Fault current analysis for a superconducting 1 kA YBCO cable

L Rostila, J Lehtonen, M Masti and R Mikkonen
Institute of Electromagnetics, Tampere University of Technology, P.O. Box 692, FIN-33101 Tampere, Finland
E-mail: lauri.rostila@tut.fi

Abstract. Superconducting cables can be used to transport large amounts of energy with small losses in considerably smaller volume compared to the conventional ones. The first YBCO cable demonstrations are under development and they are expected to outperform BSCCO cables. In the design work, the temperatures in the YBCO cables need to be simulated under any fault current conditions. In this paper, the temperature distribution in a 1 kA YBCO-cable was computed with various fault currents in order to study the thermal stability of the cable. The fault current is shared between the layers of superconducting YBCO tape and the copper shunt. FEM models were used to determine simultaneously both the current density and the temperature distributions of the cable as a function of time. Adiabatic conditions were assumed in order to obtain an upper limit for the temperature. According to the model, the copper core was able to absorb most of the heat. The cable maintained the thermal stability during 1 s with 10 and 20 kA (rms) fault currents. With 30 and 40 kA fault currents the cable was predicted to quench.

1. Introduction
Superconducting power cables are one of the most promising HTS applications. YBCO has been predicted to be among the most cost efficient HTS materials and the first prototypes of YBCO cables are under way [1]. Compared to the conventional power cables, superconducting ones are more sensitive to fault currents due to the high resistivity at the fault current and small specific heat. Therefore it is essential to model the heating process of the cable during a short circuit. In this paper, a coaxial 20 kV, 1 kA YBCO cable with two superconducting layers is studied. In a modern power grid it may have to resist 1 s fault currents up to 40 kA (rms).

Nonlinear time dependent FEM model was designed to estimate the temperature distribution in a superconducting cable during fault currents. The model includes the temperature dependent properties of the cable materials. Also the strong magnetic field and current density dependence of the resistivity of YBCO is taken into the account.

2. Computational model
One phase superconducting cable has a core and shield layers, in which the current flows to the opposite directions [2]. Here we study a 1 kA, 50 Hz YBCO cable, which can be carried out with two superconducting layers. Electrical insulation between the core and shield layers acts as a thermal insulation as well. Therefore, it is adequate to model just the core layer and the cable former, which is the main source of heat when the fault current occurs.
The computational model is based on the field theory. Ampère’s and Faraday’s laws with an assumption that the permeability is equal to $\mu_0$ lead to the magnetic diffusion equation that was solved simultaneously with the heat conduction equation to gain magnetic flux density $B$ and temperature $T$. FEM is used to solve the system of equations [3]

\[
\nabla \times [\rho(J,B,T) \nabla \times B] = -\mu_0 \frac{\partial B}{\partial t} \\
\nabla \cdot k(T) \nabla T + \rho(J,B,T)J^2 = C_p(T) \frac{\partial T}{\partial t},
\]

where the magnitude of the current density $J$ equals $\mu_0 \|\nabla \times B\|$. Thermal conductivity $k$ and volumetric specific heat $C_p$ depend on the temperature. In addition to the temperature, resistivity $\rho$ in YBCO depends on the current density $J$ and magnetic flux density $B$, as well.

In order to limit the time of the simulations the model was simplified to cylinder symmetric, in which all the quantities depend only on time $t$ and the radius $r$. Here $J$ was parallel to the cable axis and perpendicular to $B$ which had no radial component. Therefore $J$ and $B$ can be denoted with scalars $J$ and $B$, respectively [4].

In the cable, YBCO tapes are attached over a copper former side by side. The YBCO thin film is grown on a steel substrate and the outermost layer in tapes consists of a very thin silver shunt. Thus, domain of partial differential equations (1) was divided into the four sub domains: copper former, steel substrate, YBCO and silver shunt respectively. The outer radii of the material boundaries are noted with $r_1$, $r_2$, $r_3$ and $r_4$, correspondingly.

Due to the symmetry $B$ must vanish at the symmetry axis where $r_0 = 0$ and the fault current $I$ determines the boundary condition at $r_4$ as

\[
B(r_4) = \mu_0 \frac{\sqrt{2} I \sin(2\pi f t)}{2\pi r_4},
\]

where $f$ is the frequency of the fault current. Owing to the insulation the adiabatic boundary conditions are used for the heat equation. The instantaneous currents in the materials can be computed from the solution $B(t,r)$ as follows.

\[
i_p(t) = \frac{2\pi}{\mu_0} \left[ p \rho \int_0^{r_p} B(t,r_p) - r_{p-1} B(t,r_{p-1}) \right], p \in \{1,2,3,4\}
\]

