Evaluation of AC loss and temperature distribution in high temperature superconducting tape using COMSOL Multiphysics

G Konar* [1], Power Engineering Department, Jadavpur University, India

N Chakraborty [2], Power Engineering Department, Jadavpur University, India

*LB-8, Sector-III, Jadavpur University Saltlake Campus, Kolkata-700098.
gargi_konar@yahoo.co.in

Abstract

High temperature superconductors (HTS) are promising candidates for electrical power applications. The electrical devices using HTS conductors or tapes with high critical temperature (T_c) and high current carrying capability operate with more efficiency and higher power density compared to the conventional one. But the superconductor exhibits energy loss known as AC loss when exposed to time varying external magnetic field and/or transport current. This may lead to increase of temperature inside the superconductor, which may be followed by thermal run away. Therefore the study of AC loss and temperature distribution is important. In this paper, AC loss in an elliptical Ag sheathed Bi2223 (HTS) tape is calculated using the time dependent PDE mode of COMSOL Multiphysics. The HTS tape is subjected to the externally applied time varying magnetic field and transport current. After proper mesh generation in the superconductor and silver sub-domains, the time dependent solver is used to get the solution of the primary variable in COMSOL Multiphysics. The effect of amplitude of applied AC fields and transport currents are observed using the post-processing unit of COMSOL Multiphysics. Using the calculated AC losses as the heat sources in physics settings, the temperature distribution inside the superconducting tape is evaluated. This is done with the help of the heat transfer module of COMSOL Multiphysics. Proper thermal boundary conditions and anisotropic thermal conductivity of the HTS tape are applied in boundary and sub-domain settings respectively. Lastly, the temperature rise at a certain spot inside the Bi2223/Ag tape is investigated to observe the evolution of temperature rise.

Keywords

High temperature superconductor (HTS), AC loss, Magnetic vector potential, Hot-spot, Thermal run away

1. Introduction

High temperature superconductors (HTS) are used for AC superconducting power apparatus with smaller size and lesser power consumption. Super Motors and Super Generators [1, 2], HTS hysteresis motor, HTS reluctance motor and high dynamic HTS motor [3], superconducting synchronous motor [4], co-axial YBCO cable [5], high temperature superconducting power transformer [6] are designed, developed and tested to be utilized in utilities. Superconducting wires and tapes in them replace the conventional wires. But superconductor exhibits AC losses when exposed to time varying magnetic field and/or transport current. These AC losses cause the rise of the temperature inside the HTS tapes/wires beyond its critical value. If the heat generated due to the AC losses is not removed timely, it may lead to thermal run away of the tape. Hence it is important to observe the AC loss generation inside the tape and the corresponding temperature rise. At present BSCCO-2223 is the mostly used material in tapes and wires at liquid nitrogen temperature. HTS wires are commercially available in Km lengths with current carrying capability of 150 times that of the conventional copper wire [7]. Use of HTS power cables, which are capable of carrying 10 times more power, compared to conventional cables can solve the grid congestion and environmental problems. But the liquid nitrogen which is used as coolant in HTS power cable is required to be cooled periodically along the cable length to remove the heat from the tape. For stable operation of the superconducting tape, the removal of generated heat due to AC loss is essential; otherwise temperatures at certain hot-spots within the superconductor may lead to thermal run-away inside the tape [8, 9]. The AC loss of HTS tape depends on critical current density, shape of the superconducting tape, transport current, magnetic field, and power exponent (*n*) [10] whereas the temperature distribution depends on anisotropic thermal conductivity, the temperature at the boundaries and the AC loss produced inside the tape [11]. Since the investigation of AC loss inside the HTS tape is not straightforward [12, 13, 14] and involves huge cost, different methods of simulations are opted for observation. Among several numerical methods Finite Element Method (FEM) have gained marked popularity. In this regard simulation of temperature, electric field and current density distribution in conducting and superconducting sub-domains was determined [15, 16, 17] using transient thermal 3D finite element code for HTS winding made of BSCCO and YBCO. A finite volume based code has been already developed [11] to predict the temperature evolution in Bi-2223 tape with due considerations of anisotropic thermal conductivity and randomized AC losses inside the domain. In this paper a FEM based software COMSOL Multiphysics is used for simulation of AC loss and temperature evaluation. For this purpose an elliptical model of Bi-2223 Ag-sheathed tape with J_c of 2×10^8Am^{-2} is considered. The AC loss due to the applied perpendicular magnetic field and transport current is simulated, followed by the temperature evaluation due to this AC loss inside the HTS tape. The PDE based module of COMSOL Multiphysics is used for AC loss calculation and heat transfer module of the same software is used for temperature estimation in multiphysics mode.

