

# Current density, Electric Field and AC loss Simulation of Mono Block and Single Layer Polygonal HTS Cable Using COMSOL Multiphysics

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## Abstract

High temperature superconducting (HTS) cables are gaining attentions for their ability to transmit more power compared to their conventional counterparts with essentially no resistance and electromagnetic emissions. They are also appropriate for solving the grid congestion problem in the power corridors with their reduced size and weight. But the AC loss that occurs in the HTS cables reduces the efficiency of the power transfer system. Thus the investigation of AC loss in HTS cables and its reduction are important. In this paper, two dimensional numerical analysis of AC loss of mono HTS cable and a single layer polygonal cable with different number (14, 20, 28) of HTS tapes is done using PDE module of COMSOL Multiphysics. *A-V* formulation has been used to obtain the electric field and current density distribution in the cable with proper Dirichlet and Neumann boundary conditions. The superconducting material used in the HTS layer is YBCO (YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub>), 2G. Compared to the monoblock cable, the AC loss of polygonal superconducting cable is less. The simulated AC loss values of HTS cables, obtained from COMSOL Multiphysics are compared the AC loss values calculated using MATLAB.

**Keywords:** High temperature superconducting (HTS) tapes, AC loss, Critical current density, aspect ratio, Dirichlet boundary condition

## 1. Introduction

During the transmission and distribution of electric power through the conventional cable, huge amount of heat is dissipated due to Joule effect, which is about 2.5% of total energy loss [1]. Some energy is dissipated into magnetic field and some amount of energy is absorbed in the insulating material which is known as

dielectric loss. This problem can be overcome by replacing the conventional cables with the superconducting cables, more commonly known as high temperature superconducting cable. These cables are made up of high temperature superconducting materials like YBCO, BSCCO etc instead of conventional conductors. The heat produced due to the AC losses inside the HTS cables, needs removal through proper cryogenic arrangement. Some experimental works [3-9] were performed on AC loss calculation of HTS cable of different dimensions. AC loss characteristics of HTS cables conductors with different aspect ratios were also studied numerically [10,11]. The present work is concentrated on the simulation of current density, electric field and AC loss of the mono block and single layer polygonal HTS cables using finite element software COMSOL Multiphysics. The superconducting materials are too expensive. Also the experimental setup for HTS cables is very costly. That is why the simulation of AC loss of HTS cable has been opted here. Authors had already published [12] simulation work on AC loss of multilayer HTS cable with  $\frac{1}{4}$  symmetry. But the simulation of current density, electric field and AC loss of the whole cable is done in the present paper.

## 2. AC loss simulation using COMSOL Multiphysics

The basic electromagnetic equation used for simulation is expressed in equation (1)

$$\frac{1}{\mu_0} \times \nabla^2 \vec{A} + \sigma \times \frac{\partial \vec{A}}{\partial t} = -\sigma \times \nabla V \quad (1)$$

Where  $A$  denotes magnetic vector potential along  $z$  axis,  $V$  denotes applied voltage and  $\sigma$  denotes conductivity of superconductor. The current density  $J$  and the electric field  $E$  are expressed as

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

$$E = -\frac{\partial \vec{A}}{\partial t} - \sigma \nabla V \quad (3)$$

The non-linear conductivity of a HTS tape is expressed as

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

Where  $n$  denotes power exponent,  $J_c$  is critical current density at the critical electric field  $E_c$  and The AC loss is determined by

$$Q = \frac{1}{T} \iint J \cdot E ds dt \quad (5)$$

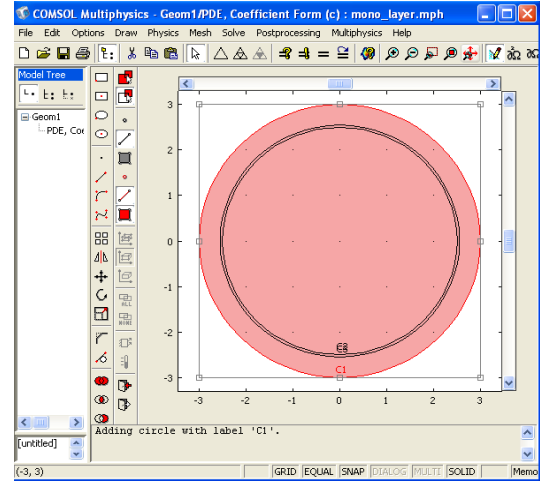
In COMSOL Multiphysics, PDE module has been used for geometry modeling of the monoblock and the single layer polygonal cable. Table 1 shows the dimensions of the cables used for simulation.

