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Effective 3-D FEM for large-scale high temperature superconducting racetrack coil

Xiangyu Huang[a], Zhen Huang[*,a], Xiaoyong Xu[a], Wan Li[b], and Zhijian Jin[a]

[a] *School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China.*
[b] *Shanghai Marine Equipment Research Institute, Shanghai, China*

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Abstract

In various types of large-scale electrical applications, the number of coil turns in such machines is usually large. Electromagnetic simulation of large-scale superconducting coils (tens to hundreds of turns) is indispensable in the design process of superconducting electrical equipment. However, due to the large scale of the coil and the large aspect ratio of super-conducting material layer in HTS coated conductor, it is usually difficult or even unable to perform 3-D transient electromagnetic simulation. This paper introduces an effective 3-D electromagnetic simulation method for large-scale HTS coated conductor coil based on T-A formulation. The simulation and experimental results show that the 3-D model based on the T-A formulation using homogeneous strategy is more accurate than the traditional 2-D models. The memory usage is not sensitive to the number of turns and this model will be even more superior as the number of turns becomes larger.

Keywords: AC loss, FEM, large-scale racetrack coil, T-A formulation

1. INTRODUCTION

The second-generation high temperature superconductor (HTS) has high current carrying ability, high critical temperature and better in-field performance. The advantages above make YBCO tapes widely used in large-scale superconducting electrical equipment such as superconducting transformer [1], superconducting motor [2] and superconducting generator [3].

The performance of superconducting coils is the key factor determining the performance of the superconducting electrical equipment. Accurately evaluating AC loss before manufacturing coils is an important step to ensure safe operation of the coils in the designed operating environment. Generally, in order to generate a large magnetic field strength in a large-scale superconducting electrical equipment, the HTS coil often has tens or even hundreds of turns, which results in a large scale of the 3-D model. The calculation time is usually too long or even a convergent solution cannot be gotten.

Based on the above questions, H formulation and T-A formulation are proposed for the FEM simulation of superconductors [4]. The H formulation is another form of Max-well's equations with the magnetic strength as an independent variable. It is widely used and has been validated by experimental results [5]. Modeling each superconductor with a very large aspect ratio is needed in FEM models. When simulating the common multi-turn coil, the calculation speed is slow, so, paper [6] proposes a homogenous method. The air and other layers such as substrate layers between adjacent superconducting layers are washed out and the HTS tapes are simplified into a bulk. This method not only greatly speeds up the calculation speed but ensures a precise estimation of AC loss.

The T-A formulation is a newly proposed simulation model by solving the T-formulation in the superconducting layer and the A-formulation in the region outside the superconducting layer. The accuracy of this model is verified by the analytical Norris model [7]. The solution speed of T-A formulation model is much faster than that of the H formulation model due to simplifying thin coated conductor into zero-thickness domain [8]. The T-A formulation can also be used to simulate complex 3-D geometries like CORC cables [9], [10], etc. efficiently.

The target of this article is to introduce an effective 3-D FEM model for large-scale racetrack coil commonly used in HTS applications which has both arc and straight parts. The proposed method solves the problems where 2-D models are not close to physical reality and lack of accuracy. In section 2, the 3-D T-A formulation model using homogeneous strategy will be introduced. In section 3, the parameters of the multi-turn double racetrack coil and AC loss experimental set-up are introduced. In section 4, the experimental and FEM results of AC loss and magnetic field distribution are compared. Then, research on the performance of 2-D and 3-D large-scale coil FEM models is conducted. Finally, the conclusion is drawn in section 5.

2. FORMULATION AND MODEL

To consider the complex anisotropy of YBCO tape in

* Corresponding author: zhen.huang@sjtu.edu.cn

our numerical model, the relationship between the critical current density and the magnetic flux density used here is [9]:

$$J_c(B)=J_c(B_{par},B_{per})=\frac{J_{c0}}{(1+\sqrt{(kB_{par})^2+B_{per}{}^2}/B_c)^b} \quad (1)$$

where B_{par} and B_{per} represent the magnetic field component parallel and perpendicular to the tape surface respectively. J_{c0} is the self-field critical current density. b, k and B_c are the critical current curve fitting parameters.

