Numerical Model to Calculate Magnetization AC Losses for Superconducting Strip used for Current Transport Applications in Electric Aircrafts

Ashish Agrawal, Abhinav Kumar

Abstract: ***High Temperature Superconducting (HTS) tapes are being proposed in the current transportation applications in electric aircrafts due to their capacities to carry large currents with low losses and higher efficiencies. Many systems are involved in the aircraft power distribution units and each component has its own magnetic field which may affect the working of surrounding systems. It has been found from many studies that perpendicular field has significant effect on the critical current of the HTS tape. In the present study, effort has been made to develop a numerical code through which magnetization AC losses due to external magnetic field are evaluated for YBCO superconductor. Calculated values are compared with Halse-Brandt model and it has been found that with the increase in the index value 'n', the results are approaching the Halse-Brandt model.***

Keywords: ***AC Losses, Superconducting Strip, Current Transport, Numerical Modelling, Roebel Cables.***

I. INTRODUCTION

High Temperature Superconducting (HTS) tapes find its applications in many engineering systems like high power transmission cables, superconducting fault current limiters, motors, generators, transformers and superconducting magnetic energy storage systems over the last few years. Scientists want to replace normal conductors with superconductors as they have almost zero losses compared to conventional conductors involved in many engineering applications. In this regard, NASA and AFRL have decided to use superconductors in the hybrid and fully electric aircrafts [1][2]. Generally, Roebel cables have been proposed by many researchers for the power transmission applications as its structural arrangement leads to fewer losses [3]–[8].

Electric aircrafts are going to be the future of aviation sector and many researchers are trying to make the technology feasible. The existing critical challenges that are delaying the technology are related with the energy or power availability and power transmission to the motors. The conceptual design of fully electric aircraft N3-X and EADS VoltAir is shown in Fig. 1 where many superconducting sub-systems are involved such as cables, motors, magnetic energy storage systems and fault current limiters to make sure a uninterrupted power distribution [9][10]. Other magnetic components like magnetic bearing are installed in the various parts of aircraft which has their own magnetic field and there may be situations where these fields can affect the performance of superconducting cables and other sub-systems. Many researchers have studied the effect of perpendicular external magnetic fields on the AC losses and critical current of the superconducting tape and they have found it has a significant effect on the system performance [11]–[15]. Therefore, in the present study, a numerical code has been developed to calculate the AC losses due to the existence of perpendicular magnetic field. The results are compared with Halse-Brandt exact solution and it has been found that with the increase in the n-value the numerical model is approaching the Halse-Brandt model [16] [17].

II. NUMERICAL MODELLING

A numerical model using Matlab has been developed for YBCO tape having specifications enlisted in Table I. The superconducting tape is modelled with E-J power law and Maxwell's equations have been used to solve the problem. A correlation for the magnetic vector potential has been derived for the current distribution where the electric field is related to the vector potential by a time derivative. Along with the E-J power law, this defines the current distribution in the tape. Numerical integration on current distribution equation has been used to evaluate the current as a function of time. Losses can be measured through the product of electric field and current density. The strip or tape used for the study is manufactured by SuperPower (SCS12050) whose critical current is 330 A at 77 K temperature. The magnetic vector potential at distance '*r*' of an infinite wire carrying current *I* can be calculated as [18]:

$$\mathbf{A} = -\frac{\mu_0 \mathbf{I}}{2\pi}\ln(r) \tag{1}$$

The vector potential at (y_i, z_i) of a thin sheet having width dy' carrying $J_j dy'$ is therefore,

