Applications of superconductors for electrical engineering in GREEN lab

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Objective – In this paper the applications of superconducting material for electrical engineering especially for transport and electric grid are exposed. Firstly, superconducting materials used in electric engineering will be presented, particularly High critical Temperature Superconductors (HTS), from a microscopic physical point of view, followed by tapes and wires used in applications. The electrical characterization of HTS tapes and coils will then be developed. Two applications of these HTS in electrical engineering will be presented, motors and cables through GREEN lab projects in collaboration with industry. Finally, the French project, PEPR SUPRAFUSION, including GREEN lab will be presented.

Keywords – High temperature superconductor, electric grid, HTS cable, HTS motor.

1. Introduction

Superconducting materials are able to transport DC current without resistance and therefore with no losses and transport AC current with low losses. At cryogenic temperature, the maximum current densities in superconductors are very high in comparison with classical conductors as copper conductor. During the 20th century these properties have led to the emergence of applications which have become industrial products as superconducting magnets for MRI using liquid helium. However, their industrial development has been limited by the significant high cost of liquid helium and by their difficulty of use. In 1986, interest in these materials has been revived by the discovery of high critical-temperature superconductors (HTS) that are superconductive at the temperature of liquid nitrogen, which is cheaper and easier to use than liquid helium. In this paper the applications of superconducting material for electrical engineering developed in GREEN lab are exposed.

2. HTS materials for the electric grid

There are two main types of HTS materials used for power system applications: BSCCO and REBCO [1]. They come either in bulk or in tape form. In this article, we focus only on HTS tapes because they form the basis of coils and cables. BSCCO and REBCO HTS tapes have different architectures: BSCCO tapes consist of BiSrCaCuO filaments embedded in a silver matrix, while REBCO tapes consist of different layers including a micrometer thick REBaCuO layer (RE for Rare earth) (Figure1). In table 1 BSCCO and YBCO (the most popular REBCO material) critical values (critical temperature T_C, critical magnetic field B_C, critical current density J_C) are presented. They can both be used at 77 K, the temperature of liquid nitrogen (LN2), which has the particularity of being an electrical insulator.

Table 1. Critical values of HTS tapes

HTS	T_c	B_c at 4K°	J_c at 77K° without external magnetic field
BSCCO	108 K°	>100T	>100 A/mm²
YBCO	90 K°	>100T	>100 A/mm²

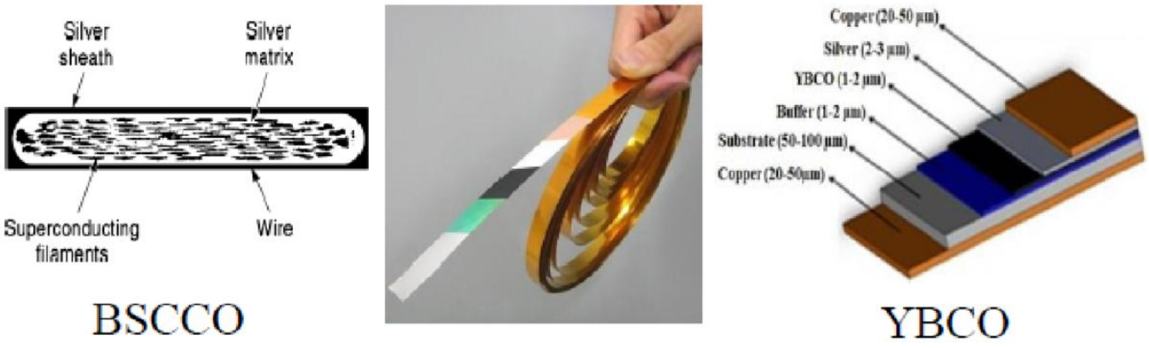

Figure 1: left: BSCCO tapes from Sumitomo, Japan. Middle: REBCO tape from Fujikura, Japan. Right: REBCO tapes from SuperOx,

3. Electric characteristic E(J) law of HTS

To remain superconducting state, the current density J in the HTS material must remain below a critical value J_C. This value depends on B and temperature T. J_C is the macroscopic critical current density and it is related to the local magnetic field H by Ampere's law. HTS materials are anisotropic and J_C has several different values for different directions. Values of critical currents are obtained experimentally by an electrical method or by a magnetic method. In the first case transport current traverses the sample. In the second case superconducting sample is subjected to a magnetic field.

The characteristic *E(J)* of a superconductor varies depending on temperature and magnetic field.

On Figure 2 the characteristic *E(J)* of HTS at very low temperatures is shown. For small values of *J* less than J_C, HTS is on superconducting state and $E = 0$. The critical current density J_C is the limit between the superconducting state and the transition to normal state. The growth of *E* is very large when $J > J_C$ and thus the material passes suddenly to the normal state when *J* increases. We can therefore consider that if the material is superconducting and $J=J_C$, this is the critical state model of Bean.

