Comparison of screening current simulation modellings of REBCO pancake coils

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***Abstract*—An irregular magnetic field generated by screening current in rare-earth barium copper oxide (REBCO) coated conductor is undesired, when REBCO magnets are applied to magnetic resonance imaging (MRI), nuclear magnetic resonance (NMR), particle accelerators. The screening current-induced fields (SCIF) have been evaluated in not only experiments but simulations. A few numerical methods have been proposed for screening current simulation. Since these methods have different characteristics, they are compared. Furthermore, a new screening current simulation model, named "ladder equivalent circuit model," is proposed.**

***Keywords*—numerical simulation, REBCO magnet, screening current, screening current-induced field**

I. Introduction

Rare-earth barium copper oxide (REBCO) coated conductors (CC) are promising for high magnetic field applications; magnetic resonance imaging (MRI), nuclear magnetic resonance (NMR), particle accelerator, and fusion. Especially for devices requiring an accurate magnetic field, the screening current-induced field is undesired. Many kinds of researches on screening current are underway [1]. To simulate the screening current, a few simulation methods have been proposed; simple equivalent circuit model [2], axisymmetric FEM [3], quasi 3D FEM with thin plate approximation [4].

As these methods have different characteristics, their superiority and drawbacks must be clarified. In this paper, the characteristics of these simulation methods are discussed. Furthermore, to overcome the drawbacks of these previously proposed method, a new screening current simulation method is proposed. The proposed method employs an equivalent electric circuit consisting of distributed inductances and resistances.

II. Screening Current Simulation (SEC) Models

A. Simple Equivalent Circuit Model

The simple equivalent circuit model [2] is the simplest among the screening current simulation models. The equivalent screening current circuit is represented with the resistive and inductive components, as shown in Fig. 1. It is magnetically coupled with the equivalent circuit of a pancake coil. To make an equivalent circuit, the following rough assumption is introduced: the screening currents flow along only the top and bottom surface of pancake coil, like Fig. 1. This model takes a short computation time, however the accuracy of screening current-induced field (SCIF) is the worst.

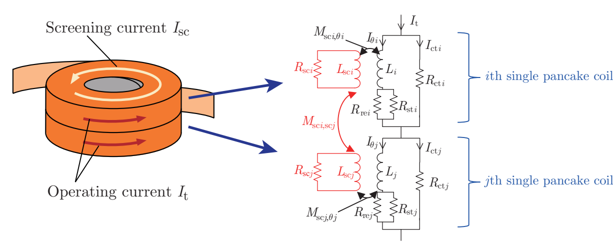

Fig. 1. Conceptual illustration of simple equivalent circuit (SEC) model.

B. Axisymmetric FEM (A-FEM)

This method is based on 2D axisymmetric finite element method [3] (Fig. 2(a)). It produces a sufficiently accurate solution, though mesh-making is a labor task. The major drawback of this model is that each turn is considered as a single turn, as shown in Fig. 2(b). Moreover, it is impossible to represent an axial current. Therefore, there is a possibility that the screening current is overestimated.

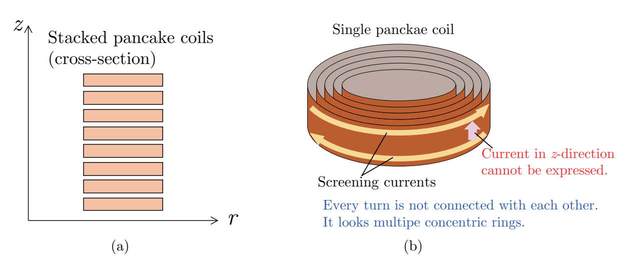

Fig. 2. (a) Simulation region on rz-plane (A-FEM). (b) Conceptual drawing of axisymmetric simulation.

C. Quasi 3D FEM (Q3D-FEM) with thin plate approximation

In this model, a current distribution is computed based on 2D FEM [4], as shown in Fig. 3. Each element is supposed to be thin plate, and the thickness of REBCO is approximated using a thin plate approximation technique. In order to compute the magnetic flux density on every element, all the elements are allocated in 3D space, as shown in Fig. 3.