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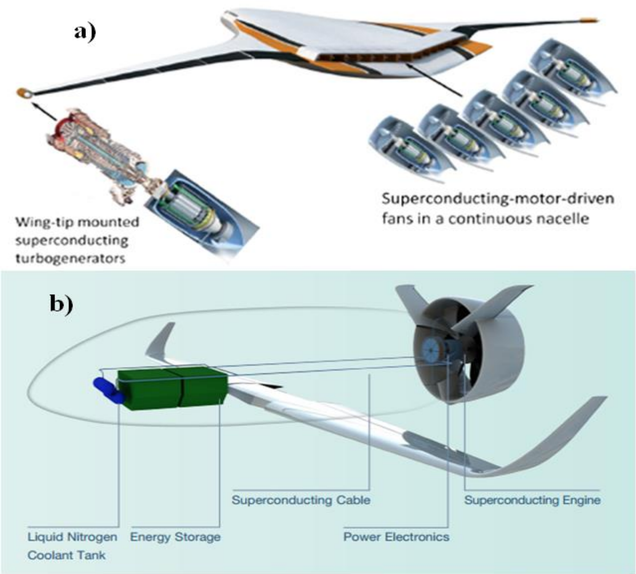

Fig. 1 Superconducting Machines in Electric aircrafts (a) N3-X, (b) EADS VoltAir

$$dA_{ij} = -\frac{\mu_0 J_j}{2\pi}\ln\left(\sqrt{(y_i - y')^2 + (z_i - z_j)^2}\right)dy'$$
$$= -\frac{\mu_0 J_j}{4\pi}\ln\left((y_i - y')^2 + (z_i - z_j)^2\right)dy' \quad (2)$$

The vector potential A_{ij} can be calculated as:

$$A_{ij} = -\frac{\mu_0 J_j}{4\pi}\int_{y_{L,j}}^{y_{R,j}}\ln\left((y_i - y')^2 + (z_i - z_j)^2\right)dy' \quad (3)$$

In order to get the vector potential of the entire cable A_i at (y_i, z_i), the contributions of all elements are sum up together:

$$A_i = -\frac{\mu_0}{4\pi}\sum J_j \int_{y_{L,j}}^{y_{R,j}}\ln\left((y_i - y')^2 + (z_i - z_j)^2\right)dy'$$

It can also be represented in current J_j and a geometrical factor K_{ij}

$$A_i = \frac{\mu_0}{4\pi}\sum K_{ij} J_j$$

where,

$$K_{ij} = -\frac{1}{2}\int_{y_{L,j}}^{y_{R,j}}\ln\left((y_i - y')^2 + (z_i - z_j)^2\right)dy'$$
$$= (y_i - y_{R,j})\left(\ln|y_i - y_{R,j}| - 1\right) \quad (4)$$
$$-(y_i - y_{R,j})\left(\ln|y_i - y_{R,j}| - 1\right) \rightarrow z_i = z_j$$

Since K depends upon the geometry only, therefore it needs to be evaluated once and remains invariant with respect to time. For external magnetic field, the vector potential can be represented as:

$$A_{ext,x}(y,z) = -yB_{ext,z} + zB_{ext,y}$$

Therefore, the total vector potential is

$$A(y_i, z_i) = -y_i B_{ext,z} + z_i B_{ext,y} + \frac{\mu_0}{2\pi}\sum_j K_{ij} J_j \quad (5)$$

$$E = -\nabla V - \frac{\partial A}{\partial t} \quad (6)$$

Vector potentials and external electric field in x-direction can be described by $V = -xE_{ext,x}$.

$$E_i(J) = -\frac{dV}{dx} - \frac{\partial}{\partial t}\left(A_i + A_{ext,x}(y_i, z_i)\right)$$
$$= E_{ext,x} - \frac{\mu_0}{2\pi}\sum_j K_{ij}\dot{J}_j + y_i\dot{B}_{ext,z} - z_i\dot{B}_{ext,y} \quad (7)$$
$$\sum_j K_{ij}\dot{J}_j = \frac{2\pi}{\mu_0}\left(E_{ext,x} - E_i(J) + y_i\dot{B}_{ext,z} - z_i\dot{B}_{ext,y}\right)$$
$$\dot{J}_j = \frac{2\pi}{\mu_0}\sum_j K_{ij}^{-1}\left(E_{ext,x} - E_j(J) + y_j\dot{B}_{ext,z} - z_j\dot{B}_{ext,y}\right)$$

$$E(J) = E_c\left(\frac{J}{J_c(B_y, B_z)}\right)^n \quad (8)$$

Using *E*(*J*) power law, this equation can be solved through Matlab and it represents the current distribution. Table I shows the strip parameter used for analysis.

