Numerical Simulation on Coupling Current for Multifilamentary HTS Wire

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Abstract. Since a high temperature superconducting (HTS) wire such as Bi-2223 (Bi₂Sr₂Ca₂Cu₃O₇) and REBCO((RE)Ba₂Cu₃O₇) tapes indicates good superconducting characteristics under high magnetic field, ultra-high field magnets wound HTS wire are applicable to a nuclear magnetic resonance (NMR) spectrometer and magnetic resonance imaging (MRI). The large and long-time-constant screening current is induced in the HTS wire, which is the tape shape and not twisted, and the magnetic field generated by screening current deteriorated the field quality such as temporal stability and spatial homogeneity. Because NMR and MRI requires highly accurate field on temporal stability and spatial homogeneity, it is necessary to investigate the influence of the screening current-induced field. In REBCO tape, the screening current can be reduced by dividing the superconductor layer. However, filaments are electrically connected because they are covered with copper due to strength and thermal stability. On the other hand, a Bi-2223 is wire which multiple superconducting filaments are covered with silver or a silver alloy, therefore, the screening current is smaller than that in a REBCO tape. However, in a Bi-2223 tape, a coupling current flows because of electrical bridge between the filaments. In this study, we discuss coupling current distribution from numerical simulation on the multifilamentary HTS coil which is given the local electrical contact between filaments. The screening-current field decreases with increasing the interval distance. In addition, the current distribution is different depending on the interval distance.

1. Introduction

High temperature superconducting (HTS) wires indicates such as Bi-2223 (Bi₂Sr₂Ca₂Cu₃O₇) and REBCO((RE)Ba₂Cu₃O₇) tapes good superconducting characteristics under high magnetic field. Therefore, the research and development on the application of HTS coil to the high field magnets for NMR, MRI, and accelerator and so on are progress [1-12]. In these application, the magnets need to create highly homogeneous and temporally stable field. However, the screening currents lead to the serious problem in HTS magnets for the applications required very high field quality. In coils wound with HTS tapes, large screening currents are induced by the radial component of the magnetic field because of tape shape and no twist. Then, the total current distributions in the tape consists of the transport and screening currents, the total current flow inhomogeneously in tape. As a result, an irregular magnetic field is generated by the screening currents. The screening-current field affects the magnetic field distribution in the following issues: (1) field reduction, (2) no-repeatability of field, (3) temporal stability, and (4) deterioration of field quality. These effects are very critical in NMR, MRI, accelerator applications. Therefore, the prediction and reduction of screening-current field are needed.

The filamentization of REBCO tape shows enables us to reduce the possibility of reducing the screening current induced magnetic field in REBCO coils [13][14]. The multi-filamentary REBCO tape...
is usually plated with copper for mechanical strength and thermal stability. The behaviour and diffusion process of screening current depend on the geometry treatment of the coil winding and the effective transverse resistivity between filaments in REBCO tape. On the other hand, a Bi-2223 is wire which multiple superconducting filaments are covered with silver or a silver alloy, therefore, the screening current is smaller than that in a REBCO tape [15]. However, in a Bi-2223 tape, a coupling current flows because of electrical bridge between the filaments. Since these are current distributions different from the transport current, they are considered to affect the temporal stability and spatial homogeneity. In this study, we focused on the bridging between filaments in HTS tape and investigated the current distribution in the multi-filamentary HTS tape by using our developed simulation code. We discuss on the effects of bridging of multi-filamentary HTS tape on the diffusion process of screening current and the behaviour of the magnetic field.

2. Numerical simulation

The screening current, which passes from end to end in HTS coil, is affected by the coil winding configuration, such as pancake winding and layer winding. Therefore, The developed three-dimensional electromagnetic-field numerical simulation code for the screening-current field have been developed [16]. This simulation is based on a finite element method (FEM) and a fast multipole method (FMM). The governing equation formulated based on thin-film approximation, Biot-Savart law, Faraday’s law of induction, and Ohm’s law is expressed as

\[
\{ \nabla \times \rho ( \nabla T \times n) \} \cdot n + \frac{\mu_0 d}{4\pi} \frac{\partial}{\partial t} \int_S \frac{(\nabla T' \times n') \times R}{R^3} \cdot n dS' = - \frac{\partial B_a}{\partial t} \cdot n \tag{1}
\]

where \( T \) is the normal component to the current vector potential of the tape’s wide face, \( n \) is the unit normal vector to the tape’s wide face, \( \rho \) is the resistivity of the superconductor, \( \mu_0 \) is the space magnetic permeability, \( B_a \) is the external magnetic field, \( R \) is the vector toward the field point from the source point, and \( d \) is the thickness of the superconducting layer. The resistivity of the superconductor, \( \rho \) is defined by the power law and Ohm’s law

\[
\rho = \frac{E_c}{J_c(B,\theta)} \left( \frac{|J|}{J_c(B,\theta)} \right)^{n(B,\theta)-1} \tag{2}
\]

where \( J \) is the current density in the superconducting layer. The validity of the numerical simulation for the screening-current field was confirmed [17][18].

In this simulation, the dependence of the \( I_c - B - \theta \) characteristic at 4.2 K as shown in Figure 1. And the \( n \)-value was set to be constant at 16.

