A novel REBCO conductor design to reduce screening-current field in REBCO magnets

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A Novel REBCO Conductor Design to Reduce Screening-Current Field in REBCO Magnets

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Abstract

Due to its very high critical fields, the second-generation high-temperature superconductor (2G HTS) has been, and is being, used in high-field magnets. However, a persistent screening current induced in the REBCO conductor under time-varying conditions distorts the magnetic field, spatially and temporally. We describe a novel REBCO conductor design composed of Narrow-Stacked (NS) wire, a bundle of 1-mm wide REBCO tapes. The design is based on a fundamental notion that the narrower the REBCO tape width, the smaller the screen-current field (SCF). In this paper, both experimental and simulation work were carried out to analyze SCF in a REBCO coil wound with an NS wire. We demonstrate that the critical current of NS wires can be consistent with the conventional REBCO tape to meet the application requirements. Meanwhile, NS wire indeed substantially results in small SCF, an important requirement in high-field magnets such as for NMR, MRI, and HEP that may rely on REBCO conductor.

Keywords: REBCO coated conductor, Screening current induced field, Narrow-Stacked wire, Temporal field stability

I. INTRODUCTION

Owing to the high critical current density in magnetic field and excellent mechanical properties, the second-generation high-temperature superconducting (2G HTS) coated conductor is suitable to high-field magnets [1,2]. To date, several high-field magnets have constructed, including a 32-T all-superconducting magnet and a 45-T hybrid magnet composed of a 11.5-T superconducting magnet and a 33.5-T resistive magnet [3,4]. However, with a high-field magnet that includes a REBCO insert, a persistent screening current, induced in the REBCO tape, will inevitably present and degrade the insert field [5–8].

As shown in figure 1, a persistent screening current loop is mostly formed in the wide superconducting layer of REBCO tape. It generates a screening-current field (SCF), which in turn distorts the original magnetic field. Because SCF decays with time, it causes a temporal field drift: another harmful effect of SCF to the field quality of high-field applications, such as NMR, MRI, and HEP magnets [9–11].

SCF substantially degrades the temporal stability and spatial homogeneity of the magnetic field and is therefore very harmful for high-resolution NMR measurements [12]. To address this problem, reducing the SCF in conventional REBCO conductor is a strategy to make REBCO applicable to high-field magnets [13–16]. Mitigation techniques that have been applied include increasing the temperature of the high-SCF sections of a magnet [17], and exceeding the coil operating current and retracting it [18]. Both techniques have an intrinsic limitation because the induced screening current is proportional to REBCO tape width; a more direct way is to narrow the REBCO tape width. However, a narrower tape, i.e., a smaller critical current (Ic), invariably increases a magnet’s total number of turns and hence its inductance, generally an unwelcome outcome for magnet protection.

We report a novel conductor design that effectively reduces SCF: Narrow-Stacked (NS) REBCO tape, a structure optimization for conventional REBCO conductor. It is derived from our related work on the soldered-stacked-square (3S) wire [19]. NS wire is prepared by three sequential steps: mechanically slicing a 4-mm wide REBCO tape into four 1-mm wide tapes, stacking 1-mm wide tapes into a bundle, and soldering them to form a monolithic REBCO conductor. In the stacking step, copper strips are introduced for mechanical stability and conductor protection. In this paper, two REBCO solenoid coils of the same inner radius and turn numbers were wound, one with NS wire and the other with 5-mm wide REBCO tape. We operated both coils at 77 K and performed numerical simulation to demonstrate that, compared with 5-mm wide REBCO tape, NS
REBCO tape is definitely effective in reducing SCF hysteresis and lessening magnetic field temporal drift. This novel REBCO conductor design is helpful to overcome the drawback caused by SCF in the practical REBCO application.

II. EXPERIMENT

A. Fabrication of NS wire and coil

Basic mechanical and transport characteristics of the REBCO conductor after narrowed and stacked have been studied in our previous work [19–21]. Specially, when the bending diameter is larger than 60 mm, the critical current of the stacked REBCO conductor will not be reduced. Figure 2(a) shows photos of 2 typical samples: an NS wire after soldering and a 5-mm wide REBCO tape, respectively. And the inset of figure 2(a) shows a schematic diagram of the 2s+1c structure with two 1.10-mm wide REBCO tapes (2s) and one copper tape (1c) of the same width in the wire. To make the conductor \( I_c \) flexible and thus enable the NS wire to meet a critical current requirement, the components of the wire are adjustable, e.g., 4s+2c, 6s.

To avoid the difference between critical currents which may affect SCF measurements, similar critical currents were selected in our coil experiments, so the original tape used to fabricate the NS wire is different from the 5 mm REBCO tape used to wind Coil B. Figure 2(b) shows critical current, at 77 K in self field (s.f.) vs. position plots of 28-m long conductors: (red, lower) (2s+1c) wire; (blue, higher) 5-mm wide REBCO tape. The critical current averages, at 77 K in s.f., of (2s+1c) wire and 5-mm wide REBCO tape are respectively 118 A and 130 A.