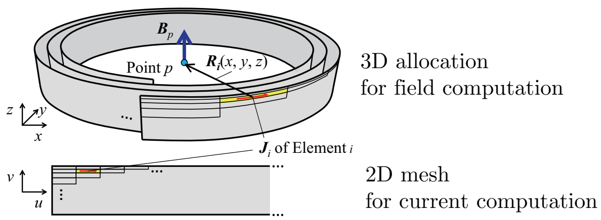

Fig. 3. Conceptual image of quasi 3D FEM (Q3D-FEM) with thin plate approximation.

This method needs a long computation time. A heavy computation task is also required to compute the magnetic flux density on every element. Hence, a special simulation technique, e.g., a fast multipole method [4], is often used.

The phenomenological drawback of this model is to neglect the thickness of REBCO layer. Since the current screening is simulated on 2D plane, the transport current is slowly penetrating into the middle of REBCO layer [5]. According to [6], the transport current should flow on not only the edge but the middle of REBCO layer.

D. Comparison Summary

Table I lists the phenomenological features of models.

TABLE I
PHENOMENOLOGICAL FEATURES OF MODELS

Features	SEC	A-FEM	Q3D-FEM
Spatial resolution of current	×	○	○
Current in axial direction	×	×	○
Winding structure of coil	×	×	○
Thickness of REBCO CC	×	○	×

○: good, ×: not good

III. LADDER EQUIVALENT CIRCUIT (LEC) MODEL

In the proposed LEC method, a REBCO CC is represented with distributed inductances and resistances, as shown in Fig. 4. The REBCO CC is divided into many short circuits in the longitudinal and transverse directions. The inductances are computed considering the winding configuration, and the resistances are obtained according to n-value power model.

Fig. 5 shows an example of simulation result. In the simulation, the current distribution of single pancake coil was obtained under the conditions of 10-A transport current and external radial magnetic field time transient $\mathrm{d}B_r/\mathrm{d}t = 0.01$ T/s. The proposed method can take into account the phenomena of axial currents, winding structure, and REBCO layer thickness effect.

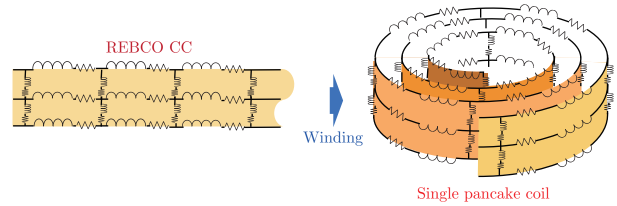

Fig. 4. Conceptual illustration of ladder equivalent circuit (LEC) model.

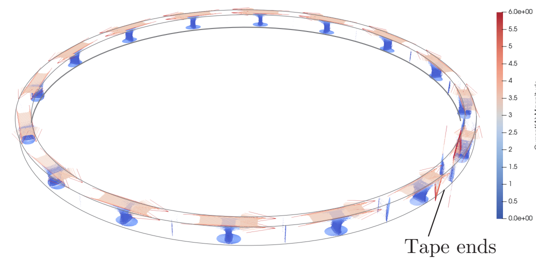

Fig. 5. Current distribution of single pancake coil with 30 turns and 4-mm height. The REBCO pancake coil is subdivided into 16 in the both circumferential and transverse direction. The large axial currents is observed at the REBCO CC tape ends.

IV. SUMMARY

The screening currents in REBCO CC generate an undesired irregular magnetic field. A center magnetic field can be sufficiently evaluated by the previously proposed methods, even though the simulated screening current distributions are a little different. Recently, plastic deformation due to screening currents attracts attention [7]. The accurate and precise current distribution is required to compute an accurate stress/strain map for magnet protection. The proposed LEC model does not have the drawbacks that the previously proposed methods have. The comparison between the screening current distributions obtained by every models will be shown and discussed.

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