2. Mathematical model

For numerical calculation, a 2D model of Ag sheathed BSCCO-2223 tape of elliptical cross section with infinite length has been chosen. The HTS tape is exposed to perpendicular field and carrying transport current as shown in figure1. This phenomenon is applicable to different power apparatus. The winding of transformer carries AC currents under influence of AC magnetic field produced by another winding of the same. The applied magnetic field is sinusoidal in nature and acting along y direction. The AC transport current is flowing into cross sectional plane of the tape. *A*-ν formulation described by equation (1) is used for numerical simulation of AC losses inside the HTS tape. The solution of equation (1) gives the distribution of magnetic vector potential *A* inside the HTS tape directly when the tape is subjected to both the external AC magnetic field and transport current. The current density *J* is acting into the cross sectional plane of the tape.

The mathematical modeling is done based on electromagnetic equation using magnetic vector potential *A* and time dependent electric scalar potential ν. The governing equation is thus described by

$$\frac{1}{\mu_0}\nabla^2\times\vec{A}+\frac{1}{\rho}\frac{\partial\vec{A}}{\partial t}=-\frac{1}{\rho}\nabla\nu \qquad (1)$$

where *A* is the magnetic vector potential and $\nabla\nu$ is the potential difference per init length of the HTS tape along *z* direction which is uniform across the tape cross section. The current density *J* can be now expressed as

$$\vec{J}=-\frac{1}{\mu_0}\nabla^2\vec{\mathrm{A}} \qquad (2)$$

Here ρ is the equivalent resistivity of the HTS tape expressed by non-linear *E-j* power law as

$$E=E_c\left(\frac{|\vec{J}|}{J_c}\right)^{n-1}\frac{\vec{J}}{J_c} \qquad (3)$$

Where $E_c=1\times10^{-4}$ V/m and *n* is the power exponent. The *n* value for a typical BSCCO-2223/Ag tape is around 10 [18]. Critical current density J_c is considered here to be of a value of 2×10^8 A/m^2.

The boundary condition for external magnetic field is obtained from $\nabla\times A=B$. Ampere's law (4) is used to determine boundary condition around the tape cross section due to the transport current (*I*) flowing through the tape.

$$I=\left(1/\mu_0\right)\int\nabla\times A.dl. \qquad (4)$$

Equation (1) is solved numerically with the anisotropic material properties of the HTS tape. The values of ρ chosen are not equal in the entire solution domain. The distribution of current density *J* and electric field *E* are found from equation (2) and (3) respectively. With these calculated values of E and J in each element, the total AC loss is obtained using the following integration over entire cross-section (S) and time period (T) as

$$Q_{sc} = \int_T \int_S E.J ds dt \quad (5)$$

The simulation of temperature distribution due AC loss generated inside HTS tape is done using heat transfer analysis. It is considered that the elliptical superconducting sub-domain is surrounded by silver, which is a thermally conducting sub-domain. A cryogenic medium surrounds the whole domain from all directions for effective cooling. Liquid nitrogen is used as cryogen here. The main mode of heat transfer is conduction. Radiation heat transfer is ignored. The thermal conductivity is considered to be anisotropic and non-homogeneous. The governing partial differential equation for heat transfer is expressed as

$$\frac{\partial}{\partial t}\left(dc_p T\right) = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + Q \quad (6)$$

where T is the temperature, d is the density, c_p is the specific heat, k is the thermal conductivity, and Q is the calculated AC loss in the Ag sheathed BSCCO-2223 tape. The values of AC losses are obtained in the previous section. The initial condition to the above equation is $T = T_{initial}$ at $t = 0$ and the boundary condition (7) is obtained from

$$-k_n \frac{\partial T}{\partial n}\Big|_b = h(T_b - T_\infty) \quad (7)$$

where n is a directional normal to the surface under consideration, h is the convective heat transfer coefficient between the system and the cryogen medium, and T_∞ is the ambient temperature.

3. Use of COMSOL Multiphysics

COMSOL PDE coefficient form is used to model the AC loss of the HTS tape. An elliptical 2D model of Ag sheathed BSCCO-2223 tape is drawn with width and thickness of 2000 μm and 320 μm respectively. The mesh geometry of the HTS tape is shown in Figure (2).

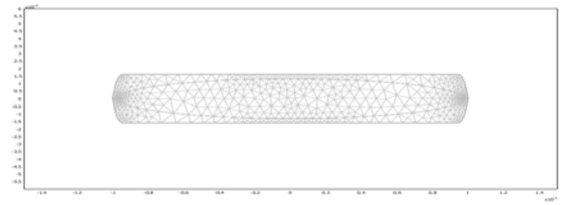
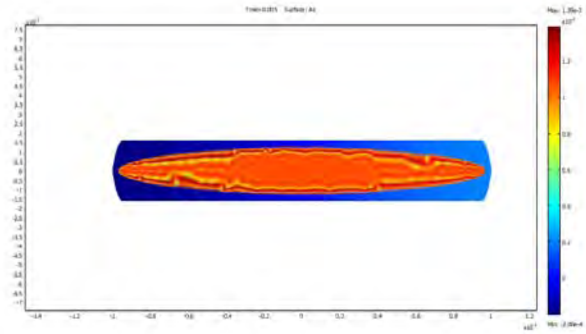


Figure 2 The meshed geometry of the 2D cross sectional model of the Ag sheathed BSCCO-2223 tape. The units of width and thickness of the tape are in meters. Total number of triangular elements is 1138 and number of degrees of freedom is 2387.