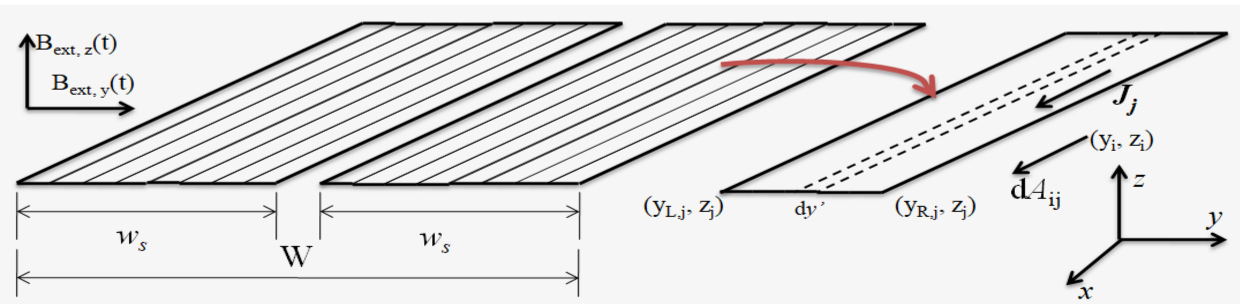

Fig. 2 Schematic of Roebel cable divided into thin sheets and current density is in x-direction

Fig. 3 to Fig. 6 describes the current distribution in the strip and it can be noticed that for normal conductor (n=1) external field has significant effect on the current distribution compared to superconductor (n=5 to 30) and this effect is decreased as the n-value increased. For comparison, from the Fig. 3 it can be observed that the Q value is 85.7 J/m/cycle and n=30 its value is 4.6 J/m/cycle.

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Table- I: Strip Parameters

Parameter	Value
Strip Width	0.012 m
Critical current/Width	27.5e3 A/m
Critical Electric Field, E_c	1e-4
n-value	1 to 30

III. AC LOSSES

AC losses have been calculated for an ideally superconducting thin strip with an n-value approaching 30. For comparison, the results are compared with the exact solution derived by Halse [16] and later by Brandt and Indenbom [17]:

$$Q = \frac{2\mu_0 J_c^2 w^2}{\pi}\left[\ln\left(\cosh\left(\frac{\pi H_0}{J_c}\right)\right) - \frac{\pi H_0}{J_c}\tanh\left(\frac{\pi H_0}{J_c}\right)\right] \quad (9)$$

In the above equation, $H_0 = B_0 / \mu_0$ is the peak external magnetic field during the cycle. It can be observed that the numerical calculated losses for various n-values are approaching to ideal superconducting strip losses as the n-value increasing. Fig. 7 shows the magnetization AC losses per cycle and Fig. 8 describes the normalized losses per cycle. Normalization is done with B_0^2 in order to observe the variation clearly and it can be observed that with the increase in the n-value the losses are approaching to the ideal superconducting behavior. Similar results can be found into study done by J. Otten [18].

