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Contacts

Editor-in-Chief
Britton L. T. Plourde
Department of Physics
Syracuse University
223 Physics Building
Syracuse, NY 13244 USA
bplourde@syr.edu
http://asfaculty.syr.edu/pages/phy/plourde-britton.html
Simulation of Screening Current Reduction Effect in REBCO Coils by External AC Magnetic Field

So Noguchi and Vlatko Cingoski

Abstract—Second-generation high-temperature superconducting (HTS) tapes have been examined for applications, such as NMR, MRI, and accelerators. Each of these applications requires a precise magnetic field profile. However, screening currents induced while charging an HTS magnet degrade its magnetic field quality. Techniques to reduce the screening current effect have been proposed in the literature. One of the means to reduce screening currents is to apply an AC magnetic field using a “shaking magnet.” The shaking effect enhances the quality of magnetic field by reallocating the screening currents inside HTS tapes. Although some experiments to study the shaking field effect were reported, the current distribution inside HTS tapes has not yet been clarified by simulation.

This paper presents the simulation results for an AC magnetic field applied to a REBCO tape to reduce the influence of screening currents. In addition, we investigated the influence of the angle of applied AC magnetic field at the magnet center. The area of negative current density is also shown. From the simulation results, we conclude that a shaking field applied at an angle between 10 and 30 deg. is effective to reduce the screening current effect.

Index Terms—Field homogeneity, REBCO tape, screening current, shaking magnet.

I. INTRODUCTION

SECOND-generation high-temperature superconducting (HTS) tapes are used to develop ultra-high-field NMR and MRI magnets, e.g., 1.3-GHz NMR [1] and 9.4-T MRI [2]. These HTS applications have two critical problems. The first one is a quench protection, and the other is the field inhomogeneity caused by screening currents. For the former, the No-Insulation winding technique is a promising solution [3], [4]. For the latter, a few techniques to reduce the influence of screening current on the field homogeneity were proposed [5], [6], however, these reports are insufficiently conclusive.

The screening currents deteriorate the field homogeneity in the neighborhood of magnet center [7]. In a REBCO tape, a large screening current is induced by the transverse field due to the tape’s flat shape. Recently, the screening current effect on the field homogeneity was clarified by simulation [8]. A promising screening-field reduction solution is to apply a small AC magnetic field to REBCO tapes using a so-called “shaking magnet” [6], [9].

The screening current phenomena in REBCO tapes were investigated in a number of works [8], [10]–[13], in which the simulation models and results were presented. Also, there exist works where the AC field shaking effect on HTS coated conductors was viewed [14], [15]. However, the current distribution caused by the shaking field inside a REBCO tape has not been simulated so far.

In this paper, we employ a 2D finite element method (FEM) just to model the current distribution inside a REBCO tape affected by an external AC magnetic field applied at different angles to the tape wide surface that, in the end, enabled me to find the most effective angle.

II. SIMULATION METHOD AND MODEL

A. Simulation Method

The governing equation is given by

\[ \nabla \times (\mu \nabla \times A) = J_0 + J_s \] (1)

where \( \mu \), \( A \), \( J_0 \), and \( J_s \) are the magnetic reluctivity, the vector potential, the transport current density, and the screening current density, respectively. Here, the transport and screening current densities are defined as follows:

\[ J_0 = -\sigma \frac{\partial A'}{\partial t} \] (2)

\[ J_s = -\sigma \left( \frac{\partial A'}{\partial t} + \nabla \phi \right) \] (3)

where \( A' + A'' = A \) and \( \phi \) is the scalar potential. Then, \( J_0 + J_s \) is represented by

\[ \int_S (J_0 + J_s) \cdot dS = -\int_S \sigma \left( \frac{\partial A}{\partial t} + \nabla \phi \right) \cdot dS = I_0 \] (4)

where \( \sigma \), \( t \), \( I_0 \), and \( S \) are the electrical conductivity, the time, the transport current, and the cross-sectional area of all the conductors, respectively. In the simulation, we assumed that the current passes only in the \( z \)-direction, and that the gradient of \( \phi \) and the electrical conductivity \( \sigma \) are constant within a given finite element. From (4), the following equation is derived [16]:

\[ \frac{\partial \phi}{\partial z} = \left( \frac{\int \sigma \frac{\partial A}{\partial t} dS - I_0}{I_0} \right) \int \sigma dS \] (5)

Substituting (4) and (5) into (1), we obtain the governing equation to be solved using the 2D FEM:
at the critical current, the index of the power law, and where

$$\sigma_S = \frac{|J_c|}{E_c \left[ \frac{J}{|J|} \right]}$$

where $J_c$, $E_c$, $n$, and $J$ are the critical current, the electric field at the critical current, the index of the power law, and $J_0 - J_S$, respectively. The Newton-Raphson method was used to solve the non-linear equations (6), subject to condition (7).

We have developed the 2D FEM program by ourselves. An AC external field is given as a boundary condition. A triangular mesh is employed, and the number of nodes and elements are approximately 2.3 million and 4.7 million, respectively (including 1.6 million nodes and 3.2 million elements for the REBCO layer).

**B. Simulation Model**

Fig. 1 shows a schematic drawing of the simulation model, ignoring buffer layers in the tape. Table I lists the REBCO tape dimensions and the simulation conditions. The magnetic field components of 6 T and 3 T are applied in the radial and axial directions. Such a combination of the field components is evidenced, for instance, at the end turns of a high-field MRI magnet [2].