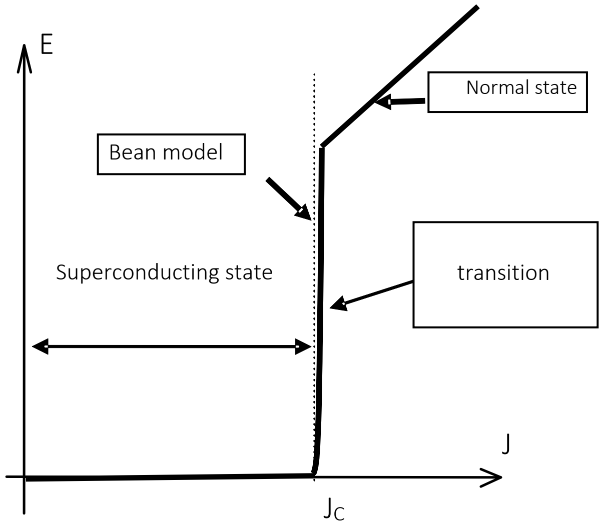

Figure 2: ***E(J)* law of superconductor at very low temperature less than 20K°**

On Figure 3 the characteristic *E (J)* of a superconductor at temperatures where the influence of thermal effects is important is shown. For low values of *E* with *J* close to the J_C curve *E (J)* is of exponential form, is the region of "flux-creep". This corresponds to displacement of the vortices due to thermal activation and thus the appearance of a weak electric field but nonzero. For high values of *E* with $J > J_C$ is the region of flux flow. It is obvious that in the case of HTS used at relatively high temperatures these phenomena related to the thermal motion become dominant. The critical current density is the value for which the material passes from the state of "flux creep" in the state of "flux flow". The transition between these two states is gradual and therefore difficult to identify experimentally. To define J_C in this case we use a critical electric field criterion (1µV/cm from IEC standard) that do not necessarily correspond to the physical border between two states but is a convenient practical criterion for comparing performance of different superconducting materials.

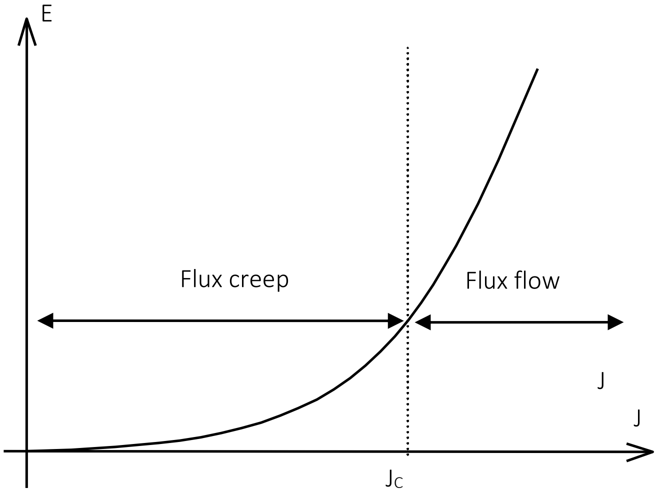

Figure 3: ***E(J)* law of superconductor at "high" temperature around 77K°**

So at "high temperature" around 77K° the relation between E and J can be modelled by:

$$\vec{E} = E_C \cdot \left(\frac{J}{J_C(B,T)} \right)^{n(B,T)} \cdot \frac{\vec{J}}{J} \tag{1}$$

The most commonly used *Jc(B)* relationships in literature are (Table 2) models of Bean [2], Kim [3] and linear [4]. The Bean model is widely used in theoretical calculations because it allows simple analytical calculations of current distribution in a superconducting material such as a plate or cylinder. The linear model allows analytic calculations of losses [5].

$\mathrm{J_{CB} = J_{C0}}$ independant of B	Bean	[2]
$\mathrm{J_{CK}(B) = \dfrac{J_{C0}}{\left(1 + \dfrac{\lvert B \rvert}{B_{K0}}\right)}}$	Kim	[3]
$\mathrm{J_{CL}(B) = \dfrac{J_{C0}\left(B_{j0} - \lvert B \rvert\right)}{B_{j0}}}$	Linear	[4]

J_{C0}, B_{K0} and B_{J0} are positive constants.

Table 2. *$J_c(B)$ laws.*

4. HTS cable for the electric grid

The HTS power cable is a popular application of HTS materials for power systems. The use of superconducting cable should generate efficiencies and reduce costs of operation and maintenance, as well as the amount of land used. The technical superiority of superconducting cables is due to the material properties of the conductor. The compactness of the superconductor, despite its cooling system, gives a capacity of power transmission five times greater than that of a copper cable of the same section, and with much lower electrical losses.

This is illustrated by various projects around the world: LIPA, Ampacity, COMED, Superlink, etc. A French project named SuperRail [7] between SNCF Réseau, Nexans, Absolut System, GREEN and GeePs is ongoing. The goal of this project is to install a DC HTS cable system to feed the Montparnasse railway station in Paris. The structure of the HTS cable is illustrated in figure 4. It’s made with commercial REBCO tapes.

Russia.

Figure 4: View of the SuperRail DC HTS power cable (3500 A, 1500 V) [7].

5. HTS motor

The most well-known application of HTS developed in GREEN is HTS motor. Some projects with SAFRAN (Figure 5) (RESUM and FROST) and Airbus projects (ASCEND) will be presented.

Figure 5: HTS motor of RESUM project.

6. Conclusion

The applications of HTS material for electrical engineering developed in GREEN lab are motors and cables.

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