HTS Coated conductor losses model using the coupling method and the T-A formulation

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Abstract—**The power loss in electric power equipment is a fundamental topic to the superconductivity large-scale applications. The literature presents several methods developed to predict these losses in superconducting tapes. The finite element method (FEM) has been widely studied among the existing methods, using formulations as the H and the T-A. However, to compute the HTS coated conductor losses in a large frequency range, just the H-formulation has presented a good accuracy and precision. Using the T-A formulation and the coupling method, the authors propose a new and innovative method to calculates the losses in a large frequency range. The results of this method are compared with the consolidated H-formulation to validate them.**

Keywords—*Coated Conductor, Coupling Method, Superconductor Losses, T-A formulation*

I. T-A 1D PROPOSED MODEL

A. T-A 1D using the coupling method

In the T-A formulation, the Magnetic vector potential and the Current Vector potential are the work variables. The Magnetic vector potential is used to compute the magnetic flux density in all domains by:

$$\mathbf{B} = \nabla \times \mathbf{A}, \tag{1}$$

$$\nabla \times (\frac{1}{\mu}\nabla \times \mathbf{A}) = \mathbf{J_{HTS}} + \mathbf{J_e} + \mathbf{J_i}, \tag{2}$$

where A is the magnetic vector potential, B is the magnetic flux density, J_{HTS}, J_e and J_i are the current density from HTS, the external current density, and the induced current calculated by A-V formulation, respectively. On the other hand, the current vector potential (**T**) computes the current density in the superconducting domain by:

$$\mathbf{J_{HTS}} = \nabla \times \mathbf{T}, \tag{3}$$

$$\nabla \times (\rho \times \mathbf{T}) = -\frac{\partial \mathbf{B}}{\partial t}, \tag{4}$$

AC losses per meter per cycle are calculated by

$$Q = \frac{2}{p} \int_{p/2}^{p} \int_{S} \mathbf{E} \cdot \mathbf{J} dS dt, \tag{5}$$

with Q as the AC losses per meter per cycle, p is the harmonic function period, S is the domain area, **J** is the current density, and t is time.

For linking the superconducting equipment to the power electrical system is used the coupling method developed in [1], [2]. To connect the high temperature superconducting (HTS) devices to the electrical power system, the HTS voltage is applied as an external source:

$$V_{HTS} = -\int_{c_{HTS}} \mathbf{E} \cdot \mathbf{dl} - \int_{c_{HTS}} \frac{\partial \mathbf{A}}{\partial t} \cdot \mathbf{dl}. \tag{6}$$

The c_{HTS} represents the contour of the superconducting devices. The constitutive relation on the superconductor computes the electric field (**E**).

Considering the superconducting tape presented in figure 1, where copper, silver, and substrate are considered as lumped parameters:

$$R_i = \rho_k \frac{l_{HTS}}{d_k.w_{HTS}}, \tag{7}$$

such that R_i is the resistance in the layer i, ρ_k is the resistivity, l_{HTS} is the tape length, d_k is the kth tape layer thickness, and w_{HTS} is the tape width.
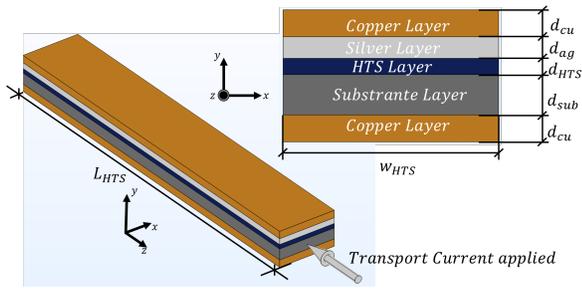
Fig. 1. Superconducting tape with all modelled layers.

According to [3], it is possible to represent the skin-effect of the thin conductor by means of a lumped inductance. This concept is associating with the coupling method [1]. The inductance between the layers k+1 and k is given as follows:

$$L_k = \mu \frac{d_i . l_{HTS}}{w_{HTS}}. \tag{8}$$

II. METHODOLOGY

A. T-A 1D with lumped parameters

In the T-A 1D formulation, the superconductor is the only layer modeled by the FEM model. The lumped parameters represent the other ones. Figure 1 shows the superconducting HTS tape layers. Applying the coupling method, the super-conducting layer can be linked to the metal layers. Figure 2 presents the circuit that represents the HTS coated conductor with all layers, and the finite element model created.
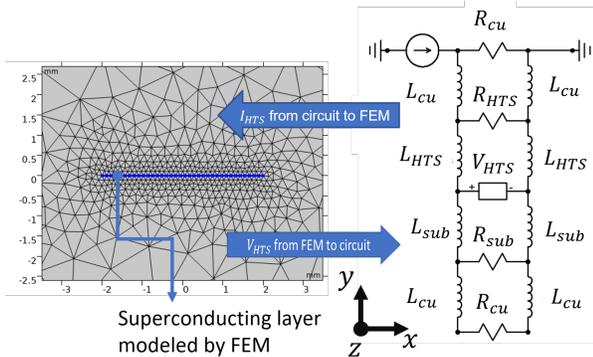
Fig. 2. HTS Coated Conductor modeled by FEM and coupling method.

A current source is connected to the upper cooper resistance. In the same resistance, on the other terminal, it places the ground. This schematic represents the real connections in the several experimental test performed on literature. It is important emphasize that in this modelling, the authors just consider the resistive part of the equation 6. Therefore, the effects of the self-inductance and the mutual inductance are disregarded, and equation 6 becomes:

$$V_{HTS} = - \int_{c_{HTS}} \mathbf{E} \cdot \mathbf{dl}. \tag{9}$$

III. RESULTS AND DISCUSSIONS

Figure 3 presents the comparisons of the losses per length for different formulations and in each layer. For the total losses, all formulations get similar results. Using the H-formulation as a reference, the copper layer losses in the T-A 1D formulation presented better results than T-A 2D. On the other hand, the T-A 2D computes the silver layer losses more precisely than the T-A 1D.
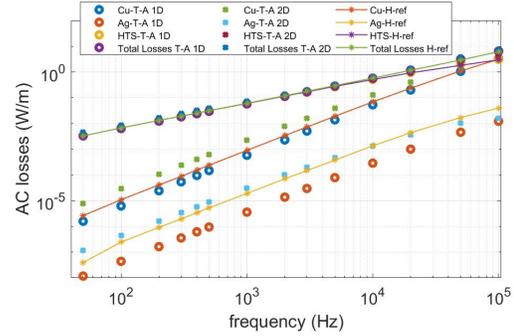
Fig. 3. HTS Coated Conductor losses for each layer.

To compare the total losses calculated by T-A 1D and by H-formulation, the error between formulation is computed as follows:

$$error = \frac{Q_{total}^{T-A1D} - Q_{total}^H}{Q_{total}^H}. \tag{10}$$

IV. CONCLUSION

The authors presented an original method to calculate the AC losses based on the T-A formulation. The proposed method was compared with the traditional H-formulation and presented a good agreement, with an error inferior to 8%. Moreover, the proposed method computes the losses in all layers of the coated conductors faster than H-formulation.

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