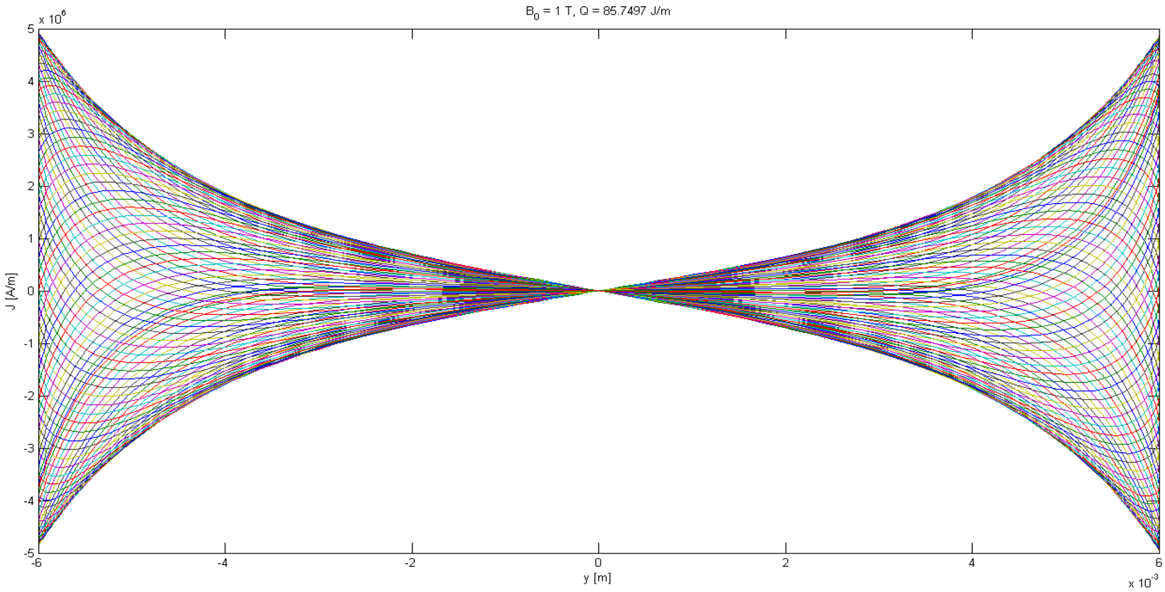

Fig. 3 Current distribution for normal conductor i.e. n=1

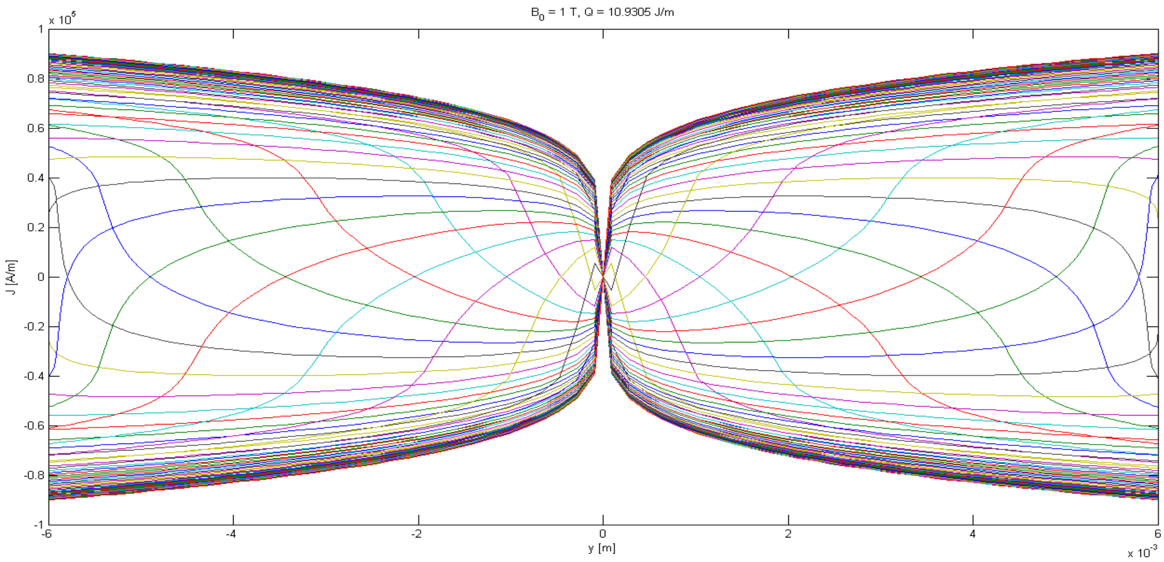

