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

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***Abstract*— Numerical methods can handle any geometrical configuration, time-depending problems and both linear and non-linear cases. Two 3D FEM models were developed in the Russian Cable Institute to optimize both coaxial and triaxial 2G HTS cables. In addition, with the help of the 3D FEM model, we can calculate the hysteresis losses in a NiW substrate of 2G HTS tapes of the cable. The transient 2D FEM model was developed and used for calculation of AC losses in the cables and stacks of 2G HTS tapes. For the correct calculation of the AC losses, it is important to determine the parameters in an empirical expression describing critical current density of the 2G HTS tapes dependence from the vector magnetic field and its non-uniformity across the tape width. In this work, the described above FEM models are briefly presented.**

Keywords—2G HTS cables, AC losses, optimization

I. Introduction

Several software based on the finite-element method (FEM) have been used to model the electromagnetic fields of electrical HTS devices. One of them is ANSYS, it implements the magnetic vector potential formulation, 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. The FEM models using the ANSYS Emag software for solving the transient electromagnetic problem for complex study (optimization and AC losses) of the 2G HTS cable had been developed.

II. Modeling of the coaxial cable

A. Optimization of the cable layout

For faster calculations necessary for the optimization of the cables, the 3D FEM model with simple geometrical configuration has been developed. In this model, a cable core and a shielding layer are modeled by a system of thin concentric layers (cylinders) where all the layers are isolated from each other. In superconducting thin cylinders, the optimized variables (the winding direction and twisting pitch of the HTS tapes) are modeled with help of the anisotropy of the electrical conductivity of each cylinder.

The detailed 3D FEM model was used to verify the result of the optimization. This model offers the possibility to model any topology of an HTS cable. The model allows to consider the spiral structure of a cable core and shielding layers to obtain current and detailed magnetic field distribution inside a cable. In Fig. 1, the mesh elements of HTS layers of the tapes of the end part of compact 2G HTS power cable [1] in detailed 3D model is shown. The cable consists of four layers in the core and two layers in the HTS shield. Only ten mesh elements across the HTS layer width of the tapes were used.

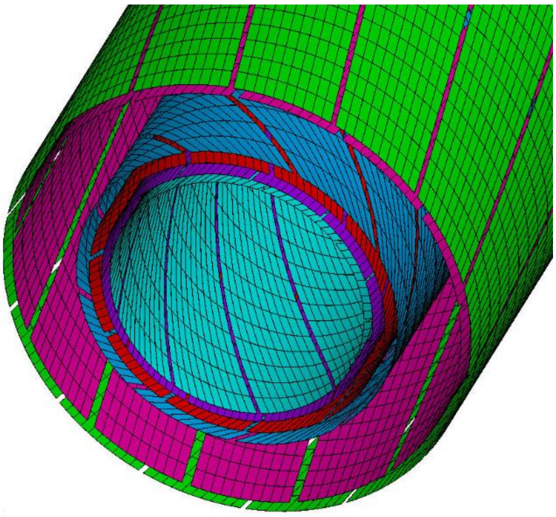

Fig. 1. The elements of HTS layers of the tapes of end part of the cable (4-layers core and the 2-layers shield) in detailed 3D FEM model.

B. Model to analyse AC losses

The AC losses in a 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 modeling B-H curves and therefore, the hysteresis losses in the magnetic materials can be calculated. For example, we used the 3D model for the calculation of hysteresis losses in a NiW substrate of the 2G HTS tapes of the power cable [2].

For the realization of the possibility to calculate hysteresis losses in the 2G HTS layer, the FEM model using ANSYS should to include the strong nonlinearity between resistivity and current density of the superconductor. This can be realized by iteration algorithm, which is 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 2G HTS layer (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 2-D model must be used to drastically reduce time and complexity of calculation of the hysteresis losses. Now in the 2-D model, we consider the total cross-section of the cable, taking into account its polygonal structure. For the correct calculation of the penetration of the magnetic flux in the superconducting material, the HTS layer was meshed with 300 nonuniform quadrilateral-shaped elements across the HTS layer width.

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:

$$J_c\left(\vec{B},x\right)=\frac{\alpha J_{c0}\left(x\right)}{\left(1+\left(k^2\cos^2(\theta)+\sin^2(\theta)\right)^{0.5}\frac{B}{B_0}\right)^{\beta}} \quad (1)$$

where θ is an orientation angle of magnetic field with respect to the tape normal, k, B_0 and β are the parameters used here for the $J_c(B,\theta)$ fitting, α - accounts the fact that critical current of the tape (I_c) is derived from measurements with the self-field of the tape.

For engineering simulation of the losses, the further increase of the computational speed of the FEM model is needed, so the following standard optimization methods were used:

- The ‘‘Bean model’’ assumption.
- For acceleration of convergence - Wegstein method.
- The AC losses in HTS layers are hysteresis losses, so it means they do not depend on frequency. The losses are uniquely determined by the current density profiles in the HTS layers at the maximal magnitude of the applied current. Losses independence from frequency makes it possible to make only one step in time-dependent solution at I_m. This means that $\Delta\tau$ = 1/4 total cycle. Thus the vector potential approach for calculation of the hysteresis losses can be used.

Using these methods, the maximum number of iterations can be reduced by an order of magnitude.

An example of the calculated distribution of a current density in the HTS layers of cable, at the moment when the peak current equals 80 A, is presented in Fig. 2.

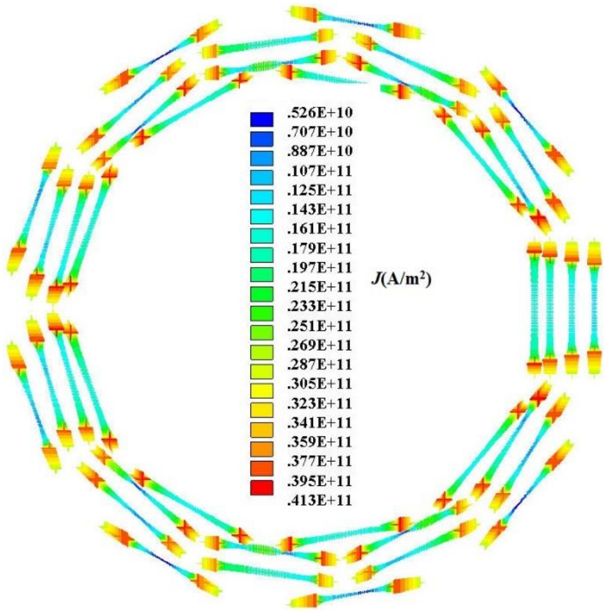

Fig. 2. The current density distribution in the HTS layers of the tape of the core of the cable at the moment when the instantaneous value of a transport current is 80A.

III. Modeling of the triaxial cable

For achieving the high current density in the triaxial cable cables, a multilayer structure for each phase is required. We have developed the cable prototype with two layers per phase made with ReBaCuO tape recently. The optimal parameters of the cable have been determined using 3D FEM models. Results of modeling and testing of the this triaxial cable will be presented at ASC-2020.

IV. Conclusion

The main disadvantage of the licensed software is long time of calculation of the detailed 3D FEM models. This limitation can be overcame by the use of some open-source software products [3] that usually do not suffer from such shortcomings because of the possibility of changing the mathematical models of the investigated processes and a wide choice of algorithms and methods for generating finite element meshes, analyzing their quality, optimizing for different criteria, and subsequent solving of systems of linear equations.

References

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