The constitutive relationship between electric field strength and current density in the superconducting domain is modeled by the so-called E-J power law relation [11]：

$$E(J)=\frac{E_0 J}{J_c(B)}\left|\frac{J}{J_c(B)}\right|^{(N-1)} \quad (2)$$

where E_0 is the critical electrical field which is usually set as 10^{-4} V/m. N is the curve fitting parameter.

2.1. T-A formulation

The key idea of the T-A formulation is to divide the solving domain into two parts: 'superconducting-domain' (1-D lines for 2-D models and 2-D bands for 3-D models ignoring the thickness of the thin HTS coated conductor) and 'non-superconducting-domain'.

The current density vector potential T is defined in the 'superconducting-domain' to solve the current density distribution in the HTS coated conductor:

$$J=\nabla\times T \quad (3)$$

The magnetic vector potential A is defined in the 'non-superconducting-domain' to solve the magnetic flux density distribution in the domain outside HTS coated conductor:

$$B=\nabla\times A \quad (4)$$

The boundary condition for T-formulation is set according to the current value flowing in the coil:

$$I_0=\iint_S JdS=\iint_S \nabla\times TdS=\oint_{\partial S} T_t dl \quad (5)$$

where I_0 is the value of the transport current. S is the cross-section of the conductor and dS is its micro-element. ∂S is the boundary of the cross-section of the conductor and dl is its micro-element. T_t is the tangential component of the current density vector potential.

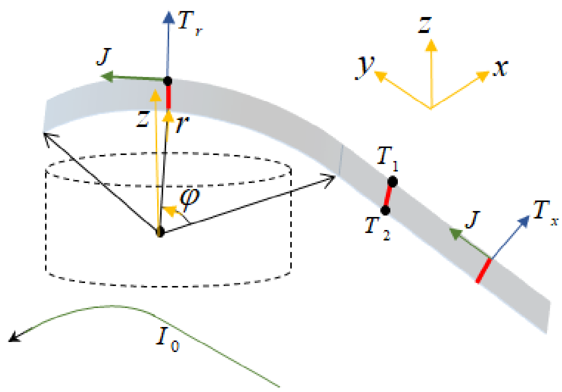

Fig. 1. Schematic diagram of 3-D T-A formulation for racetrack coil.

2.2. 3-D T-A Full Model

For 3-D racetrack coil model, the governing equations of the T-formulation and the boundary conditions need to be analyzed in two parts: straight and arc parts of the coil. Since the HTS tape is thin band conductor, the 3-D HTS coated conductor is simplified into a 2-D band ignoring the current density distribution in the thickness direction as shown in Fig. 1. The direction of T is consistent with the direction of the thin shell HTS conductor plane normal vector because the current only flows in the thin shell conductor plane. Corresponding T-formulation of straight part for (3) is (6) and (7), and the boundary condition of straight part for (5) is (8) [7] [8]:

$$J_y=\frac{\partial T_x}{\partial z} \quad (6)$$

$$J_z=-\frac{\partial T_x}{\partial y} \quad (7)$$

$$(T_{1x}-T_{2x})\cdot d=I_0 \quad (8)$$

where, T_1 and T_2 are the current density vector potential of the boundary. J is current density and d is the thickness of the HTS layer.

In order to simplify the description of the derivation process, we define cylindrical coordinate system for the arc part. The coordinate origin is set in the center of the arc as shown in Fig. 1. Corresponding T-formulation and boundary condition of φ micro-element of arc part are:

$$J_\varphi=\frac{\partial T_r}{\partial z} \quad (9)$$

$$J_z=-\frac{\partial T_r}{r\partial\varphi} \quad (10)$$

$$(T_{1r}-T_{2r})\cdot d=I_0 \quad (11)$$

The boundary condition for the two parts have the same form:

$$(T_1-T_2)\cdot d=I_0 \quad (12)$$

The Faraday's law for the straight part of the racetrack coil is:

$$\frac{\partial E_z}{\partial y}-\frac{\partial E_y}{\partial z}=-\frac{\partial B_x}{\partial t} \quad (13)$$

