CIRCUIT MODEL FOR CURRENT LEADS MADE OF HTS TAPES

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Abstract

Authors propose an equivalent circuit model that describes the behaviour of a current lead build of HTS tapes. Transient analysis of HTS leads using PSpice environment was made. The model is based on the physical structure and behaviour of HTS tapes. It was possible to calculate the temperature distribution in the lead as well as the transient current and power. The quench processes of HTS leads under sinusoidal current with different amplitudes were simulated. Obtained results can be very useful in the analysis of quench states of the superconducting current leads.

Keywords: ABM lumped model, current leads, HTS tapes, PSpice analysis

INTRODUCTION

The development of the HTS tape manufacturing technologies leads to evolution of many superconducting devices. It is possible to build the current lead based on the high temperature superconducting tapes (Fig. 1). For this kind of current leads it is very important to keep the heat sources on the very low level (even 1 Joule).

Fig. 1. Current lead build of HTS tapes
HTS TAPES

The discovery of superconductivity generated interest in practical applications, mainly because of its potential to save energy. Replacement of the copper or other normal conductors by superconductors avoids heat dissipation and energy losses due to finite resist ance. Discovery of the HTS materials was the first step in development of new generation superconducting applications. Many of HTS materials are superconductors and carry significant current above the boiling point of liquid nitrogen at 77.4 K.

High performance high temperature superconductor wire underlies the worldwide opportunity to revolutionize the electric power grid, transportation, materials processing and many other industries, with a new generation of high efficiency, compact and environmentally friendly electrical equipment. Rapid progress in commercializing these many applications has been enabled by an HTS wire known as first generation (1G) [1].

This wire is a composite structure consisting of number of filaments of HTS material embedded in a silver alloy matrix. First generation HTS wire is characterized usually by low critical current, therefore many companies are making researches on improved performance of HTS wires (Fig. 2).

Second generation wire has quite different architecture compared with first generation wire. The 2G HTS wire comprises multiple coatings on a base material or substrate. This architecture is designed to achieve the highest degree of alignment of the atoms in the superconductor material. The reason of such construction is reaching the highest possible electrical current. The 2G wire architecture consists of slit 2G tape sandwiched between thin copper strips.

Second generation (2G) HTS wire consists of a tape-shaped base, or substrate, upon which a thin coating of superconductor compound, usually YBa$_2$Cu$_3$O$_7$ (“YBCO”) is deposited or grown such that the crystalline lattice of the YBCO in the final product is highly aligned, creating a coating that is virtually a single crystal. The superconductor coating in this coated conductor wire architecture typically has a thickness of the order of one micron (Fig. 3) [1].
Another important aspect in HTS wire is the value of the critical current in external magnetic field. When the magnetic flux increases the critical current decreases rapidly, even 10 times in some cases. To counteract this disadvantage the HTS wires are produced with special defects, so called pinning centres. Pinning can be achieved by introducing defects into the HTS material on a nanometer scale, comparable to the diameter of the flux lines passing through the HTS surface. While tubular defects can match the flux line geometry most optimally, a more practical approach is to find ways to introduce a high density of very fine particles called nanoparticles or nanodots.

The magnetic field angle dependence of the critical current density is another important aspect of the pinning phenomenon. Depending on the type and orientation of the pinning defects, the pinning can be different along different magnetic field directions (Fig. 4) [1].

Fig. 3. First generation (1G) versus second generation (2G) HTS tape [1]

Fig. 4. Magnetic field dependence of HTS wire with and without holmium, 3 T (field perpendicular to sample plane) [1]
CURRENT LEADS

Current leads are used for energy transfer between superconducting devices and power supplying system. In such cryogenic application, it is necessary to pass electrical current from a power source at room temperature to a particular device at cryogenic temperatures. These current can range from a few milli-Amperes for instrumentation to 10 000 Amperes for high magnetic field superconducting magnets. The design of cryogenic power leads must attempt to minimize the refrigeration/liquefaction system capacity required for stable operation.

Fig. 5. Conventional current leads

Conventional current leads are usually made of conductor (copper) and cooled with liquid nitrogen or liquid helium (Fig. 5).

With HTS development current leads gain new compact design and better capabilities. HTS superconducting current leads architecture usually comprises of HTS tube with silver ends (for better connection) and/or shield made of metal or plastic (Fig. 6).

Fig. 6. Different types HTS current leads
The authors built the numerical model basing on existing HTS current lead design. [2] Current lead is made of HTS tapes connected together as shown in figure 7. HTS tape pieces are placed on tube support made of copper or stainless steel. The outer jacket performs a function of electrical insulation and mechanical protection.

![Fig. 7. Current lead made of HTS BSCCO tapes](image)

**ELECTRO-THERMAL LUMPED MODEL**

Transient circuit analysis is performed in domain of time. To get basic distribution of an interesting physical quantity (for instance: temperature) along a slender object as a current lead it’s necessary to make certain simplifying assumptions. In numerical experiment described below AC losses have been neglected.