Fig. 4 Current distribution for Superconductor i.e. n=5

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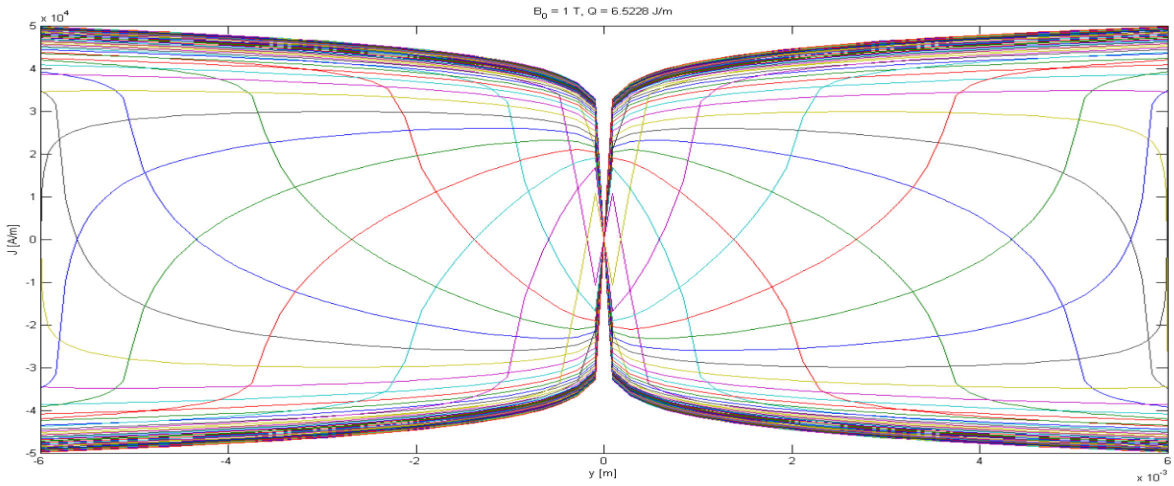