Using the same cylindrical coordinate system, we can know that the Faraday's law for the arc part of the racetrack coil is:

$$\frac{\partial E_z}{r\partial\varphi}-\frac{\partial E_\varphi}{\partial z}=-\frac{\partial B_r}{\partial t} \quad (14)$$

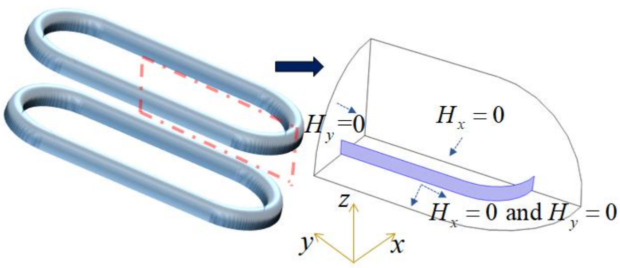

Fig. 2. Schematic diagram of symmetric conditions in three symmetric planes for 1/8 double racetrack coil model.

The 3-D FEM model mentioned in this paper use symmetric boundary conditions to simplify the double racetrack coil into one-eighth model to accelerate the simulation process [12]. Fig. 2 shows the three symmetric planes and corresponding symmetric boundary conditions of the 1/8 double racetrack coil model.

2.3. 3-D T-A Homogenized Model

The homogeneous method is suitable for such cases combined: 1) the current almost only flows in superconductor layer; 2) substrate layers use non-magnetic material; 3) the eddy current loss can be neglected; 4) the coil has too many turns making simulation time-consuming and memory-consuming. This method ignores all other layers and air between adjacent superconducting layers. Rationality builds on two premises which have been validated [6]. First, relative permeability of all materials in HTS tape is equivalent, which means they are ‘magnetic homogeneous’. Second, for the large-scale coil, if the gap between adjacent turns is ignored, the current density and magnetic field will still have similar distributions compared to the full model.

For 2-D T-A homogeneous models, the equivalent 2-D superconductor bulk is filled with densely packed tapes having an infinitesimal thickness (1-D lines). As seen in Fig. 3(a), the boundary condition is set in the two black end edges of the equivalent 2-D bulk instead of the 2*n* black end points in each turn [13].

For 3-D T-A homogeneous models, the difference is that the equivalent 3-D superconductor bulk is filled with densely packed bands having an infinitesimal thickness (2-D bands). As seen in Fig. 3(b), the boundary condition is set in the two black end faces of the equivalent 3-D bulk instead of the 2*n* black end edges in each turn.

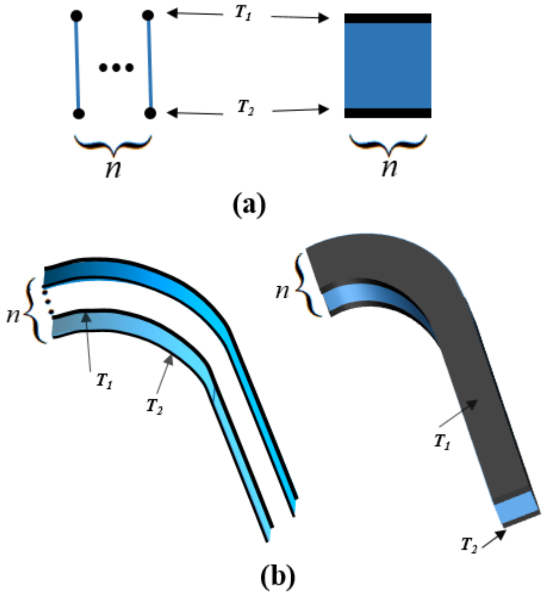

Fig. 3. Schematic diagram for 2-D and 3-D T-A homogeneous model. T_1 and T_2 are boundary conditions for T-formulation. (a) 2-D full *n*-turn (left) and 2-D homogeneous *n*-turn model (right). (b) 3-D full *n*-turn (left) and 3-D homogeneous *n*-turn model (right).