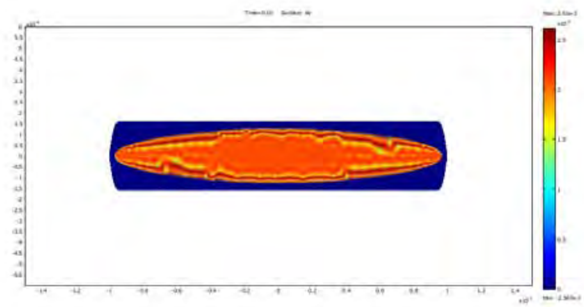
In the physics settings the values of resistivity are given following an anisotropic model of tape material. The Neumann boundary condition ($\frac{\partial A}{\partial n} = 0$) is applied at the top and bottom boundaries of the cross section and Dirichlet boundary conditions ($A_0 Sin\ (\omega t)$ and $-A_0 Sin\ (\omega t)$) are applied on the right and left boundaries respectively. The expressions of E and J are specified in the sub-domain expression and the expression of Q is entered in the scalar expression of the superconducting and the silver sub-domain. Then the simulation is done for different time instants for the applied sinusoidal field and the transport current. The frequency of the applied field and the AC transport current is chosen as 50 Hz. For evaluation of the temperature, the heat transfer mode of analysis is added with the PDE coefficient mode initially used. The coefficients like density, specific heat, thermal conductivity of BSCCO and Silver are specified in the physics settings and the values of convective heat transfer coefficient, ambient temperatures are entered in the boundary settings of the heat transfer mode of Multiphysics. The heat source is defined as $E.J$ in W/m^3 (which was calculated as AC loss) in the physics settings.

4. Results and discussions

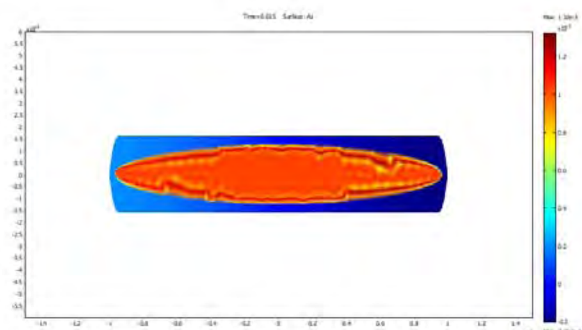
Using COMSOL Multiphysics the distributions of magnetic vector potential in the HTS tape due to applied magnetic field of 100 mT and an applied voltage of 230 V for ωt = π/2, π, 3π/2 and 2π are plotted in Figure 3 (a, b, c and d).



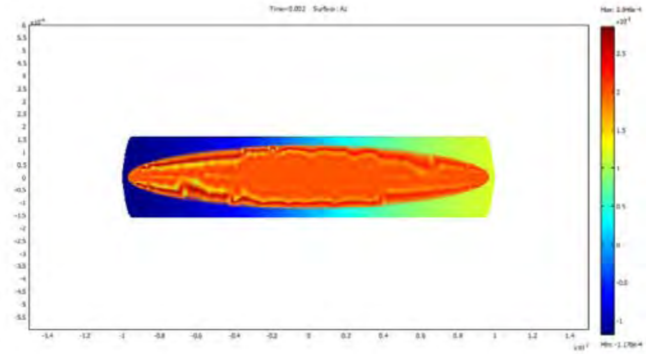
(a)



(b)



(c)



(d)

Figure 3 The surface plots of the magnetic vector potential in the elliptical cross sectional model of the Ag sheathed BSCCO-2223 tape due to applied field and transport current both at 50 Hz frequency are shown for $\omega t = \pi/2$ (a), π (b), $3\pi/2$ (c) and 2π (d).