In the simulation, a sinusoidal magnetic field, $B_{sh}$, with an amplitude of 30 mT is applied to the REBCO tape by the shaking magnet (Fig. 2), after the main magnet is fully charged. The shaking field frequency is 50 Hz, and the number of cycles is 3. The shaking field direction relative to the tape (by the field angle) is varied from $\alpha = 0$ to 360 deg. during the simulations. The assumed operating temperature and the transport current were 10 K and 200 A, respectively.

Fig. 3(a) shows the current density distribution in the REBCO layer after the transport current reaches 200 A, where the scale of $r$ axis is enlarged a thousand-fold. The current density nearby the bottom of the REBCO layer is negative due to the screening current effect. The current density distribution shown in Fig. 3(a) represents the initial condition for the shaking field effect simulation.

**III. Simulation Results**

**A. Shaking Magnetic Field Parallel to Tape Surface**

The simulation was done first with the shaking field applied parallel to the REBCO tape surface, $\alpha = 0$ deg. The current density distribution for all conductors: copper stabilizer, Hastelloy substrate, silver overlayer, and REBCO layer, at $t = 60$ ms is shown in Fig. 4. As seen, current flows only in the REBCO layer. Since the current in the REBCO layer cannot be seen in Fig. 4, Fig. 3(b)–(i) show the enlarged current density distributions/maps in the REBCO layer at $t = 5$, 10, 15, 20, 30, 40, and 50, and 60 ms, respectively. At the start of the simulation, the negative current density is observed within a large area, however, the shape of the current-carrying region varies with time. Finally, at 60 ms, large negative currents flow only near the outer surface of the REBCO, while small negative currents flow near the bottom middle of the layer. The shapes of both negative current regions are like thin needles. Such shapes weaken the influence of the screening current on the magnetic field near the magnet center, compared to the initial condition as shown in Fig. 3(a).

**B. Various Angled Shaking Magnetic Field**

Fig. 5 shows the current density distributions within the REBCO layer at $t = 60$ ms, when applying the shaking field at the following angles: $\alpha = -30$ to 30, and 150 to 210 deg.

As seen from Fig. 5, the negative current in the REBCO layer exists far from the coil axis in the cases of $\alpha = -30$ to 30 deg.
deg. On the other hand, the negative current is closer to the coil axis when $\alpha = 150$ to 210 deg. Evidently, the cases of $\alpha = -30$ to 30 deg. are superior to $\alpha = 150$ to 210 deg.

IV. EVALUATION OF SHAKING FIELD

It is difficult to quantify the superiority of the shaking field angle on the field homogeneity. In this work, the shaking field is evaluated from the viewpoint of the contribution from a given conductor to the center field and the area of the negative current inside the conductor.

A. Contribution to Center Field

The effect of the current distribution due to the shaking field on the center field is investigated first. In the calculations, the simulated REBCO tape is placed in an arbitrary position. The axial magnetic field generated by a single-turn coil is shown in Fig. 6. The superposition of magnet fields generated by the individual finite elements at the magnet center is given by

$$B_z = \frac{\mu_0}{2} \sum_{i=1}^{n} J_i S_i r_i^2$$

where $\mu_0$, $J_i$, $S_i$, $r_i$, $l_i$, and $n$ are the permeability of free space, the current density, the area, the radius, and the distance from the origin for $i$th element, and the total number of finite elements, respectively.

Fig. 7 shows the field contribution at the magnet center for every shaking angle, where the values are normalized to the contribution for an ideal, homogeneous current distribution. The simulated REBCO tape is placed at $R = 50$ cm and $Z = 70$ cm. In Fig. 7, the “initial” value means the current distribution just after energizing the single-turn coil. The magnetic field of the initial condition is small, and it approaches 1 after applying a shaking field at any angle to the tape.

Next, Fig. 8 shows the ratio of the field contributions from the negative and positive current $B_{z-} / B_{z+}$, where $B_{z-}$, $B_{z+}$ are center field components generated by the negative and positive current, respectively. Since it takes a very long time to decay, it is desirable that the ratio $B_{z-} / B_{z+}$ is close to zero to minimize the screening current effect.

From Fig. 8, the initial condition is the worst among them, i.e., the negative current density appears over a large region close to the magnet center inside the REBCO layer. It would
deteriorate the field homogeneity if the REBCO layer on consideration was in a real magnet winding. From Fig. 8, the angle of 5 deg. minimizes the negative current contribution.

B. Area of Negative Current

Fig. 9 shows the area of the high negative current density (< -60 kA/mm²) inside the REBCO layer. The area is obviously small at 0–10 and 180 deg.

Considering the above results, the best shaking field angle is between 0 and 10 deg.

V. CONCLUSION

Simulation results of the current distribution inside a REBCO tape in the shaking field applied at different angles are presented. From the obtained simulation results, the center magnetic field generated by a single-turn coil with the current distributions is also investigated. The shaking field applied at almost any angle effectively reduces the negative effect of the screening current on the magnet central field. The best shaking field angle value is -30 deg., albeit only from the standpoint of the screening current effect reduction.

Since the negative currents decay for a long time, a minimal amount of negative current is desirable. From the results, we concluded that an AC magnetic field with angle between 0 and 10 deg. produces the greatest shaking effect.

In this paper, only one REBCO tape is considered in the shaking field simulation. However, since there are many turns of a REBCO tape in a magnet, the electromagnetic interaction between the turns should be included appropriately. Also, the authors plan to investigate the effect of the shaking field strength on the screening current reduction.

REFERENCES