In the homogeneous model, since the superconducting domain has been extended, the critical current density needs to be converted into engineering critical current density [6]:

$$J_{c\_e}(B) = V_f J_c(B) \tag{15}$$

where $J_{c\_e}(B)$ is the engineering critical current density. V_f is the volume factor, i.e. the volume of all superconducting layers in the coil divided by the equivalent 3-D superconducting bulk.

The boundary condition for the 3-D T-A homogeneous model is changed into:

$$(T_1 - T_2) \cdot d = V_f I_0 \tag{16}$$

Except for the boundary condition for T-formulation, other equations are the same as the full model.

All FEM models discussed in this paper were run in COMSOL Multiphysics 5.4. The air domain closes to the coil uses finer mesh while the air domain away from the coil uses coarser mesh to achieve both fast calculation speed and high accuracy [14].

The T-formulation is implemented by coefficient form PDE module using first order Lagrange elements and the A-formulation is implemented by magnetic field module using second order Lagrange elements. The selection of the order of elements for T-A formulation should consider the spurious oscillations phenomena in current density [13]. The H formulation is implemented by general form PDE module using first order curl elements.

The AC loss power of the whole coil can be calculated using the power density integration [15] in the superconducting homogeneous domain:

$$Q_{AC\_loss} = \frac{2}{T}\int_{0.5T}^{T}\int_{\Omega} E \cdot J d\Omega dt \tag{17}$$

where T is the period of the cycle and Ω is the superconducting homogeneous domain.

3. COIL AND EXPERIMENT

3.1. Double racetrack coil

The 86-turn HTS double racetrack coil that will be used in the semi-superconducting synchronous generator project (i.e. HTS coils are on the armature) is used as a verification coil for the 3-D T-A homogenous model. The HTS tapes are supplied by Shanghai Superconductor Technology Company (SSTC). Before winding the coil, the *V-I* curve of the HTS tape was measured to guarantee the performance of the tape and get the critical current value and the *N* value of the tape. The overall picture of the racetrack coil is shown in Fig. 4, and the parameters of the HTS double racetrack coil are summarized in table I.

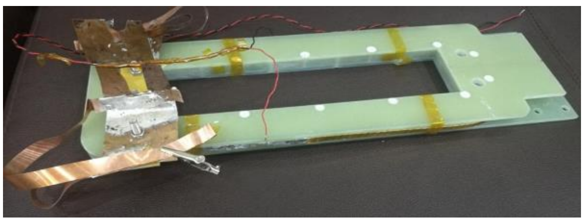

Fig. 4. Overall picture of the double racetrack coil.

TABLE I
COIL PARAMTERS.

Parameter	Value
Tape	YBCO
Manufacturer	SSTC
Tape thickness	1 um
Tape width	4 mm
Substrate material	Hastelloy
N	28
Critical current (77 K, self-field)	205 A
b	1.05795
k	0.0605
B_c	0.1942 T
Turns	86
Inner/outer radius of the coil	37 / 54.2 mm
Straight length	244 mm
Total length of HTS tapes	66 m

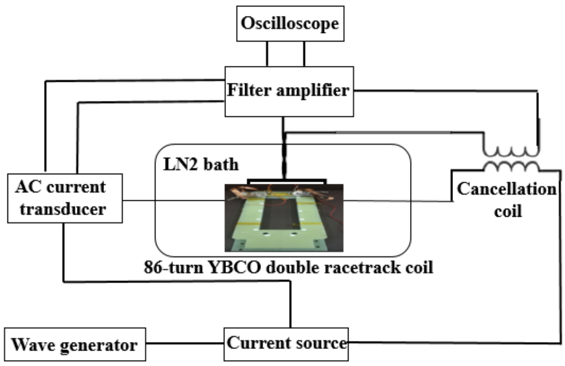

Fig. 5. Schematic of the experimental system for ac loss measurement.