The above plots explain how the magnetic vector potential changes with time in the HTS tape when the applied field and the transport current vary sinusoidally with time. It is also observed that the field values are more inside the superconducting sub-domain compare to the silver sub-domain. Figure 4 shows the change of current density inside the HTS tape with respect to the tape width at half thickness. It is observed that the current density is more near the boundaries compared to the center of the tape. The AC loss due to the applied perpendicular magnetic field is plotted in figure 5. The simulated AC loss shows good agreement with the analytical results [19]. The AC loss values (W/m^3) due to the applied magnetic field and transport current are now used for the temperature calculation in the heat transfer mode of COMSOL Multiphysics. The surface and the contour plot of temperature distribution at 10 sec are shown in figure 6. Figure 7 shows the rise of temperature at certain spot (-730μm, 47μm) in the HTS tape. The temperature at that point (near the BSCCO and silver interface at left hand side of the tape) increases initially at above 83K and drops to 78K, which is followed by a steady increase of temperature up to 82K. The initial rise of temperature at the spot causes large conductive heat fluxes, which finally lead to the removal of thermal energy to the cryogen through silver. As the temperature differences between the hotspot and the silver decreases the heat flux is reduced and the temperature due to the AC loss inside the superconductor is increased almost linearly.

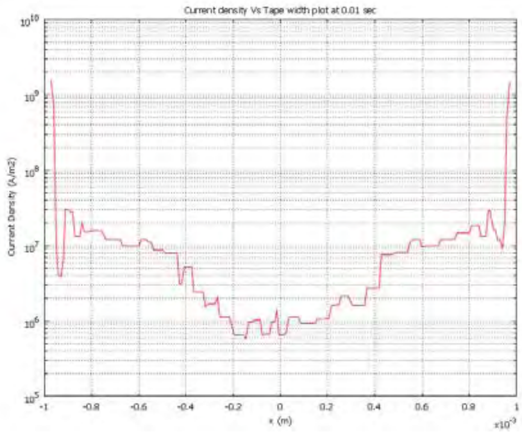


Figure 4 Semi log plot of current density vs tape width at half thickness of the Ag sheathed BSCCO tape.

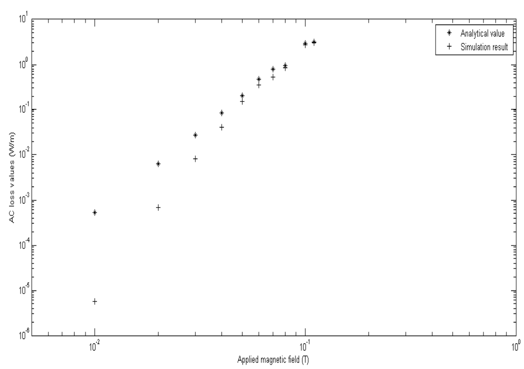


Figure 5 AC loss (W/m) plot due to the applied perpendicular magnetic field (T) at 50 Hz. The plots are based on simulation in COMSOL Multiphysics and analytical calculation [19]

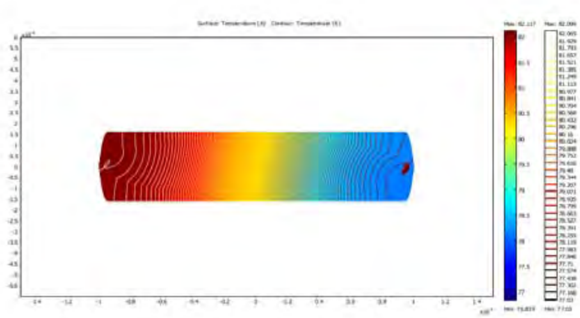


Figure 6 Surface plot and contour plot of temperature distribution inside the Ag sheathed BSCCO-2223 tape at t = 10 sec due to the AC loss generated in the HTS tape at 100 mT and carrying AC transport current of 250 A at 50 Hz.

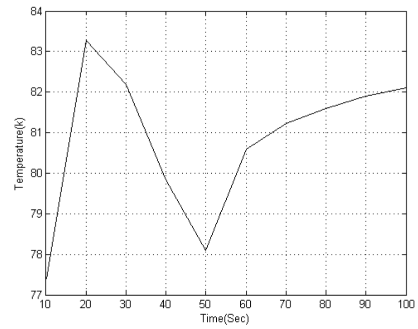


Figure 7 Temperature variations with time at certain spot (-730μm, 47μm) near the superconductor and silver interface.

5. Conclusions

In this paper the mathematical model for AC loss calculation and corresponding heat transfer analysis are proposed using COMSOL Multiphysics. The simulation is done in multiphysics mode where the PDE mode and the heat transfer mode are added to achieve the complete solution. In PDE mode for calculation of AC loss the anisotropic material property is used in terms of resistivity and in the heat transfer mode anisotropic thermal conductivity is opted. The simulation results for AC loss using COMSOL Multiphysics is compared with an analytical calculation, which showed good agreement. Using the simulated values of AC loss due to applied magnetic field and transport current as the heat source in the heat transfer analysis, the temperature distribution and temperature variation at certain spots are evaluated. It is concluded that using COMSOL Multiphysics software it is possible to achieve AC loss and thermal modeling of superconducting tape used in different superconducting apparatus.

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