Magnetization simulation of high temperature superconductors using the ANSYS ***A-V-A*** formulation: 2D and 3D, critical state model and flux creep model

Kai Zhang, Marco Calvi, Sebastian Hellmann, Thomas Schmidt
Insertion Device Group, Photon Science Division
Paul Scherrer Institute
Villigen, CH
E-mail: kai.zhang@psi.ch

***Abstract*—A new iterative algorithm is developed to model 2D and 3D magnetization of the high temperature superconductor by using the *A-V-A* formulation in ANSYS. This algorithm can simulate the critical state model by forcing the trapped J_T to J_c for all superconducting elements after each iterative load step, as well as simulating the flux creep model by updating the *E-J* power law based resistivity values. Benchmarks on a disked shaped HTS bulk during zero field cooling (ZFC) and field cooling (FC) magnetization are simulated and compared with using the *H*-formulation in COMSOL. Specially, we confirm this new method is friendly of adding ferromagnetic materials into the FEA model or defining the J_c as a function of magnetic field, field angle or mechanical strain. The simulation results are reported for more complex FEA models, like the HTS tape stack and the HTS bulk staged array undulator. The advantages and disadvantages of this new method are seriously discussed.**

Keywords—ANSYS, A-V-A formulation, HTS, 3D, critical state model

I. INTRODUCTION

The commercial software COMSOL is getting exceptionally popular in simulating the high temperature superconductors [1-5] for its easiness of implementing the ***E-J*** power law into the ***H***-formulation. However, the computational efficiency of using ***H***-formulation is low because the eddy current effect in non-superconductors has to be simulated. Recently a so-called ***T-A*** formulation is developed to speed up the simulation of HTS tape stacks and cables [6-7]. The ***H***-formulation also meets challenges in simulating the rotating machines. In [8] Brambilla *et al* tried to solve this problem by using the mixed ***H-A*** formulation in COMSOL where the ***A***-formulation is used for non-superconductor areas. In [9] Mykola *et al* presented their method of extending the ***A***-formulation in COMSOL from 2D to 3D. It's clear we can see that the ***A***-formulation is always of great interest for electromagnetic computations.

Another multi-physics software ANSYS is also investigated to model the magnetization of superconductors. The resistivity adaptation algorithm (RAA), proposed to solve AC magnetization problems [10-11], can successfully find a final resistivity matrix to reach the critical state model. But the intermediate magnetization process and the possible magnetic relaxation due to flux creep effects are missed. This problem was recently resolved through using the ***A-V-A*** formulation based iterative algorithm method [12-13]. This new method minimizes the computation time by calculating both the eddy current and the magnetic field (***A-V*** formulation, Maxwell's equation) in superconductors but only the magnetic field (***A***-formulation, Ampere's Law) in non-superconductor areas.

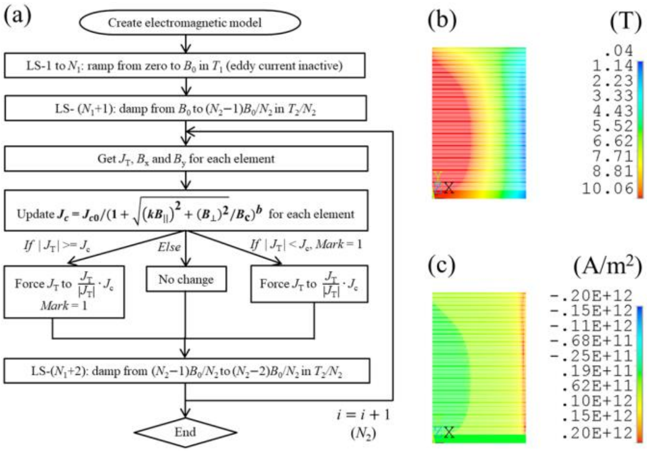

Fig. 1. (a) 2D axis-symmetric half FEA model created in ANSYS for the FC magnetization of the ReBCO tape stack; the (b) trapped magnetic field and (c) trapped current density in the ReBCO bulk after FC magnetization.

II. EXAMPLE OF MODELING THE HTS TAPE STACKS

The ReBCO tape stack simulated in this paper consists of two identical cylindrical stacks with 1 mm gap in between. Each of the half cylindrical stack is 9.2 mm high, consisting of 200 layers of 46 μm ReBCO tapes. The 2D axis-symmetric half FEA model, consisting of 200 layers of 2 μm HTS layers and 200 layers of 44 μm substrates (the 3 μm silver layer is approximated into the substrate), is created in ANSYS. The solenoid is added to generate uniform magnetic field to penetrate the tape stack.

The critical state model based iterative algorithm is developed to simulate the magnetization process of this HTS tape stack as shown in Fig.1 (a). After each iterative load step the value of the trapped current density J_T in each superconducting element is forced to the J_c which is a function of the magnetic field and the field angle.