**Table 1** Dimensions of HTS cables used for simulation.

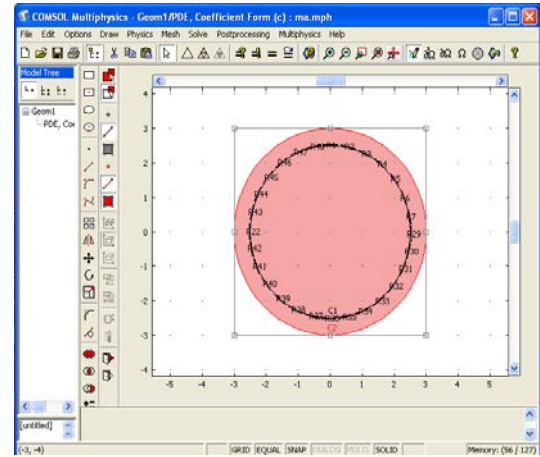
Mono block and Single layer polygonal cable	Outer diameter of Vacuum layer	48 mm
	Thickness of the YBCO layer	0.2 mm
	Diameter of the copper core	40 mm

In mono block cable, a continuous layer of high temperature superconductor made of YBCO is used whereas in single layer polygonal cable 28 numbers of HTS tapes are placed on the copper core. Each HTS tape has a width of 3.5mm and thickness of 0.2mm. The aspect ratio chosen here is 17.5 [10]. The geometries of these cables (as drawn in COMSOL) are shown in figure 1 and 2. Using the triangular elements meshing of both the geometries is done. Dirichlet boundary conditions are applied at the outer boundary of the cable. Using Ampere's law  $\nabla \times A = B$ , the values of  $A$  at the boundaries are

calculated.



**Figure 1** Geometry of mono block HTS cable.

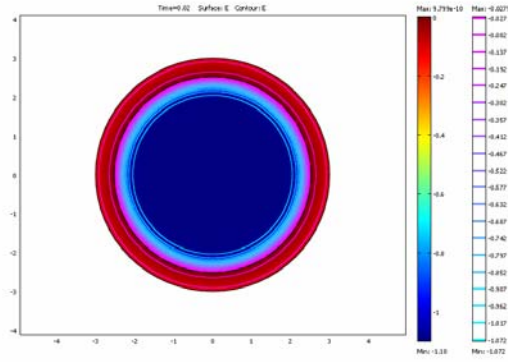


**Figure 2** Geometry of Single layer Polygonal HTS cable having 28 numbers of HTS tapes.

### 3. Results and discussions

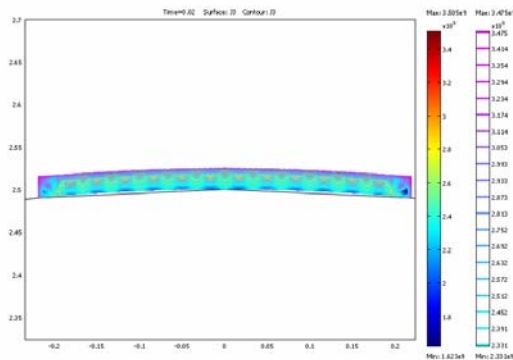
The simulation of electric field, current density and AC loss are reported here. The alternating transport current flowing through each tape is responsible for self field loss in itself, but acting as the applied field for the others.

The surface plot of electric field of Single layer Polygonal HTS cable having 28 numbers of HTS tapes is shown in figure 3. It is observed that the field concentration is maximum in the HTS tapes compared to the copper core. The width and thickness of cable cross section have been scaled up as 1scale unit = 8 mm. This is applicable for all figures.