![Figure 1. \( I_c - B - \theta \) characteristic.](image)
Figure 2 shows the schematic drawing of the model of multi-filamentary HTS wire with bridging. In this study, the interval of bridging between filaments is assumed to be non-random and equal distance in order to investigate the fundamental behavior of coupling current in the multi-filamentary HTS wire with bridging. Table 1 and 2 list the specifications of the model HTS wire and HTS coil, respectively, in this simulation. The resistivity values is determined from characteristics of silver and copper at 4.2 K [19][20]. Table 3 lists three cases of the interval distance and the model of the multifilamentary wire shows as Figure 2.

![Model of the multifilamentary HTS wire.](image)

**Figure 2.** Model of the multifilamentary HTS wire.

| Table 1. HTS wire specifications |
|---------------------------------|
| Superconductor layer thickness (μm) | 1.0 |
| Tape width (mm) | 4.5 |
| Number of filaments | 10 |
| Gap between filaments (μm) | 100 |
| Resistivity between filaments (Ωm) | 1.0×10^{-7} |
| Bridge resistivity (Ωm) | 1.0×10^{-10} |

| Table 2. Coil specifications |
|-----------------------------|
| Inner diameter (mm) | 80 |
| Outer diameter (mm) | 108.08 |
| Height (mm) | 101 |
| Turns / Single pancake coil | 39 |
| Number of Single pancake coils | 20 |
| Gap between coils (mm) | 1.0 |
| Transport current (A) | 295.72 |
| Magnetic field @ center (T) | 2.0 |

| Table 3. Interval distance between bridges |
|------------------------------------------|
| Interval distance (mm) | Case I | Case II | Case III |
|-------------------------|--------|--------|---------|
| 16.75~22.64          | 205.2~277.3 | 2089.8~2823.8 |

3. Simulation results and discussion

In this study, the transport current was 259.72 A at sweep rate of 1.0 A/s and 5.0 A/s. The calculation results of screening-current field at the coil center at 1.0 A/s and 5.0 A/s are shown as Figure 3. The screening current field is defined as the result of subtracting the ideal magnetic field which does not consider the screening current from the result used in this simulation. As shown in Figure 3, the
screening-current field increases during charge the coil because the area in which screening current flows is expanded. And the screening-current field decreases with increasing the interval distance of the bridge resistivity. When we compared with 1.0 A/s and 5.0 A/s just after the excitation to 295.72 A, the difference between the Case I and III about the screening-current field is 3.7 mT and 1.8 mT.

Figure 3. Behavior of screening-current field time dependency at coil center in the (a) 1.0 A/s and (b) 5.0 A/s.

The current distributions of the topmost single-pancake coil in 20-stacked coil just after the excitation to 295.72 A are shown in Figure 4. This figure shows the expanding view from the start of winding to the end of winding. The screening current in pancake-wound coils mostly flows at the edge of the coil because the component of the magnetic field perpendicular to the wide face of the tape is large. In the pancake-wound coil, because the tapes at the edges of the coil are exposed completely to the perpendicular component of the magnetic field, the path of the screening current circulates from end to end of the tape. As shown in Figure 4, the coupling currents between filaments decrease with increasing the interval distance between bridges. And at the sweep rate of 5.0 A/s, the coupling currents between filaments increase because the magnetic field is hard to penetrate in multimilitary HTS wire. Figure 5 shows schematic drawing of the local-loop current in the multifilamentary HTS wire with bridging. As seen in Figure 5(a), when the interval distance is shorter, the screening current flows in the local short loop and the magnetic field penetrates from the side of wire. The current distribution as shown in Figure 4(a) and (d) are explain in the case of Figure 5(a). On the other hand, when the interval distance is longer, the magnetic field penetrates from the end of wire as shown in Figure 5(b). The current distribution as shown in Figure 4(c) and (f) are explain in the case of Figure 5(b). Therefore, the deviation of the current across the tape is relaxed, the screening-current field decrease as shown in Figure 3. Also, the change in the magnetic field at a fixed time increases as the sweep rate becomes faster, so that the influence of the interval distance becomes smaller.

4. Conclusion

In this paper, we numerically investigated the influence on the screening-current field and current distribution for multifilamentary HTS wire with bridging. The screening-current field decreases with increasing the interval distance. And the influence of the interval distance is decrease when the sweep rate becomes faster. In addition, the current distribution is different because of local current loop depending on the interval distance.

In the future, we will establish the model of Bi2223 and investigate the effect of screening-current for ultra-high-field NMR and accelerator. And we will evaluate the field homogeneity and temporal stability for shimming.
Figure 4. Current distribution at charging complete on the tape winding of top single pancake coil in the (a) Case I, (b) Case II, (c) Case III (1.0 A/s), (d) Case I, (e) Case II, (f) Case III (5.0 A/s).

Figure 5. Schematic drawing of the local-loop current in the multifilamentary HTS wire with bridging of (a) short interval distance and (b) long interval distance.

Acknowledgments
The part of this work was supported by Grant-in-Aid for Scientific Research (C), the Ministry of Education, Science, Sports and Culture (No.16K06222).

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