3.2. AC loss experiments

The transport AC loss measurement experiment set-up is based on the electrical method. As can be seen from Fig. 5, the coil is bathed in LN2 (77 K) during the experiment. The wave generator is used to produce the transport current which is 50 Hz sine wave in our experiment. Using the cancellation coil, the resistive component of coil voltage can be gotten. Filter amplifier can amplify the tiny resistive component voltage and filter the high frequency interference signal. The wave can be observed on the oscilloscope. We can calculate the transport AC loss power of coil by [16]:

$$Q_{AC\_loss} = V_{rms} I_{rms} f \tag{18}$$

where V_{rms}, I_{rms} and f are the effective value of the resistive voltage component, rms value of the transport current and frequency of the transport current, respectively. The critical current of the coil is 105 A, so the maximum peak value of transport current in this experiment is set as 65 A to prevent hurting the coil.

4. RESULTS AND DISCUSSIONS

4.1. Comparison of AC loss results of experiment and model

Total AC loss estimation results of different FEM models together with the experimental results are shown in Fig. 6. The figure shows that for 2-D FEM models [4] [6], the AC loss estimation values are almost the same. When the transport current is relatively low, the results of experiment and FEM models show discrepancy. This discrepancy can be caused by many reasons like the experimental measurement error and the non-uniformity of the tape along the length caused by complicated HTS tape production process [17].

As the transport current becomes larger, the AC loss becomes larger and the experimental measurement error will relatively have lower influence. When the transport current becomes larger, the experimental data fits better with 3-D T-A homogeneous model than 2-D models. The 2-D model tends to underestimate the AC loss value of the double racetrack coil. This discrepancy between 2-D and 3-D FEM model happening in larger transport current should not be ignored because the HTS coil used in large-scale electrical application is usually designed in larger current to maximize the use of high current carrying properties of HTS materials and the AC loss value needs to be considered precisely for the safe operation.

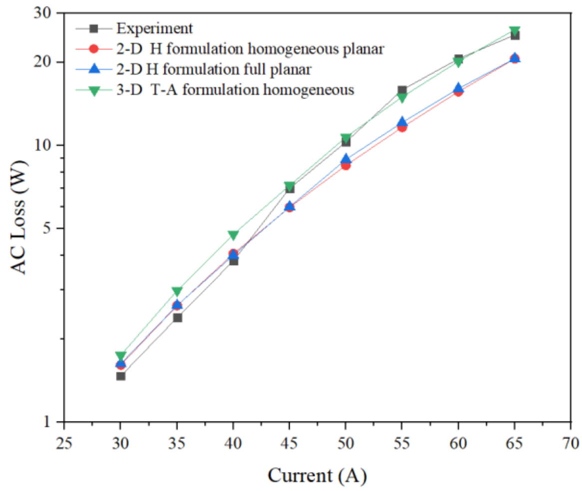

Fig. 6. AC loss value comparison between experiment and FEM models.

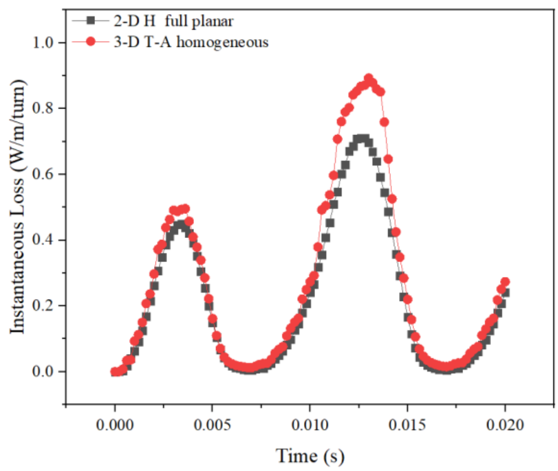

Fig. 7. Average instantaneous AC loss of FEM models.

Fig. 7 shows the average instantaneous AC loss of the racetrack coil calculated by the 3-D and 2-D model in 65A case. The average instantaneous AC loss of the coil calculated by the 3-D T-A homogeneous model is larger than that of the 2-D model.