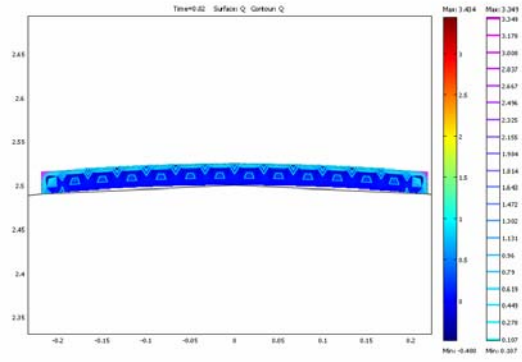


**Figure 3** Distribution of electric field of single layer polygonal HTS cable having 28 numbers of tapes.

Figure 4 shows the current density plot of a single tape of the polygonal HTS cable. The current density decreases from the outer boundary towards the center of the tape. The current density distribution is not uniform inside the tape due to the anisotropic conductivity of the superconducting material. It is observed that the value of maximum current density is less compared to the critical current density ( $10^{10}$  A/m<sup>2</sup>). The AC loss plot of the same is shown in figure 5. Since the conductivity of HTS material is maximum compared to the other conducting parts of the cable, the current density and AC loss values are maximum in this part. Hence the surface and contour plots of the current density and AC loss are shown for a single HTS tape of the cable instead of the whole cable. The plots of electric field for polygonal cable having 20 and 14 numbers of tapes are also shown in figure 6 and 7 respectively. Both the plots reveal that the fields are mostly concentrated inside the HTS tapes compared to the other parts of the cable.



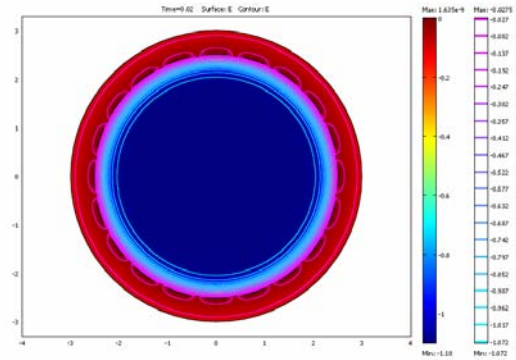
**Figure 4** Current density plot of single layer polygonal HTS cable having 28 numbers of tapes.



**Figure 5** Surface and contour plot of AC loss of single layer polygonal HTS cable having 28 numbers of tapes.

Table 2 shows a comparative study of total AC loss that incurred in single layer polygonal cable having 14, 20 and 28 numbers of YBCO tapes. It is observed that with the increase of numbers of tapes AC loss reduces. Comparison of current densities and electric fields for these three cables are also compared there.

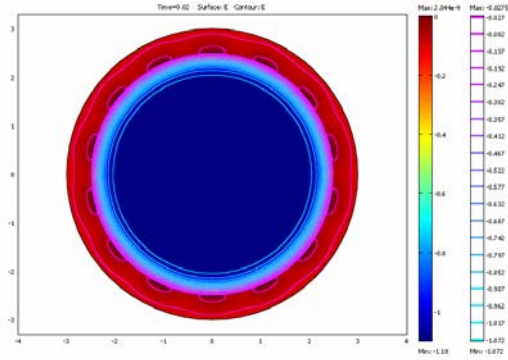
The simulated AC loss values for different  $J/J_c$  of Single layer Polygonal HTS cable having 28 numbers of HTS tapes obtained from COMSOL Multi-physics are compared with the AC loss values calculated using MATLAB (table 3).



**Figure 6** Simulation of electric field of single layer polygonal HTS cable having 20 numbers of tapes.

**Table 2** Comparison of three type polygonal HTS tapes

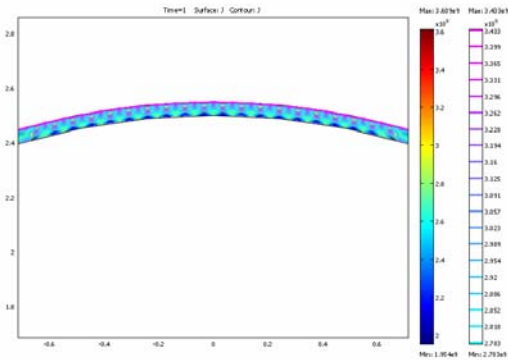
No of tapes	AC loss (W/m)	Current density (A/m <sup>2</sup> )	Electric field (V/m)
14	7.65	$3.747 \times 10^9$	$9.79 \times 10^{-10}$
20	6.05	$3.67 \times 10^9$	$1.63 \times 10^{-9}$
28	3.4	$3.5 \times 10^9$	$2.04 \times 10^{-9}$



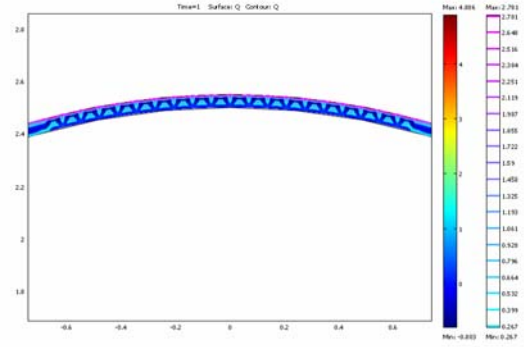
**Figure 7** Simulation of electric field of single layer polygonal HTS cable having 14 numbers of tapes.