Comparing with the sum (120 A) of \( I_c \) values of two 1-mm wide REBCO tapes, the (2s+1c) wire \( I_c \) after stacking and soldering steps, is reduced only by 2%. Thus, our fabricating process of NS wire practically makes no significant degradation of the critical current per width.

Using (2s+1c) wire and 5-mm wide REBCO tape, we wound two solenoids, respectively. First, the prepared (2s+1c)-wire and 5-mm REBCO tape, both longer than 28 m, need to be insulated. Through the wrapping device, Kapton was wrapped on these two conductors for insulation. Then, the insulated conductors were wound on the bobbins for fabricating the solenoid coils. Both coils, which consist of 108 turns, have 80-mm inner diameter and 48-mm height. The degradation of \( I_c \) caused by winding can be ignored due to the large winding diameter. Finally, the coil end parts were soldered to the copper terminals, and then high-precision power supply was connected to the copper terminals through the current leads. Figure 3 shows the photographs of Coil A and Coil B. Detailed coil parameters are listed in Table 1. As shown in Table 1, critical currents are 74 A for Coil A and 84 A for Coil B, respectively. Both are lower than those of short samples, which is due to the magnetic field dependent \( I_c \) of REBCO tapes.

B. Experimental measurement of Field

Using Lakeshore 425 Gaussmeter with Hall probe HGCA-
we measured the axial center magnetic field; we calculated each coil’s SCF through the following procedure. Firstly, when each coil was in the normal state, current was applied incrementally, each increment obviously inducing no screening current. In this manner, we determined a central field constant $C_s$ from the slope of center field vs. current. For a coil energized at 77 K, its SCF, $B_s$, may be determined from equation (1)

$$B_s = B_0 - B_c$$

(1)

where $B_0$ is its axial center field and $B_c$ is a magnetic field with no SCF, calculated by the product of $C_s$ and applied current [22]. For this experiment, we used Lakeshore 625 power supply with a ±60 A current range, 0.1 mA output resolution, and 1 mA/hr stability (after warm-up).

To experimentally determine a coil’s SCF, we energized and de-energized the coil at 77 K and measured its center field during each experimental sequence. As shown in figure 4, where left- and right-column plots correspond respectively to those of Coil A and Coil B: (a) and (b), we first charged each coil to 60 A with a ramp rate of 1 A/s; (c) and (d), we held the current at 60 A for 1 hour; (e) and (f), we discharged the current to 0 A and measured $B_0$ for over 3 hours. The Lakeshore 625 performed well to ensure no discernable current drift over a period of >3000 s when the power supply current was kept constant at 60 A. Figure 4(c) and (d) show the temporal $B_0$ drift at 60 A. Coil A $B_0$ drift was 0.4 Gs in 200 s, and then $B_0$ stayed at 886.4 Gs with a deviation of ±0.1 Gs. On the contrary, Coil B $B_0$ showed a positive drift of 5.1 Gs during 3600 s. In comparison with Coil B, a standard HTS coil, no pronounced temporal drift could be detected in Coil A. Then, because SCF of an energized coil generates a remanent magnetic field after the coil is de-energized, figure 4(e) and (f) show the remanent field: 2.9 Gs for Coil A, and 12.9 Gs for Coil B. Measurement confirms that the NS wire reduces the remanent field significantly, here by 78%, which is approximately proportional to the REBCO tape width.

![Figure 4](image-url)

C. SCF hysteresis loop measurement

In the second experiment, to measure the hysteresis loop of SCF, we charged each coil with a 1.5-cycle triangular waveform current at a current ramp rate of 0.05 A/s for an operating current period of 1200 s. Relationships among $B_0$, $B_r$, $B_s$, transport current, and time are shown in figure 5(a) (Coil A) and 5(b) (Coil B); corresponding SCF hysteresis loops from the experiment are plotted in figure 5(c) (Coil A) and figure 5(d) (Coil B). The positive direction of $B_r$ is defined as the same as the center field direction at positive current. When the operating current reached 60 A in the first charging sequence, $B_r$ was $-2.5$ Gs in Coil A and $-13.6$ Gs in Coil B, resulting in nearly an order of magnitude reduction in the center field by $B_r$ in Coil A vs. Coil B. When the coils were de-energized after the first half cycle, the corresponding $B_r$ was $+3.0$ Gs in Coil A and $+14.4$ Gs in Coil B. Each coil clearly shows a hysteresis effect, but Coil A has a hysteresis loop area much smaller than Coil B. Despite inevitable parameter differences between the two coils, such as critical current and turns distribution, we may conclude that NS wire is a conductor design that effectively reduces SCF and its hysteresis loop size.
formulation in two-dimensional (2D) axial symmetrical geometry [24, 25]. The main advantage of the $T$-$A$ formulation is that it treats a superconducting tape as a thin sheet with zero thickness. The governing equation for the superconducting region is expressed as

$$
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}
$$

$$
\mathbf{J} = \nabla \times (\mathbf{T} \cdot \mathbf{n})
$$

$$
\mathbf{E} = \rho \cdot \mathbf{J}
$$

where $\mathbf{T}$ is the magnitude of current vector potential, $\mathbf{n}$ is the unit normal vector of the tape surface, and $\rho$ is the electrical resistivity. Electric field $\mathbf{E}$, current density $\mathbf{J}$, and magnetic field $\mathbf{B}$ may be obtained by equation (2). The non-superconducting region solved by magnetic potential $\mathbf{A}$ is expressed as

