Models for optimization and AC Losses Analysis in a 2G HTS Cable

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Abstract. Finite element method (FEM) for both linear and nonlinear cases is widely used for solving time-dependent problems related to the geometrical configuration of electrical HTS devices and AC losses. This paper presents our FEM models used in the development of the HTS cables. Transient 3D FEM models have been developed for optimization of both coaxial and triaxial 2G HTS cables. In these models, only linear magnetic materials are considered. The transient 2D FEM model was developed and used for the calculation of AC losses in the cables made from 2G HTS tapes. The 2G HTS layer of the tape has strong nonlinearity between resistivity and current density and requires careful modeling. Also, it is important to determine the parameters in an empirical expression that describes the critical current density of the 2G HTS layer dependence from the vector magnetic field and its non-uniformity across the tape width.

1. Introduction
Several types of software based on the finite-element method (FEM) have been used to model the electromagnetic fields of electrical HTS devices [1,2]. One of them is ANSYS [3], for example [4-6]. The ANSYS includes Emag software for engineering simulation of the 3D and 2D transient electromagnetics in the electrical devices, where the magnetic vector potential formulation is implemented, which uses three degrees of freedom in the non-conducting regions, the magnetic vector potential components, and adds an extra degree of freedom, the time-integrated electric voltage, in the conducting regions (A-V-A formulation). ANSYS allows efficient mesh generation, post-processing, graphics window, optimization coupling, and so on.

The transient 3D FEM models using the ANSYS Emag software for complex study and optimization of both coaxial and triaxial 2G HTS cable have been developed. The transient 2D FEM model using this software for the calculation of AC losses in the cables made from the second generation HTS tapes (2G or Coated Conductors) was also developed. The models have been created with the help of APDL (ANSYS Parametric Design Language).

2. Models for geometry optimization of the HTS cables
The current distribution in the multi-layered cable for its geometry optimization can be easily analyzed with the electric circuit model. But for more detailed analysis two 3D FEM models have been also developed for geometry optimization of both coaxial and triaxial 2G HTS cable [7-9]. Only linear magnetic materials are considered in these models.
For geometry optimization the faster calculation of one variant of the geometry of the cable is needed, for this, the 3D FEM model with simpler geometrical configuration has been developed, in which layers of cable core and shielding of the coaxial cable or in which layers the phases of the triaxial cable are modeled by a system of thin concentric layers (cylinders), where all the layers are isolated from each other [7-9]. In the thin cylinders, the winding direction and twist pitch of the HTS tapes in the layers are modeled as the anisotropy of the electrical conductivity.

The electrical conductivity of the anisotropic thin conductor is a tensor of 2nd order, where all off-diagonal elements are zero. In coordinates $x', y', z'$ a tensor has the form:

$$\sigma = \begin{bmatrix} \sigma_{x'} & 0 & 0 \\ 0 & \sigma_{y'} & 0 \\ 0 & 0 & \sigma_{z'} \end{bmatrix},$$

where $\sigma_{x'} = \sigma_{y'} \neq \sigma_{z'}$ – electrical conductivity in the corresponding coordinates, $z'$ is a coordinate parallel to winding direction of the superconducting tape in the layer.

In this model, the optimized variables are the direction of electric conductivity $\sigma_{z'}$ for each cylinder.

The detailed 3D FEM model offers the possibility of modelling any topology of an HTS cable. So, the 3D model permits taking into account the spiral structure of a cable core and shielding layers to obtain current and magnetic field distribution inside of the cable. However, the problem is that the task is too complicated and takes a long computing time to perform calculations. Thus, the detailed 3D FEM model could be only used to test the optimized parameters of the cable.

In figure 1 and figure 2, the mesh elements of HTS layers of the tapes at the end part of the compact coaxial 2G HTS power cable [7-8] and the triaxial cable [9] in detailed 3D models are shown. 10 mesh elements across the HTS tape width of the tapes were used. The coaxial cable consists of four layers in the core and two layers in the HTS shield, the triaxial cable consists of two layers per phase. Only ten mesh elements across the HTS layer width of the tapes were used.

**Figure 1.** The mesh elements of the HTS layers of the tapes of the end part of the cable (4-layer core and the 2-layer shield) in the detailed 3D FEM model.

**Figure 2.** The mesh elements of the HTS layers of the tapes in the detailed 3D FEM model of the layers of the HTS tapes on the end part of the triaxial cable. Letters A, B, C indicate the phases of the cable.

The optimization time of geometry of cables by the first FEM model is several hours. The gradient method was used for this task. The calculation by the detailed FEM model with optimal parameters of one variant of the cable geometry also requires approximately equal time.

All of the calculations were performed on the computer based on the 3.70 GHz Intel® Core™ i9-4960X CPU and 64GB of RAM.

After modelling and optimization of the geometry, the prototypes of the cables were manufactured and electrical tests were carried out [7-9]. As a result of optimization, the uniform current distribution has
been demonstrated in the coaxial cable (4-layer core and the 2-layer shield) and in a triaxial HTS cable, each phase of which consists of two layers.

