Screening Current Simulations of Quasi-Layer-Wound and Pancake-Wound REBCO Coils

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***Abstract*—This paper reports screening current simulations of two REBCO coils with different winding approaches considered: one with quasi-layer winding and the other with pancake winding. In-house simulation models were used to calculate the screening current, Lorentz force, and mechanical stress of each coil. The comparison showed that the maximum hoop stress of a quasi-layer-wound coil was lower than that of a pancake-wound coil by more than 10%. Detailed analysis confirmed that such mitigation resulted from the benefit of a quasi-layer-wound coil. The key was that the direction of screening current induction can be manipulated, thus offsetting the superposition of the Lorentz force amplified by the screening current. This result suggests that a quasi-layer winding approach could be a competitive option in the insert module of a high-field superconducting magnet in terms of stress/strain margin. This paper provides a quasi-layer-wound coil simulation model, simulations of quasi-layer-wound and pancake-wound coils, and comparison results. We then discuss quasi-layer winding and cabling approaches to reduce excessive electromagnetic stresses in high-field superconducting magnets.**

***Index Terms*—High field, high stress, layer winding, REBCO coated conductor, screening current stress.**

I. Introduction

LAYER winding approach is an established, straightforward option in winding a coil. Researchers have applied the layer winding approach to electromagnets and even low-temperature superconductor magnets as the coil winding technique for many decades. However, this approach has not been frequently used in fabricating superconducting magnets made of rare-earth barium copper oxide class (hereafter REBCO, RE=rare-earth) coated conductors. This difference in such applicability results from the fact that the coated conductor is produced as a thin rectangular shape with brittle superconducting materials. In addition to this, other reasons for this limited use of the layer winding approach are the limitation of the conductor piece length, challenges in coil modularization, high back-tension requirements at turn-over sections at the top and bottom of a coil, hard-way bending issue resulting from the thin tape configuration of the coated conductor, the necessity of conductor insulation, etc [1].

Despite such limitations, the layer winding approach is still a competitive option for some high-field REBCO magnet applications, e.g., nuclear magnetic resonance (NMR) spectrometers that require high-field uniformity. The state-of-the-art high-field GHz-level NMR magnets had to utilize layer-wound REBCO insert magnets to generate high fields together with low-temperature superconducting background magnets [2], [3]. Beyond this dedicated application, recently, this approach was used in a general-purpose HTS 20 T user magnet, including a layer-wound REBCO insert coil and a pancake-wound REBCO outsert coil [4]. This progress is notable enough to make magnet researchers consider this approach an option for high-field superconducting magnets. At present, however, relevant studies are insufficient, although Japanese researchers have published numerical and experimental results of layer-wound REBCO coils [5], [6], [7], [8], [9], [10]. Hence, we have performed a numerical study of a quasi-layer-wound REBCO coil for high-field applications as a part of a preliminary research step, thus investigating competitive points compared to the conventionally used pancake winding approach, referring to our 'Little Big Coil' program [11].

This paper reports screening current simulations of two REBCO coils wound with two different winding approaches, i.e., one with quasi-layer winding and the other with pancake winding. We assumed that the two coils have the same specifications, and they are exposed to the background magnetic field of 31 T. In-house 2D axisymmetric simulation models were used to compute screening current, Lorentz force, screening current stress (SCS), and mechanical stress [12], [13], [14], [15]. The comparison results showed that the peak hoop stress of a quasi-layer-wound coil was lower than that of a pancake-wound coil by over 10%. The feature of a quasi-layer-wound coil that the direction of screening current induction is crossed resulted in this mitigation by offsetting the Lorentz force. We provide the concept and simulation model of a quasi-layer-wound coil, simulation results, and a comparison between quasi-layer-wound and pancake-wound coils, and then a discussion of quasi-layer winding and cabling options for a high-field, high-stress superconducting magnet.

