

# Simulation of AC Loss in High Temperature Superconducting Cable using COMSOL Multiphysics

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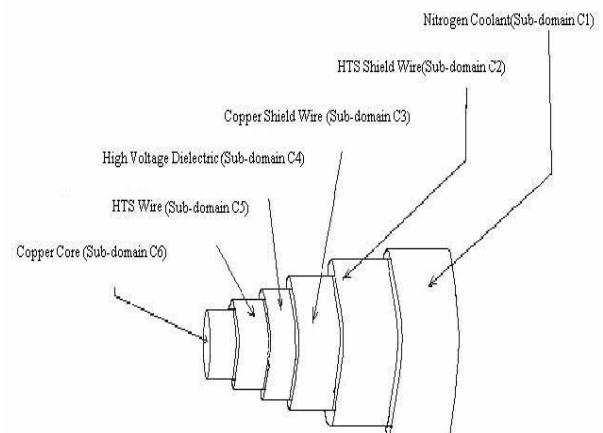
**Abstract:** In this paper simulation of the alternating current loss (AC loss) in a high temperature superconducting tape and a HTS cable having 4 layers of polygon conductors using COMSOL Multiphysics software has been reported. The simulation results for the single rectangular tape are verified with the Norris equation for a HTS tape. The effect of increased number of layers on AC loss is also observed using the simulation. All the simulations are done using two dimensional cross-section of HTS tape and the multiple numbers of tapes are assembled to form the polygon conductor. Using A-V formulation, the dynamic electromagnetic analysis has been done. For this, two dimensional PDE based module of COMSOL Multiphysics has been used with two dimensional geometry with proper Dirichlet and Neumann boundary conditions.

**Keywords:** HTS tape, AC loss, polygon conductor cable, YBCO tape.

## 1. Introduction

Use of superconductors rather than conventional conductors is a revolution of 21<sup>st</sup> century. In order to provide higher power capacity, higher current density and lower impedance, HTS cables offer significant benefits over conventional overhead and underground power cables. These cables are able to carry as much as 10 times more power & 150 times more current than conventional cable which make them ideal solution for network upgrades & urban profit projects. HTS cables also provide a good solution to grid congestion. High temperature superconductors have transition temperature above Liquid Nitrogen temperature of 77K. The best known high temperature superconductors presently used for power cables are Bismuth Strontium Calcium Copper Oxide (BSCCO) & Yttrium Barium Copper Oxide (YBCO). Other than higher current & power

carrying capacity HTS cables extend the operating life of the existing high load corridors. There are no soil heating & no oil leak leading to environment friendly power transmission and distribution. The most challenging task for designing an appropriate HTS cable is to calculate AC loss due to transport current (self field) and / or applied field, because it finally leads to thermal runaway of the cable. In this study, a single phase HTS cable (figure 1) has been used. This HTS cable has of 4 layers of polygon HTS conductors in sub-domain C6, each assembled by HTS tapes having proper aspect ratio. For simulation of AC loss we are considering only this sub-domain. The numerical simulations for current distribution and the AC loss are carried out for an isolated tape of rectangular cross section and the results are verified by Norris' theory [1]. The simulation of AC loss characteristics for the polygon conductors in 4 layers is also done and the influence of the number of layers on AC loss is observed. All the simulations are performed using the COMSOL Multiphysics software.



**Figure 1** Schematic diagram of single phase HTS cable. For simulation of AC loss sub-domain C5 has been used only.

## 2. Mathematical modeling

In this study the polygon conductors comprised of multiple HTS tapes are carrying the AC transport currents. They are also subjected to the AC magnetic field produced by the transport currents in the neighboring tapes. Each tape of the polygon conductor is multifilamentary and considered as bulk superconductor. Figure 2 illustrates the schematic diagram of an isolated tape and figure 3 shows the schematic diagram of 1/4th symmetry of the 4-layer polygon conductor cable. The detail specifications of the cable are shown in table 1. For a single HTS tape (figure 2) an orthogonal coordinate system  $(x, y, z)$  has been opted where the  $z$ -axis coincides with the axis of the tape and the transport current flows along the  $z$ -axis i.e. along the length of the tape. Considering a uniform electromagnetic field in  $z$  direction, the electric field and the current density have only the  $z$  component. The basic electromagnetic equation for the dynamic analysis is expressed as