3. Model to analyse AC losses in the cable

The AC losses in an HTS device consist of hysteresis losses caused by the penetration of the magnetic flux in the superconducting material, hysteresis losses in magnetic materials, and eddy current losses in the normal metal parts of the HTS device. ANSYS can calculate eddy current distribution in any conventional conductors without taking into account the nonlinear resistivity. In addition, ANSYS is able to solve processes for real nonlinear anisotropic magnetic materials, as there is a capability for modelling B-H curves and therefore, the hysteresis losses in the magnetic materials can be calculated. For example, we used the detailed 3D model for the calculation of hysteresis losses only in the ferromagnetic NiW substrate of the 2G HTS tapes of the power cable [10], with only 4 mesh elements across the HTS tape width of the tapes used.

3.1. Hysteresis losses in the 2G HTS layers of the tape of the cable

For the realization of the possibility to calculate hysteresis losses in the 2G HTS layer, the FEM model using ANSYS should include the strong nonlinearity between resistivity and current density of the superconductor. This can be realized by the resistivity adaptation algorithm (RAA) [11], which is the iteration algorithm based on the fact that the field penetration into the superconductor can be always simulated by solving eddy current distribution in a conventional conductor divided into elements that have local resistivity. Mainly due to high the nonlinear resistivity of the HTS materials (a large number of iterations are required), and because of the high aspect ratio of the 2G HTS layer (a large number of small elements in the mesh), the simulation of the hysteresis losses in the superconducting material is the most difficult task that requires long calculation time and demands large computer memory.

The 2D model must be used to drastically reduce the time and complexity of the calculation of the hysteresis losses. In the 2D model, we consider the full cross-section of the cable, considering its polygonal structure. For the correct calculation of the penetration of the magnetic flux in the superconducting material, the HTS layer was meshed with nonuniform (less computational time) quadrilateral-shaped elements across the HTS layer width (fine mesh is located only on the edge of the HTS layer). The number of mesh elements in the HTS layer (N) = 300. After the FEM model in ANSYS was built and the initial value of resistivity for each (i) element of the HTS layer ($\rho_i^0$) was set, it is possible compute the currents density ($J_i^0$) in each element. Then the resistivity in each element is iteratively changed (successive substitutions) according to the relation expressing the nonlinearity between resistivity ($\rho$) and current density ($J$) of the superconductor. We used the power law relation:

$$\rho_i^0, \quad \rho_i^{k+1} = f(\rho_i^k) = \frac{E_0}{J_{c,i}} \left( \frac{J_i^k}{J_{c,i}} \right)^n, \quad (2)$$

where $E_0 = 1\mu$V/cm is the electric field, when the critical current density is reached, and $n$ is a power law index, $J_{c,i}$ is the critical currents density in the each element.

Stopping criterion for the resistivity is

$$\frac{\rho_i^{k+1} - \rho_i^k}{\rho_i^k} < \zeta.$$  

The appropriate minimum initial values of $\rho_i^0$ are $10^{-17} \Omega\cdot m$ and $\zeta$ is $10^{-4}$.

While using power law relation (2) for the resistivity at $k+1$-th iteration $\rho_i^{k+1}$ it is better to calculate this equation with the relaxation factor $\alpha = 0.1$:

$$\rho_i^{k+1} = \rho_i^k + \alpha \left( \rho_i^{k+1} - \rho_i^k \right). \quad (3)$$
The AC losses in the HTS layers are hysteresis losses, so it means they, being recalculated per cycle, do not depend on frequency, and after all iterations, the losses in the HTS layer (with cross section \( S \)) per unit length and per cycle are given by:

\[
Q = 4 \cdot \int_0^T \int_S \rho dS d\tau = 4 \cdot \sum_{i}^{N_i} \tau_i \sum_{i}^{N} J_i^2 \rho_i \zeta_i, \tag{4}
\]

where \( N_i \) - number of step in time-dependent solution from 0 to maximal value \( T_m \) of the applied transport current \( I_m \) (1/4 total cycle), \( S_i \) - the cross section of each element of the HTS layer, \( \Delta \tau \) - time step.

For the correct calculation of the AC losses, it is also important to determine the parameters in an empirical expression that describes the dependence of the critical current density of the 2G HTS tapes from a vector magnetic field and its non-uniformity across the tape width. The following expression was used [12]:

\[
J_c (B, \theta, x) = J_c (B, \theta) \cdot J_{c0} (x) = \frac{\alpha J_{c0} (x)}{1 + \left(k^2 \cos^2 (\theta) + \sin^2 (\theta)\right)^{0.5} \frac{B}{B_0}}^\beta, \tag{5}
\]

where \( J_{c0} (x) \) describes the non-uniformity of critical current density at zero magnetic field across the HTS layer, \( \theta \) is an orientation angle of magnetic field with respect to the tape normal, \( k, B_0 \) and \( \beta \) are the parameters used here for fitting, \( \alpha \) - accounts the fact that critical current of the tape \( (I_c) \) is derived from measurements with the self-field of the tape.