Our ABM lumped model of the HTS current lead consists of series connection of 48 segments. Electrical properties of HTS tape can be described as a parallel connection of silver alloy and superconductor (Fig. 8). Resistivity of silver alloy can be expressed as a linear function of temperature [2]. Resistivity of a HTS can be described by power law $E \sim J^n$.

Uniform segment temperature of HTS current lead can be expressed as (1) and it is computed using equivalent circuit (Fig. 9).

$$T = T_0 + \frac{1}{C_{\text{TH}}} \int_{t_0}^{t} \left( u_{\text{tape}} i_{\text{tape}} + \frac{T_p + T_n - 2T}{R_{\text{cond}}} + \frac{T_0 - T}{R_{\text{conv}}} \right) dt$$

(1)

where: $C_{\text{TH}} = m_{\text{Bi}} C_{p\text{Bi}} + m_{\text{Ag}} C_{p\text{Ag}}$ – thermal capacity of current lead segment;  
$T_0$ – ambient temperature;  
$m_{\text{Bi}}, m_{\text{Ag}}$ – superconductor and silver alloy masses per segment;  
$C_{p\text{Bi}}, C_{p\text{Ag}}$ – superconductor and silver alloy specific heats;  
$u_{\text{tape}}, i_{\text{tape}}$ – voltage and current of the current lead segment;  
$T_p, T_n$ – inter-segment boundary temperatures;  
$R_{\text{cond}}, R_{\text{conv}}$ – heat conduction and convection equivalent representations (heat radiation neglected).
Electro-thermal lumped model of HTS current lead is depicted in Fig. 10. Each of 48 elementary segments has the same subcircuit diagram shown in Fig. 11.

Numerical simulation parameters have been compiled using [2, 3, 4, 5]. They are presented in Table 1.
Table 1. Simulation parameters of HTS current lead
(33 x HTS tape: Bi(Pb)-2223/AgAu)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I_{\text{ES}}) (77 K, self field)</td>
<td>16 A</td>
</tr>
<tr>
<td>(T_C)</td>
<td>100 K</td>
</tr>
<tr>
<td>(A_{\text{Tape}})</td>
<td>4.30 x 0.25 mm(^2)</td>
</tr>
<tr>
<td>(L)</td>
<td>48 x 7.29 mm</td>
</tr>
<tr>
<td>tape filling factor</td>
<td>30 %</td>
</tr>
<tr>
<td>(E_C)</td>
<td>(10^4) V/m</td>
</tr>
<tr>
<td>(n_0) (77 K)</td>
<td>15</td>
</tr>
<tr>
<td>(R_{\text{res}})</td>
<td>(10^{11}) (\Omega)</td>
</tr>
<tr>
<td>(T_{\text{0w}})</td>
<td>77 K</td>
</tr>
</tbody>
</table>

\(a\) and \(b\) values:
- \(a\): 7.1 \(\times\) \(10^{-11}\) \(\Omega\) m/K
- \(b\): -6.6 \(\times\) \(10^{-10}\) \(\Omega\) m

\(C_{\text{pBi}}\): 120 J/(kg K)
\(C_{\text{pAg}}\): 170 J/(kg K)
\(\gamma_{\text{Bi}}\): 6000 kg/m\(^3\)
\(\gamma_{\text{Ag}}\): 10500 kg/m\(^3\)
\(h_{\text{conv}}\): 1500 W/(m\(^2\) K)
\(\lambda_{\text{cond}}\): 200 W/(m K)

**NUMERICAL SIMULATION RESULTS**

Transient analysis of the current lead has been performed using PSpice. Comparison of the current lead performance under its nominal current and short over-current is depicted in Fig. 12 and 13. Response to long lasting over-current is shown in Fig. 14 and 15.

Fig. 12. Temperature (stated here in Volts) of the warmest segment, instantaneous power, voltage and currents of HTS current lead under nominal current \(I_N = 600\ A_{\text{peak}}\).
Fig. 13. Temperature of the warmest segment, instantaneous power, voltage and currents of HTS current lead under over-current $I = 3000 \, \text{A}_{\text{peak}}$

Fig. 14. Average power of the whole lead, average power of the warmest and the coldest segments (top); temperatures of first four segments (bottom) vs. time under over-current $I = 3000 \, \text{A}_p$

Fig. 15. Temperature distribution along HTS current lead under over-current $I = 3000 \, \text{A}_p$
CONCLUSION

Evolution in high temperature superconductor manufacturing allows to build modern and compact superconducting devices.

Circuit modeling of HTS tape is leading to complicated mathematical expressions which take into account geometric, thermal and electrical properties of the HTS.

It’s possible to perform simplified electro-thermal analysis (coupled problems) using common circuit simulator like PSpice.

Nested sub-circuit simulation permits to perform numerical analysis of lumped-parameter systems. The maximum number of sub-circuits depends on computer resources.

Numerical simulation shows remarkable overload performance of HTS current lead. Short period AC over-currents doesn’t pose a threat for system stability. Fastness to long lasting over-currents depends on cooling system efficiency.

REFERENCES