Fig. 1 (b-c) shows the trapped magnetic field and the trapped J_T in the ReBCO tape stack after FC magnetization from 10 T to zero. The stress-strain state of the tape stack during FC magnetization can be analyzed by importing the Lorentz force load into the HTS layers after each time step.

III. EXAMPLE OF MODELING THE FLUX CREEP MODEL

The disk-shaped HTS bulk is ZFC magnetized as shown in Fig. 2 (a). Fig. 2 (b) shows the developed iterative algorithm for simulating the flux creep model based magnetization process. After each iterative load step the resistivity is calculated by using the ***E-J*** power law and updated by retaining partial of the old resistivity value.

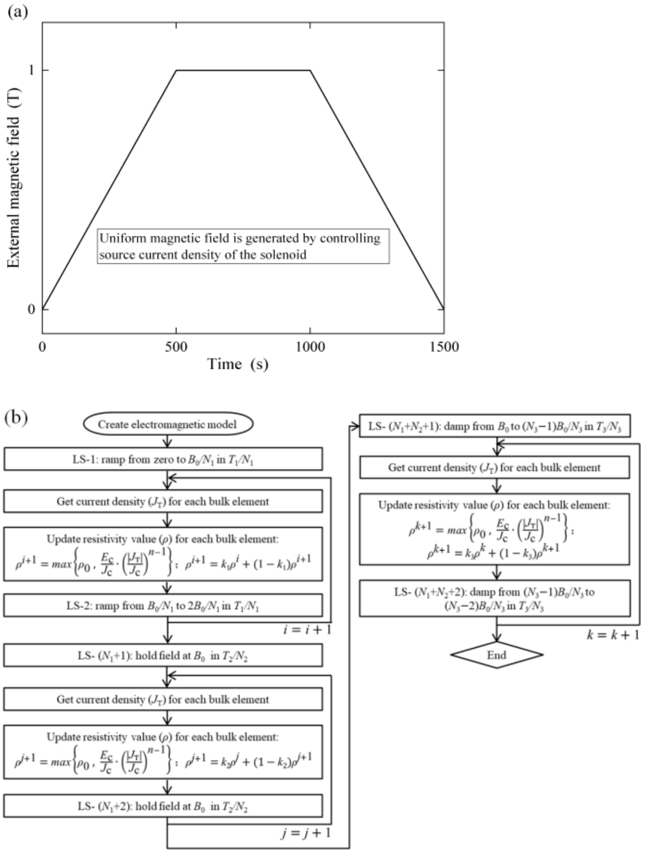

Fig. 2. (a) ZFC magnetization - external magnetic field rises linearly from zero to 1 T in 500 seconds, and then holds at 1 T for 500 seconds and finally drops linearly to zero in 500 seconds; (b) Iterative algorithm for simulating flux creep model based ZFC magnetization.

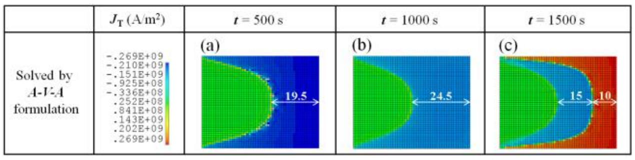

Fig. 3. Trapped J_T in ReBCO bulk at (a) t=500 s; (b) t=1000 s; (c) t=1500 s. (J_c=3x10^8 A/m^2, n=20)

Fig. 3 (a) plots the trapped J_T in the ReBCO bulk after external $\boldsymbol{B}$ rises from zero to 1 T in 500 seconds. Fig. 3 (b) plots the relaxed J_T in the ReBCO bulk after external $\boldsymbol{B}$ is kept at 1 T for another 500 seconds. Fig. 3 (c) plots the trapped J_T in the ReBCO bulk after external $\boldsymbol{B}$ drops from 1 T to zero in 500 seconds.

IV. EXAMPLE OF 3D MODELING

Fig. 4 (a) plots the trapped J_T in a 1/8 3D ReBCO bulk model after external magnetic field rises from zero to 1 T (a constant J_c of 3x10^8 A/m^2 is assumed). Fig. 4 (b) plots the trapped J_T in a periodical ReBCO bulk staggered undulator model after FC magnetization from 10 T to zero (J_c-B is defined). More details can be found from the presentation or later publications.

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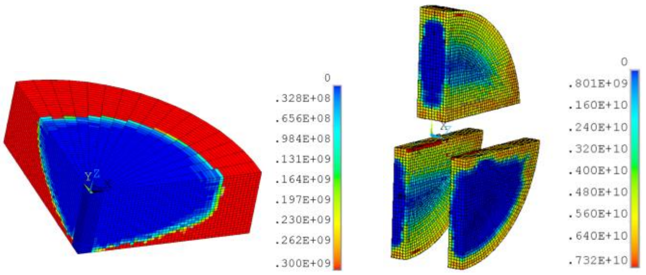

Fig. 4. (a) ZFC Magnetization of the 1/8 3D ReBCO bulk; (b) FC Magnetization of periodical ReBCO bulk staggered array undulator model.

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