For the engineering simulation of the losses, the further increase of the computational speed of the FEM model is desired, so the following standard methods should be used:

- The “Bean model” assumption.
  The following function for the resistivity at \( k+1 \)-th iteration for each \( (i) \) mesh element can be used:

\[
\rho_i^{k+1} = \rho_i^k \frac{J_i^k}{J_{c,i}}, \tag{6}
\]

- For an superconductor that obeys the “Bean model” the losses are uniquely determined by the current density profiles in the HTS layers at the maximal magnitude \( (I_m) \) of the applied current, it gives possible to make only one step in time-dependent solution and decrease time of calculation, and as shown in [13] the losses can be calculated from equation:

\[
Q = 4 \cdot \int_S \Psi ds, \quad \Psi \text{ is the flux between an arbitrary point of the superconductor and "kernel".}
\]

“Kernel” is a location or line inside the superconductor where the electric field stays zero throughout the AC cycle [13] and the location where \( J \neq J_c \) and \( B = 0 \) [5]. And for magnetic vector potential approach \( \Psi = \oint A dl \) for calculation the losses in the HTS layer per unit length and per cycle can used the equation:

\[
Q = 4 \cdot \sum_{i}^{N_i} J_i \left(A_{z,i} - A_{z,0}\right) S_i, \tag{7}
\]

where \( A_{z,i} \) is the magnetic vector potential at a node of each \( (i) \) mesh elements, \( A_{z,0} \) is the magnetic vector potential at a node near of the “kernel”.

The maximum number of iterations can be reduced by an order of magnitude by use of “Bean model” assumption and number of iterations is about 5-40 to achieve convergence (\( \zeta \) is \( 10^{-4} \)) for calculation of the AC losses at the applied transport current.
Also, for acceleration of convergence for function in form $\rho = f(\rho)$ instead of successive substitution method [14] the Wegstein method [15] can be used, which is easy to implement in the FEM model.

\[
\rho_i^0, \quad \rho_i^1 = f(\rho_i^0) \\
\rho_i^{k+1} = f(\rho_i^k) + \frac{(f(\rho_i^k) - f(\rho_i^{k-1})) \cdot (f(\rho_i^k) - \rho_i^k)}{(f(\rho_i^k) - f(\rho_i^{k-1})) - (\rho_i^k - \rho_i^{k-1})}, \quad k \geq 2
\]  

This method is a two-step one, and to start the calculations, two initial approximations are required. Wegstein’s method converges slower than, for example, the Aitken’s delta-squared method [16], however, it requires only one ANSYS calculation per iteration of the current density in each element of the HTS layer and, as a result of this, it turns out to have a less computation time.

An example of the calculated distribution of a current density in the HTS layers of a cable at the moment when the peak current equals 70 A, is presented in figure 3. The distribution of magnetic field in some tapes of the core at the same moment is presented in figure 4 (also one can see the mesh elements of HTS tape). The 2G HTS tapes produced by SuperOx Company [7] with the total thickness of the tapes $\sim 0.105$ mm were used for the cable. In order to reduce the polygonality of the layers in the core, we used the HTS tapes with 3 mm width. The average critical current of these tapes in the self-field at 77.4K is $\sim 80$ A. For the shield, we used the 2G HTS tapes with 4 mm width. Their average critical current in self-field at 77.4K is $\sim 120$ A.

Figure 3. The current density distribution in the HTS layers of the cable (4-layer core and the 2-layer shield).  
Figure 4. Distribution of the magnetic field in the selected tapes of the core. (Also one can see the mesh elements of HTS tape).  

Figure 5 illustrates the calculated losses by the Norris models and by the FEM model in the layers of the core of the cable. The losses per one tape and per meter are shown as a function of ratio $I/I_c$ for the cable core. The calculated losses by the FEM model are close to the measured data [7]. The computation time of this result by the FEM model is about an hour. The calculations were performed on the same computer (see paragraph 2).
Figure 5. Calculated losses with Norris model and by FEM model in layers of the core of the cable versus ratio $I/I_c$.

4. Conclusion

This paper presents two transient ANSYS 3D FEM models to optimize the design of the HTS power cables. The first 3D FEM model has a simpler geometrical configuration of a cable and takes a small amount of computing time to perform calculations of one variant of a geometry of a cable. The second detailed 3D FEM model offers the possibility of modelling any topology of an HTS cable. However, the problem is that the task is too complicated and takes a long computational time to perform calculations. The first 3D FEM model was used for optimization, and the second one was used to test and verify the optimized parameters of the cable and to obtain current and magnetic field distribution inside of the cable. As a result of such two-step modelling, the uniform current distribution has been demonstrated in the coaxial cable (4-layer core and the 2-layer shield) and in a triaxial HTS cable, each phase of which consists of two layers.

In this work we also present the transient ANSYS 2D FEM model to simulate the AC losses in the cables made from 2G HTS tape. For the realization of the possibility to calculate hysteresis losses in the 2G HTS layer of the tape of the cable, the FEM model uses the iteration algorithm. To decrease the computational time of the FEM model, the well-known “Bean model” assumption was used.

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