The reason for this phenomenon is mainly due to two reasons. First, for large-scale racetrack coil, the complex geometry having both straight and arc parts and the complex anisotropy of the YBCO tape combined result in 2-D FEM model not applicable. The 3-D FEM model is necessary if more accurate results and more electromagnetic details close to physical reality are needed. Second, comparing to 2-D models, only in 3-D model can the current density in the direction of the width of the tapes be considered (the z-axis direction in Fig. 1). The consideration of the current density in this direction in 3-D model will cause the AC loss estimation value larger and the experiment values prove that this consideration is more reasonable and necessary if we want high precision results.

4.2. Comparison of magnetic flux density distribution of FEM models

To further investigate the electromagnetic property of the racetrack coil, the magnetic flux density distribution of 2-D and 3-D FEM models will be compared and discussed.

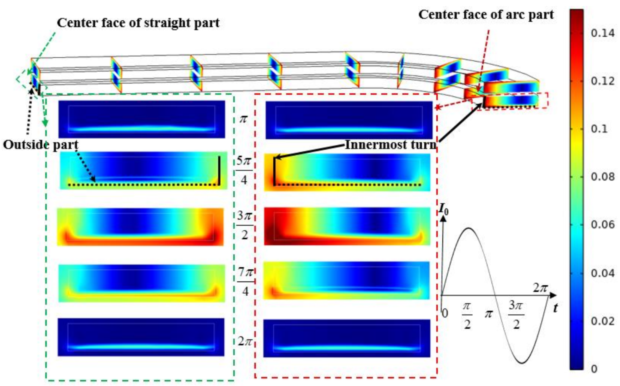

Fig. 8. Magnetic flux density magnitude distribution for half AC cycle in 65 A 3-D T-A homogeneous case. Results shown at different phase values: from pi to 2pi in pi/4 increments. The meaning of each phase value is explained by the transport current sinusoidal waveform in the figure.

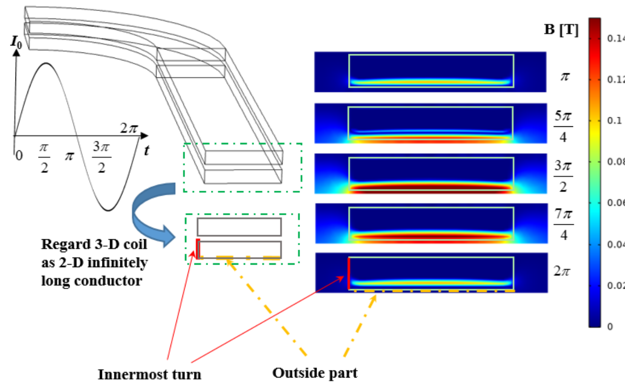

Fig. 9. Magnetic flux density magnitude distribution for half AC cycle in 65 A 2-D H homogeneous case. Results shown at different phase values: from pi to 2pi in pi/4 increments. The meaning of each phase value is explained by the transport current sinusoidal waveform in the figure.

In Fig. 8, the magnetic flux density magnitude distribution for half AC cycle in 3-D T-A homogeneous 65 A case is shown. The innermost turn of both arc and straight parts is under the largest magnetic flux density magnitude among all turns. For each turn of the coil, the outside end exposes to the largest magnetic flux density magnitude along the width direction of YBCO tape. In overall view, the arc and straight parts have similar distribution of magnetic flux density magnitude while the arc part has larger average magnetic flux density magnitude. However, in 2-D H formulation homogeneous 65 A case which is shown in Fig. 9, such detailed message cannot be shown resulting in lower AC loss estimation than the 3-D FEM model. The 2-D H formulation model only regards the racetrack coil as infinitely long conductor causing the magnetic field distribution symmetry: the innermost and the outermost turn have no difference.