$$\nabla \frac{1}{\mu_0} \nabla A + \sigma \frac{\partial A}{\partial t} = -\sigma \nabla V \quad (1)$$

where  $A$  is the magnetic vector potential due to self field and the external field produced due to the currents through the neighboring tapes.  $\nabla V$  is the voltage gradient. The electric field is expressed as

$$E = -\frac{\partial A}{\partial t} - \nabla V \quad (2)$$

The  $E$ - $j$  relationship as proposed by Rhyner [2] is expressed as

$$E = E_0 \left( \frac{|J|}{J_c} \right)^{n-1} \frac{\vec{J}}{J_c} \quad (3)$$

Here  $n$  is the power exponent and the  $J_c$  is the critical current density at  $E_0$ . Both of them are dependent on local magnetic field.  $E_0$  has the value of  $10^{-4}$  V/m which is universally accepted [3]. From equation (3) the non-linear conductivity  $\sigma$  is expressed as follows:

$$\sigma = \frac{J_c}{\frac{1}{E_c^n}} \left| E \right|^{\frac{1-n}{n}} \quad (4)$$

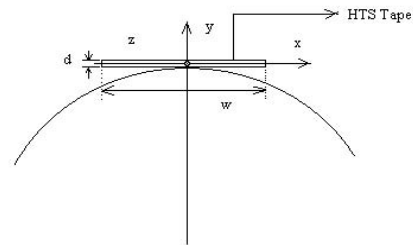
By numerically solving the equations (1) – (3) and using (4), the distribution of current density and the electric field across the isolated tape cross

section can be evaluated. Then the AC losses per unit length are computed by equation (5) for an isolated tape. Then the AC loss is calculated for the 4 layer polygon conductors.

$$P = \frac{1}{T} \int_0^T dt \int_s J \cdot E dS \quad (5)$$

## 3. Use of COMSOL Multiphysics

In the model navigator of COMSOL Multiphysics the PDE based mode has been chosen first. The magnetic vector potential ( $A$ ) is considered as dependent variable. A rectangular HTS strip is drawn in  $2D$  plane using draw menu. Proper constants for simulations ( $E_0, J_c, n, f$  etc) are entered in the option menu. Then the equations for current density, electric field, AC loss etc are specified as scalar expressions in the same option menu. The expression of non-linear conductivity (4) is written in the sub-domain expression field. The expressions of  $A$  at the boundaries, determined from  $\nabla \times A = B$ , are specified in the boundary expression. Then in the physics setting menu the proper value/expressions of different coefficients of PDE (1) are set. Boundary conditions are also specified at different boundaries as Dirichlet or Neumann boundary condition. Then the shape function and the initial values of the variable  $A$  are set in the element edit field and in the Init field respectively. After choosing the free mesh parameters from mesh menu, meshing is done with maximum element size of  $1e-2$  in the superconducting sub-domain. Then the solution is done by clicking the solve menu and setting proper solver parameters. The simulation is done for a single time period. The post processing menu has been used to get surface plots  $A, J, Q, E$  etc and other plots. Following the same procedure the simulation of AC loss has been done for HTS wire with 4 layers of polygon conductors.



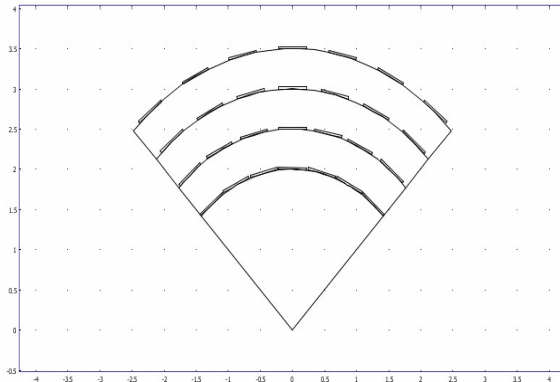
**Figure 2** Schematic diagram of an isolated tape of a polygon conductor,  $w=3.5$  mm and  $d=200\mu\text{m}$ .

