YBCO CC samples as function of temperature from 80 K up to 260 K; the highest resistance values are measured for the Y_ns sample, due to the absence of metal stabilizer. But, for these specimens the risk of hot-spots increases with possible burn-out during short-circuit events, owing to the absence of current bypass. The steel stabilized YBCO CC owns higher resistance values compared with the Y_Cu sample, that exhibit R values comparable with whose of MgB$_2$ specimens (see figure 8).

**Figure 1.** A YBCO CC mounted sample for DC characterization.

**Figure 3.** E-I curves for a Y_SS specimen as function of temperature ($65 \text{ K} < T < 80 \text{ K}$).

**Figure 4.** $I_C$ normalized to width as function of temperature for different YBCO CC samples.
4.2. MgB$_2$ tape short samples and coils

Figure 8 shows the resistance of MgB$_2$ samples as a function of temperature from 80 K up to 280 K; owing to the presence of the copper core the MFT tape exhibits lower R values compared to the M$_Cu$ sample. The copper core ensures that the heat generated at local positions could be efficiently transferred to the outer matrix and then to the cryogen thus preventing hot spots formation and the tape burnout even when high currents are injected.

Figure 9 shows the SEM image of the cross-sections of multifilamentary Nickel-sheathed MgB$_2$ tapes having a stabilizing copper central core. In particular, specimen M$_Coil$, which has been used to manufacture the 132 m long coil, has 14 MgB$_2$ filaments and the copper core surrounded by an iron barrier, in order to prevent the diffusion of copper in the nickel matrix.
The MgB₂ coil is made by a 132-meters long tape (M_Coil) wound on a cylindrical support made of fiberglass reinforced plastic (G10) obtaining an anti-inductive winding composed by two superconducting layers. During the final assembling, both layers have been lapped with fiberglass tape and the whole system has been impregnated with epoxy resin [4] [5]. Several voltage taps have been incorporated at different positions along the coil to monitor the voltage drop across i) each layer, ii) the junction between the layers and iii) the whole winding.

The critical current measurements performed in liquid helium at 4.2K on the MgB₂ coil evidenced the slightly different performance between the two layers: inner layer \( I_C > 700 \text{ A} \) whereas the outer layer exhibits an \( I_C \) value of about 670 A.

Figure 10 shows the result of the electrical characterization on the whole coil; owing to the very steep transition of the E-I curve and the layer performance the applied current has been limited to about 700 A, to avoid any damaging of the coil. By using the 0.1\( \mu \text{V/cm} \) electric field criterion the whole coil shows a critical current \( I_C \) value of 687 A.

![Figure 10. Critical current measurement at 4.2 K for a two-layer 135 m-long MgB₂ winding.](image)

5. Conclusion
In this work, we reported on critical current measurement results on MgB₂ tapes and windings and YBCO CC at 4.2 K and in the temperature range 65 - 80 K, respectively. Results of electrical characterizations on MgB₂ and YBCO specimens having different metallic matrix, are used in a numerical model able to predict the behavior of SFCL devices during short-circuit events.

The electrical properties of the metallic matrix of different YBCO CC and MgB₂ specimens have been compared in view of SFCL applications. Other important characteristics, namely mechanical properties, are presently under investigation. In fact, for power applications and in particular for the SFCL devices under fault conditions, the HTS windings experience large electrodynamic and thermal expansion stresses. In this case, stainless steel stabilized HTS conductors could be much less sensitive to degradation and therefore a better conductor option.

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