**Table 3** Comparison of AC loss values for different  $J/J_c$  as obtained for Single layer Polygonal HTS cable with 28 tapes using COMSOL Multiphysics and MATLAB.

$J/J_c$	Current density ( $J$ ) ( $A/m^2$ )		AC loss( $Q$ ) (w/m)	
	COMSOL	MATLAB	COMSOL	MATLAB
	0.39	$4.11 \times 10^9$	$3.90 \times 10^9$	0.968
0.41	$4.33 \times 10^9$	$4.16 \times 10^9$	2.077	1.61
0.43	$4.52 \times 10^9$	$4.30 \times 10^9$	3.08	2.40
0.45	$4.74 \times 10^9$	$4.52 \times 10^9$	5.37	4.51



**Figure 8** Current density plot of a portion of Mono Block HTS cable

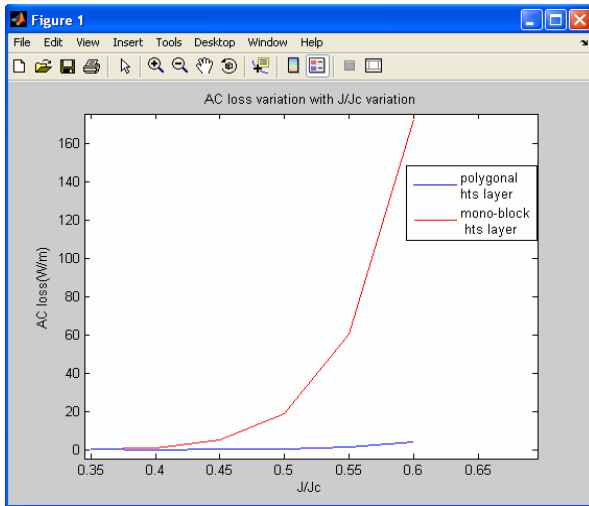


**Figure 9** Simulation of AC loss of Mono Block HTS cable

**Table 4** AC loss obtained in two different soft wares of mono-block HTS cable

$J/J_c$	Current density ( $J$ ) ( $A/m^2$ )		AC loss( $Q$ ) (w/m)	
	COMSOL	MATLAB	COMSOL	MATLAB
0.35	$3.68 \times 10^9$	$3.50 \times 10^9$	0.261	0.197
0.40	$4.10 \times 10^9$	$4.00 \times 10^9$	0.968	0.769
0.45	$4.72 \times 10^9$	$4.50 \times 10^9$	5.23	3.917
0.50	$5.26 \times 10^9$	$5.00 \times 10^9$	18.79	13.96

The current density and AC loss plots of the mono block HTS cables are shown in figure 8 and 9 respectively. AC loss is more in this HTS cable compared to the polygonal cable having 28 and 20 numbers of HTS tapes. But compared to the polygonal HTS cables having 14 numbers of HTS tapes, the AC loss in mono block cable is less. Hence, with respect to AC loss and heat generation due to transport current and applied field, HTS cables with large numbers of tapes (28) are preferred. Figure 10 shows the comparison of AC losses in mono block and polygonal HTS cable (28 tapes).



**Figure 10** Comparison of AC loss of two type of HTS cable

### 3. Conclusions

In this paper, AC loss and current density of two types of HTS cables are simulated and compared using COMSOL Multiphysics and MATLAB. Drawing of complex geometry and meshing the same become easier in COMSOL Multiphysics compared to the MATLAB. Computation time is also less in the earlier one. It is seen that the Single layer polygonal HTS cable is preferred over the Mono block HTS cable due to lower AC loss. As  $J/J_c$  tends to 1 the AC loss of mono block cable becomes much higher than Single layer polygonal HTS cable. It is also found that the AC loss decreases if we increase in the number of tapes in the Polygonal HTS cable.

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