**Table 1** Specification of each layer of HTS polygon conductor cable

Layer No.	Radius (mm)	Tape width (mm)	Tape thickness ( $\mu\text{m}$ )	Tape number	Gap (mm)
1	28	3.5	200	28	2.8
2	24	3.5	200	28	1.9
3	20	3.5	200	28	1
4	16	3.5	200	28	0.1

#### 4. Numerical results and discussion

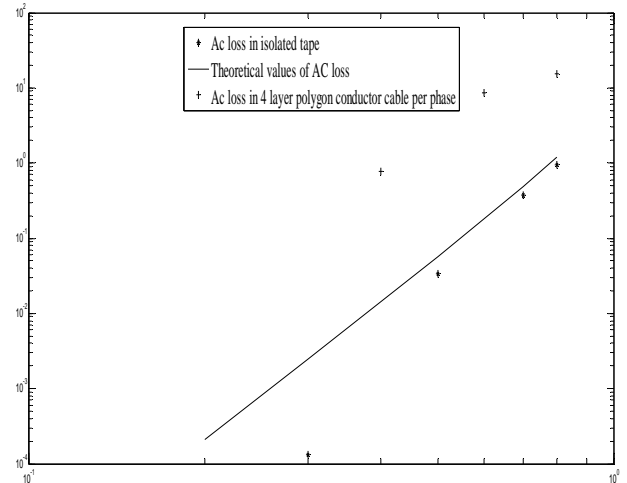
The AC losses of an isolated tape are simulated using COMSOL multiphysics software for different values of transport currents (self field) and under influence of applied field. External applied fields are due to transport currents in the neighboring tapes. Figure 4 shows the AC losses in the isolated tape for different RMS values of transport currents normalized by critical current density. The AC losses are calculated for an aspect ratio of 17.5. For higher value of aspect ratio the tape cross-section becomes almost one dimensional. To get better simulation results, here we have considered two dimensional tape cross-sections with the above aspect ratio. The simulation results are verified with the theoretical values obtained from Norris equation of AC loss for rectangular strip. As shown in Figure 4, the AC loss for an isolated tape has been



**Figure 3** Schematic diagram of  $1/4^{\text{th}}$  symmetry of 4-layer HTS polygon conductor cable with suitable gap between two tapes; x and y axis are drawn in mm (1 unit = 8mm).

increased with the increased value of transport current through itself and through the neighboring

tapes. These simulated loss values obtained by COMSOL multiphysics match well with the theoretical values of AC loss. They are almost proportional to the  $I^4$  where  $I$  is the rms current. Next the AC loss calculation for a single layer polygon conductor is done for  $J/J_c = 0.7$ . This value is obtained in two ways. Firstly, simply multiplying the AC loss value of an isolated tape with the number of tapes in an individual layer. Secondly, the loss value has been simulated for the layer with  $1/4^{\text{th}}$  symmetry using COMSOL multiphysics. A single layer polygon conductor contains 28 numbers of tapes. For the first case the obtained AC loss value is 3.64 W/m. The later method gives a lower value of AC loss (2.98 W/m) which may be due to partial cancellation of self fields produced by two adjacent tapes of the polygon conductor. Next the numbers of layers have been increased to four [4]. It is found that the values of AC losses for different current densities are more for increased numbers of layers. For all these above calculations the  $n$ -value i.e. is the power index has been chosen to be 50 which suits better for the YBCO tapes [7].



**Figure 4** AC loss values for an isolated tape are plotted and compared with the theoretical values from Norris equation. Also the plot of simulated AC loss values of cable with 4 layers of HTS conductors per phase has been shown.

#### 5. Conclusion

The AC loss simulation of assembled conductor of multiple thin HTS tapes in polygon arrangement has been done using COMSOL multiphysics. The simulation results are verified

with the theoretical values. So the application of this software for AC loss calculation for large number of thin tapes in a polygon arrangement with multiple numbers of layers is justified and helps in the numerical analysis of loss with different geometrical configurations. It could be better, if we can include some iteration for calculating the nonlinear conductivity values in the superconducting sub-domain using this software, which might be given better matching of AC loss values with the theoretical values.

## 6. References

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