$$
\nabla \times \nabla \times \mathbf{A} = \mu \mathbf{J}
$$

$$
\mathbf{B} = \nabla \times \mathbf{A}
$$

The two different regional parts are coupled to calculate the $T$-$A$ model. To make the model precise and reasonable, the measurements of magnetic field dependence are considered both for (2s+1c) wire and 5-mm wide tape in our simulations. Figure 6 shows an anisotropic magnetic field dependence of normalized critical current density $J_c/J_{c0}$ for (2s+1c) wire, which is applied to the model with an interpolation function, $\text{int}(B_\parallel, B_\perp)$ [26]. Based on the related measured data, the resistivity of superconducting sheet is as follows

$$
\rho_{HTS} = \frac{E_c}{J_c} \left( \frac{J}{J_{c0}} \cdot \text{int}(B_\parallel, B_\perp) \right)^n
$$

where $J_{c0}$ is the critical current density at zero local field, $n=27$, and $E_c = 1\mu V/cm$ as the criterion.

### III. NUMERICAL SIMULATION

#### A. Model description

Because the screening current in a REBCO tape is mainly generated by the perpendicular field to the wide surface of REBCO tape, the magnetic moment produced by the screening current is positively correlated to the tape width [23]. A narrower width is obviously beneficial to reduce the influence of SCF. However, it is difficult to find analytical equations to describe the complex situation considering both the transport current and non-uniform distributed field for the HTS coils. Thus, for analyzing the SCF reduction effect, based on the finite element method, we carried out a numerical study by using a $T$-$A$ formulation in two-dimensional (2D) axial symmetrical geometry [24, 25]. The main advantage of the $T$-$A$ formulation is that it treats a superconducting tape as a thin sheet with zero thickness. The governing equation for the superconducting region is expressed as

$$
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The two different regional parts are coupled to calculate the $T$-$A$ model. To make the model precise and reasonable, the measurements of magnetic field dependence are considered both for (2s+1c) wire and 5-mm wide tape in our simulations. Figure 6 shows an anisotropic magnetic field dependence of normalized critical current density $J_c/J_{c0}$ for (2s+1c) wire, which is applied to the model with an interpolation function, $\text{int}(B_\parallel, B_\perp)$ [26]. Based on the related measured data, the resistivity of superconducting sheet is as follows

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$$

where $J_{c0}$ is the critical current density at zero local field, $n=27$, and $E_c = 1\mu V/cm$ as the criterion.

#### B. Current density analysis for SCF

The simulated SCF hysteresis loops are also shown in figure...
5(c) and 5(d). For both Coil A and B, the simulated results agree well with the experimental results, so the $T_A$ model for calculating SCF is verified. The experimental results shown in figure 4 is a time-consuming observation experiment, which is difficult to be simulated directly. Actually, the SCF hysteresis loop is the most intuitive representation of the SCF influence on the coils. Thus, the effect of NS wire on the temporal drift and the remanent field shown in figure 4 can also be explained by the related results from SCF hysteresis loop.

Because screening current is most pronounced at the ends of a solenoid coil [27], its top innermost turn is chosen to study the reason for SCF reduction by using the $(2s + 1)c$ wire. Through the simulated result from SCF hysteresis loop, figure 7(a) and 7(b) show the normalized current density vs. conductor width plots of the top innermost turns in Coils A and B, respectively, at 60 A after the first charging sequence and current returned to zero after the first half cycle. The region with lower current density than $J_c$ is considered as the non-critical region, whose length is positively correlated with the magnetic moment produced by the screening current.

The superconducting property in the non-critical region makes the screening current persistent in REBCO tape. When the screening current is induced in the critical region, the added current density makes the region to exceed its $J_c$, then this dissipates the screening current in the critical region. Therefore, the non-critical region constrains the screening current generation, and so is SCF magnitude. It is clear that the non-critical region of $(2s + 1)c$ wire in Coil A is indeed smaller than that of the $5$ mm wide tape in Coil B, corresponding to a lower SCF. In the $(2s + 1)c$ wire, the screening current effects are mitigated so that the temporal drift and the remanent field shown in figure 4 are both suppressed and reduced substantially.

**Figure 7.** Calculated normalized current density vs. conductor width plots of the top innermost turns in Coils A and B: (a) at 60 A after the first charging sequence; (b) current returned to zero after the first half cycle.

**IV. CONCLUSIONS**

Screening-current field (SCF) can lead to the degradation of the central field, spatial field homogeneity and temporal stability in REBCO magnets. In this paper, we conclude that a novel NS wire composed of $1$ mm wide REBCO tape is an effective conductor for REBCO coils to minimize SCF. Our conclusion is based on experimental and analytical study on two REBCO coils, Coil A of NS wire and Coil B of $5$ mm wide REBCO tape. We believe that NS wire will be helpful to promote the design and implementation of REBCO conductor in high-field application.

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