3. Results

The cable geometry in the simulations was defined as $r_1 = 11000 \mu m$, $r_2 = 11100 \mu m$, $r_3 = 11101.5 \mu m$ and $r_4 = 11102 \mu m$. $C_p(T)$ and $k(T)$ for copper, steel, YBCO and silver were taken from the references [5 - 10] and $\rho(T)$ of copper, steel and silver from [5] and [8]. The power law was used to model the resistivity of YBCO as

\[
\rho_{sc}(B,T,J) = \begin{cases} 
\rho_n \left( \frac{E_c}{J_c(B,T)} \left( \frac{J}{J_c(B,T)} \right)^{n-1} \right), & \text{when } T < T^* \\
\rho_n, & \text{when } T \geq T^*
\end{cases}
\]
where $E_c$ is the electric field criterion, $1 \, \mu \text{V cm}^{-1}$ and $\rho_n$ the normal state resistivity of YBCO, $1.5 \cdot 10^{-8} \, \Omega \cdot \text{m}$ [11]. Constant $n$-value 10 was used in order to ensure monotony of the critical current density $J_c(B,T)$. Kim model was used to approximate $J_c(B)$ dependency [12] and the temperature dependence of $J_c$ was modeled as affine, such that from $T_0$ to $T^*$, $J_c$ drops uniformly from $J_c(B,T_0)$ to $J_c(B,T^*)=0$ [13]. The $J_c(B,T)$ function was

$$J_c(B,T) = \frac{1}{1 + \left( \frac{B}{B_0} \right)^\beta} \left( \frac{T^* - T}{T^* - T_0} \right) J_{c0}, \text{ when } T < T^*,$$

where the parameter values $B_0 = 55.6 \, \text{mT}$, $\beta = 0.6$, $T_0 = 77 \, \text{K}$ and $T^* = 89 \, \text{K}$ were used here. The critical current density at 0 T and $T_0$ was $J_{c0} = 1.35 \cdot 10^{10} \, \text{Am}^{-2}$, which equals the amplitude of 1 kA (rms) divided with the cross-section of YBCO.

System of equations (1) for $t = [0,1] \, \text{s}$ was solved with sinusoidal fault currents of 10, 20, 30 and 40 kA (rms) and the current sharing was obtained from the results of equation (3). The current sharing is presented in figure 1a for the 10 kA fault current. The fault current was shared mainly between the former and YBCO, in which the $B$ dependent resistivity created an unusually shaped current wave form. In figure 1b, the temperature profiles of the cable with 0.2 s intervals are also shown. The temperature of YBCO rose almost linearly which can be seen well in figure 2a, which presents the temperature evolution in YBCO during all simulated fault currents.

Simulations predict that the cable can cope with 10 and 20 kA fault currents but with 30 and 40 kA the cable quenches at 0.50 and 0.26 s, respectively. That is due to the skin effect, which creates strong losses in the former. However, the heating can be reduced if the diameter of the copper former is changed. The skin effect is not as high when the modern segmental fraction designed conductor is used as a former [14].

![Figure 1](image.png)

**Figure 1.** a) Currents in the copper and YBCO layer from the start of the 10 kA fault current. b) The temperature profiles are presented with 0.2 s interval.
Figure 2. a) Temperature of YBCO layer during 10, 20, 30 and 40 kA fault currents. Critical temperature is marked with dashed line. b) Temperature profiles right after 1 s fault currents.

4. Conclusions

The nonlinear and time dependent FEM model was developed in order to simulate the temperature distribution in a superconducting YBCO cable during fault currents. The model included temperature dependent thermal and electrical properties of materials. Also the magnetic field and temperature dependent critical current density was taken into account.

According to the simulations the 1 s fault currents at different magnitudes lifted the temperature of YBCO almost linearly as a function of time. The cable was able to cope with fault currents up to 20 kA. At higher fault currents, the eddy currents in the copper former generated strong losses and the stability was lost.

References

[1] Tsukamoto O 2004 Supercond. Sci. Technol. 17 185
[2] Mukoyama S, Maruyama S, Yagi M, Yagi Y, Ishii N, Sato O, Amemiya M, Kimura H and Kimura A 2005 Cryogenics 45 11
[3] Lehtonen J, Mikkonen R and Paasi J 1998 Physica C 310 340
[4] Arfken G and Weber H 2001 Mathematical methods for physicists (US: Harcourt Academic Press) 5th ed.
[5] Iwasa Y 1994 Case studies in superconducting magnets Design and operational issues (New York: Plenum Press)
[6] Gray D E 1972 American institute of physics handbook (New York: McGraw-Hill Book Co.)
[7] Ho C Y, Powell R W and Liley P E J. Phys. Chem. Ref. Data 1974 3 607
[8] Reed R P and Clark A F 1983 Materials at low temperatures (US: Carnes Publication Services Inc.)
[9] Becman O, Lundgren L, Nordblad P, Sandlund L, Svedlindh P, Lundström T and Rundqvist S 1987 Physics letters A 125 425
[10] Morelli D T, Heremans J and Swets D E 1987 Physical Review B 36 3917
[11] Paasi J, Herrmann P F, Verhaege T, Lehtonen J, Bock J, Cowey L, Freyhardt H C, Usoskin A, Moulaert G and Collet M 2001 Physica C 354 1
[12] Kim Y B, Hempstead C F and Strnad A R 1964 Rev. Mod. Phys. 36 43
[13] Kottman P 1996 The Influence of Magnetic Field and Temperature on Critical Currents in High-Tc, Superconductors (Tampere, Finland: Tampere University of Technology) PhD thesis
[14] Anders G J 1997 Rating of electric power cables (US: IEEE Press and McGraw-Hill)