The AC loss value is influenced by many factors combined: coil geometry structure, magnetic field distribution and the performance of the tapes. In short, the proposed 3-D T-A homogeneous FEM model is a kind of valuable tool for its ability showing complex electromagnetic details. The only obvious disadvantage is that the calculating time of the 3-D T-A homogeneous FEM model is longer than 2-D FEM models. For example, the time needed for 3-D T-A homogeneous and 2-D H homogeneous 65 A case is 37289 s (about 10.5 hours) and 361 s (about 6 minutes) respectively.

4.3. Performance of FEM models for large-scale coil

Furthermore, another superiority in 3-D FEM simulation of large-scale racetrack coil will be shown in this section. The 2-D and 3-D FEM simulations of large-scale double racetrack coil are conducted. These cases have 200 to 2000 turns and all other coil parameters are the same as the experiment coil. The 86 turns 30 A FEM case shown in Fig. 6 is also added. The transport current is sine wave with peak value of 30 A and frequency of 50 Hz.

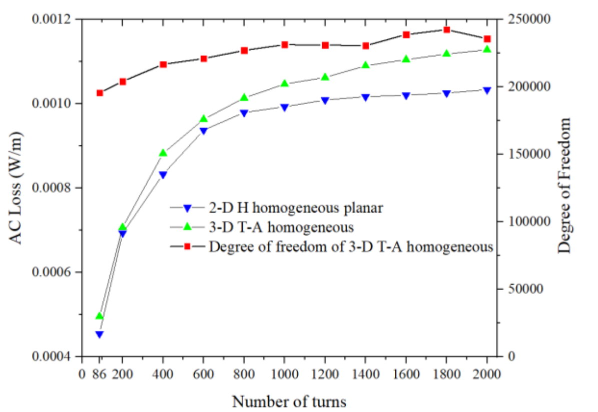

Fig. 10. Relation between degrees of freedom and AC loss per meter with the number of turns of large-scale racetrack coil.

Fig. 10 shows the relations between the degrees of freedom together with AC loss per meter and the number of turns of large-scale double racetrack coil. The deviance between 2-D and 3-D models becomes larger as the number of turns increase. Such phenomenon means that for large-scale racetrack coils, the 2-D FEM model will have larger error making the 3-D FEM model the only good choice. This phenomenon can be explained by the complex electromagnetic interactions which will be more intensive for larger coils between straight and arc parts of each turn of the coil and the anisotropy of HTS tapes.

Besides, we can see that as the number of turns goes up, the degrees of freedom of homogeneous models do not increase a lot making the memory usage of PC acceptable. This is mainly due to the superiority of homogeneous method because it just needs to model one big superconducting bulk instead of full models modeling each turn of the coil. The full model needs more meshes and degrees of freedom causing larger memory usage and slower calculation speed and the homogeneous model solves this problem [6].

5. CONCLUSION

The T-A formulation and homogeneous strategy are both fast simulation methods for superconductor FEM research. In this paper, a new 3-D T-A formulation model using homogeneous strategy is presented. Large-scale racetrack coil cannot be accurately modeled using traditional 2-D FEM models. By experimental validation, the 2-D model cannot accurately estimate AC loss which is dangerous if the safe operation of the coil need to be guaranteed during the designing stage. However, the 3-D FEM model introduced in this paper not only provides more accurate AC loss estimation but also reveals more electromagnetic details. The discrepancy of the 2-D FEM models and experiments are explained by the magnetic field distribution results of the 3-D FEM model. Besides, the usage of PC RAM of the 3-D T-A homogeneous model is not sensitive to the number of turns and the superiority above can be even more advantageous in large-scale coil. The 2-D FEM models will have larger error caused by the complex 3-D geometry and the anisotropy of YBCO tapes as the number of turns of the coil increases.

The accuracy and efficiency of the preliminary design of large-scale superconducting coils used in the crucial HTS power applications is important. Considering that the 2-D models are not close to the physical reality and the traditional 3-D models are time-consuming and memory-consuming, the effective 3-D T-A homogeneous FEM model is valuable which provides more convincing results to ensure the design of the coils credible in reasonable time.

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