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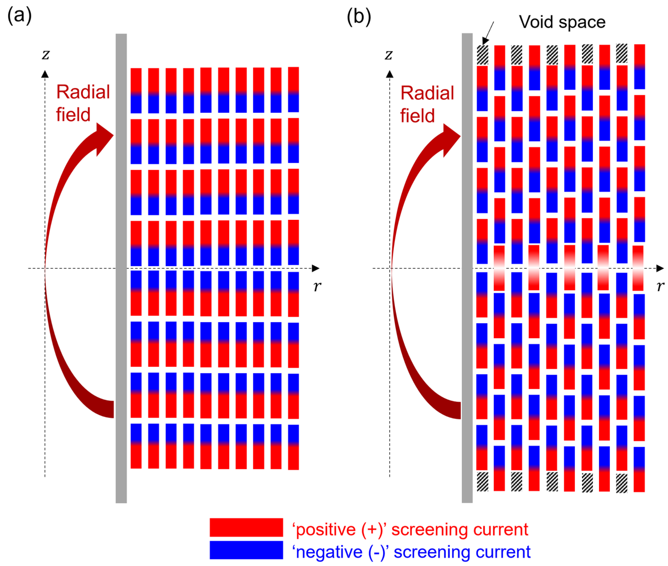

Fig. 1. The schematic drawings of the screening current distribution in two coils in the 2D axisymmetric domain, a cylindrical coordinate, assuming full penetration: (a) pancake wound coil and (b) quasi-layer-wound coil.

II. Concept of a Quasi-Layer-Winding and Mechanism of SCS Mitigation

The concept of a quasi-layer-winding and the mechanism of SCS mitigation are described in Fig. 1. This figure presents the schematic drawing of the screening current distribution in two coils in the 2D axisymmetric domain, a cylindrical coordinate, assuming the positive coil current flowing along the azimuthal direction and full penetration: (a) pancake-wound coil and (b) quasi-layer-wound coil. For the quasi-layer-wound coil, we did not consider the winding angle change between odd and even layers and the turn-over section at the top and bottom, assuming an ideal case. Due to the nature of screening current that expels a penetrating field, the positive direction of screening current appears at all outward edges away from the coil center, and the negative direction of it does at all inward edges facing towards the coil center. In the pancake winding case, the direction of such induction is the same and superposed along the radial direction, but in the quasi-layer winding case, it can be manipulated depending on the decision of the person who is winding. For instance, the winding can be done by overlapping it one turn at a time (in this case, it is the same as Fig. 1(a)) or by overlapping it half (as in Fig. 1(b)) or some portion of a turn at a time. Since the primary electromagnetic force, the local screening current stress, is proportional to the local critical current density (J_c) and the axial field (B_z), we can expect a stress mitigation effect in the quasi-layer winding case via the superposition of two counter forces at turn-to-turn boundaries in Fig 1(b).

III. A 2D Axisymmetric Screening Current Simulation Model for a Quasi-Layer-Wound Coil

This section describes a 2D axisymmetric simulation model for a quasi-layer-wound coil. A 3D simulation model of a layer-wound coil was developed by Ueda et al. to precisely calculate the screening current induced field, considering the non-axisymmetric configuration [16], [17]. This model aims for precise calculation, thus requiring considerable computation time and memory usage. Hence, we have developed a 2D axisymmetric model, which is straightforward and fast for performing preliminary numerical studies, using a commercial finite element method simulation program, COMSOL. This model utilizes H-formulation and multiphysics coupling (electromagnetics and mechanics), different from the 3D model using T-formulation and a decoupled computation process. The coupling details are provided in our previous work [13].

The key difference between screening current simulation models for quasi-layer-wound and pancake-wound coils is how to set the boundary conditions. Except for this, all settings are the same. So in this work, we provide some details of quasi-layer-wound coil simulation settings, which have not been reported yet. Meanwhile, we should note here that such details are described in certain terms used in COMSOL, which means different terms could be used in other simulation programs, even if they perform the same functions.

The screening current simulation model for a pancake-wound coil requires an integral constraint of current, which is implemented by a built-in nonlocal coupling operator named "Linear Projection." However, this operator does not work for a quasi-layer-wound coil simulation since a linear mapping from the source to the destination is no longer effective for a quasi-layer-wound coil. To address this issue, another built-in nonlocal coupling operator named "General Projection" is needed to enable mapping points in the source geometry to those in the destination geometry, including linear and non-linear mappings. This general projection option results in a simple screening current simulation of a quasi-layer-wound coil without additional weak form constraints and even without additional use of Lagrange multipliers for such weak form constraints, leading to the benefit that computation load and time of a quasi-layer-wound coil simulation are comparable to those of a pancake-wound coil simulation.