Fig. 5 Current distribution for Superconductor i.e. n=10

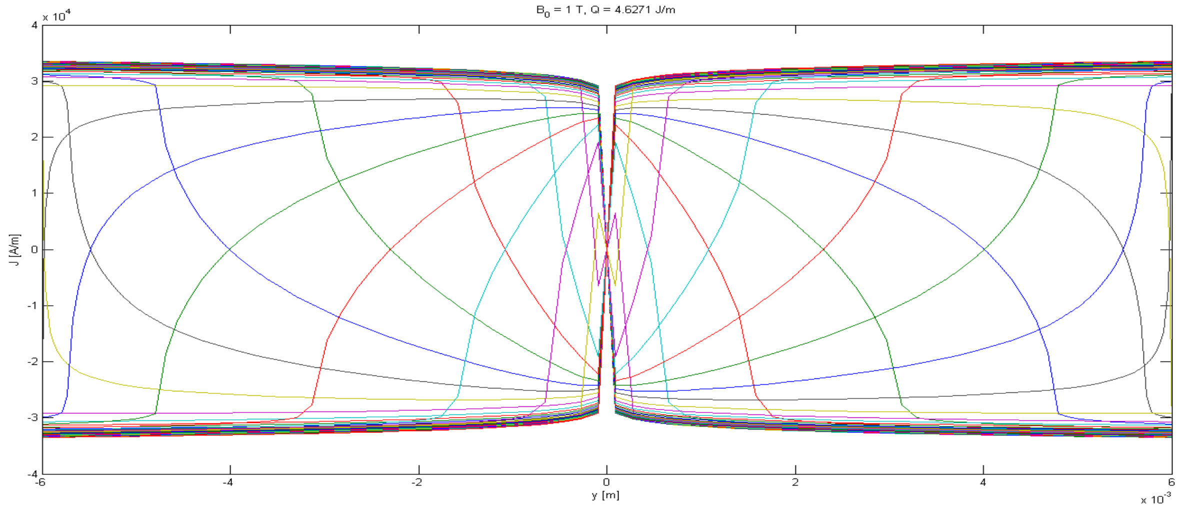

Fig. 6 Current distribution for Superconductor i.e. n=30

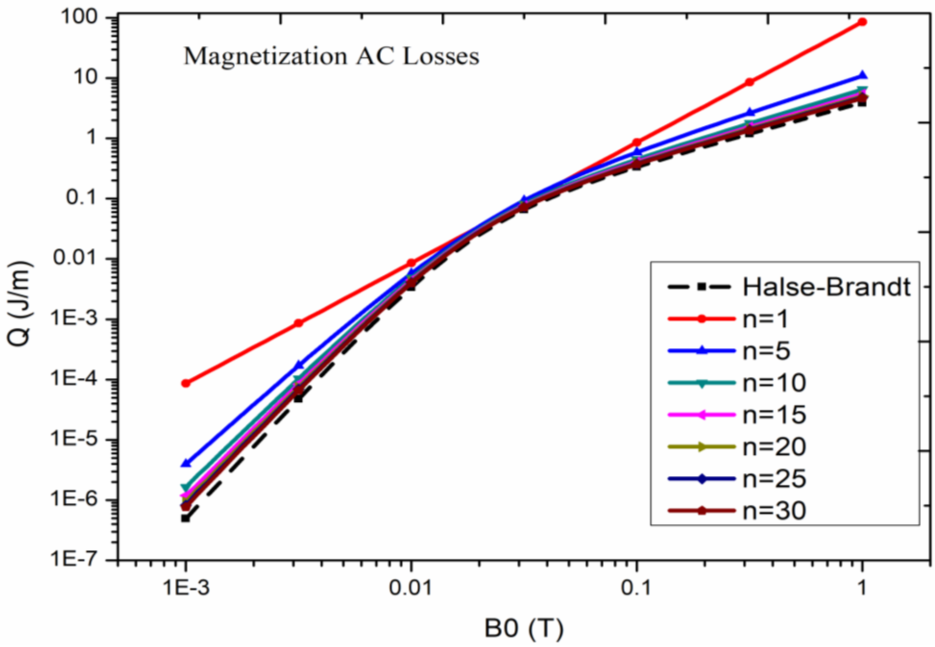

Fig. 7 Magnetization AC losses for numeric and Halse-Brandt

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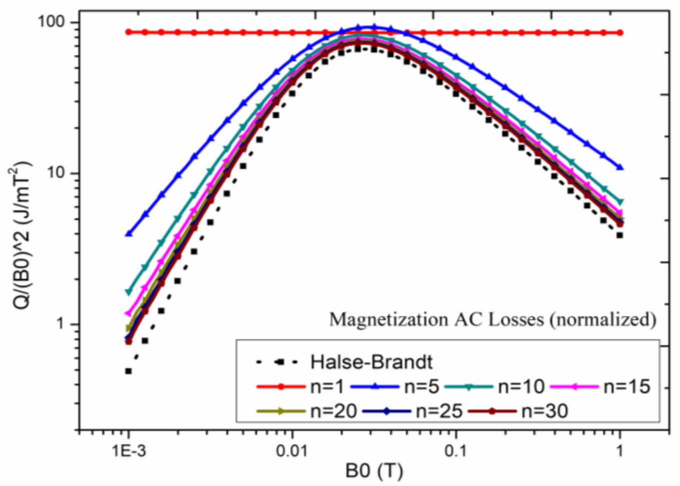

Fig. 8 Normalized Magnetization AC losses for numeric and Halse-Brandt

IV. CONCLUSION

A numerical model using Matlab has been developed to calculate the magnetization AC losses due to external field. The simulations are done for one cycle and the study reveals that the higher n-values can result into lower losses. Therefore, while designing the cables or aircraft power system one should try to have a superconductor with high n-value.

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