IV. Screening Current and SCS Simulation Results

Numerical studies were performed to compare two different winding approaches. We assumed two coils exposed to a 31 T background field (axial field only). One is a pancake-wound coil consisting of twelve pancakes wound with 4 mm wide and 45 μ m thick REBCO tape, where the inner and outer diameters of every pancake are 14 mm and 36 mm. The other one is a quasi-layer-wound coil having 245 layers (the number of tapes along the radial direction), where each layer contains 12 and 13 turns (the number of tapes along the axial direction) at even and odd layers, respectively. It was assumed that the voids resulting from the difference in the number of turns between layers, i.e., the rectangular area including the diagonal lines near the top and bottom sections in Fig. 1(b), were filled with 2 mm wide and 45 μ m thick Hastelloy tapes. Lastly, key parameters for electromagnetic and mechanical simulations and boundary conditions are summarized below:

- The operating current of 250 A charging with a constant ramp rate of 1 As^{-1}
- A constant critical current density of 500 A
- A constant value for the power-law model of 30
- No gaps between all individual tapes
- One engineering turn combining five "real" turns
- The fixed boundary condition at the coil mandrel
- The roller boundary condition at the coil mid-plane

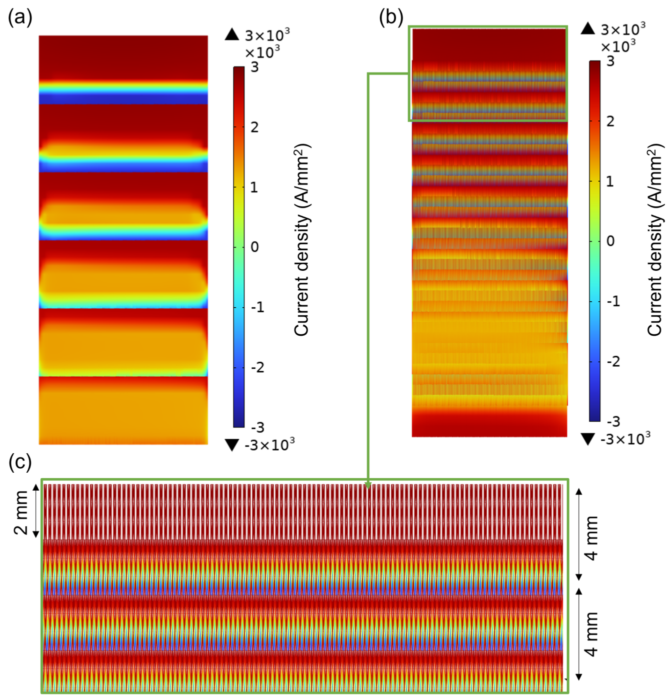

Fig. 2. Current density distribution displayed in the upper half section of two REBCO coils: (a) a pancake-wound coil and (b) a quasi-layer-wound coil. (c) shows an enlarged view of the top section of (b).

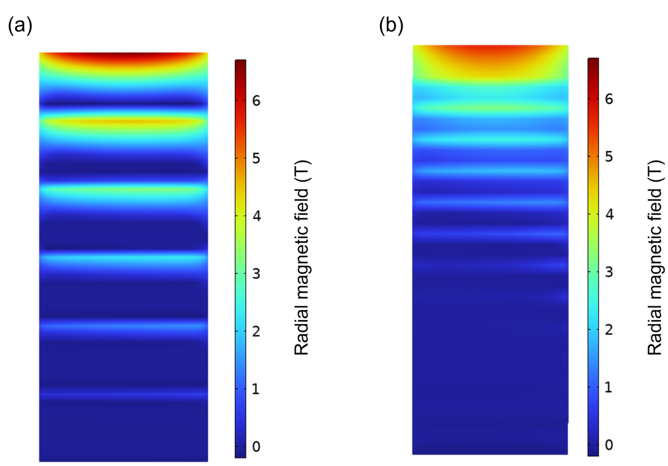

Fig. 3. Radial field distribution displayed in the upper half section of two REBCO coils: (a) a pancake-wound coil and (b) a quasi-layer-wound coil.

- The contact boundary condition at every adjacent tape along the radial direction
- The identical boundary condition at every adjacent tape along the axial direction
- Pure elastic mechanical property of orthotropic Young's modulus: $(\sigma_r, \sigma_\phi, \sigma_z) = (69, 144, 144)$ [Unit: GPa] [18]

Figs. 2, 3, and 4 show the screening current simulation results of the current density, radial field, and axial field (the background field excluded) distribution, which are displayed in the upper half section of two chosen, different types of REBCO coils. As expected, comparison of the current distribution shows the key difference in screening current induction between the two simulations. As expected, the pancake-wound coil simulation results

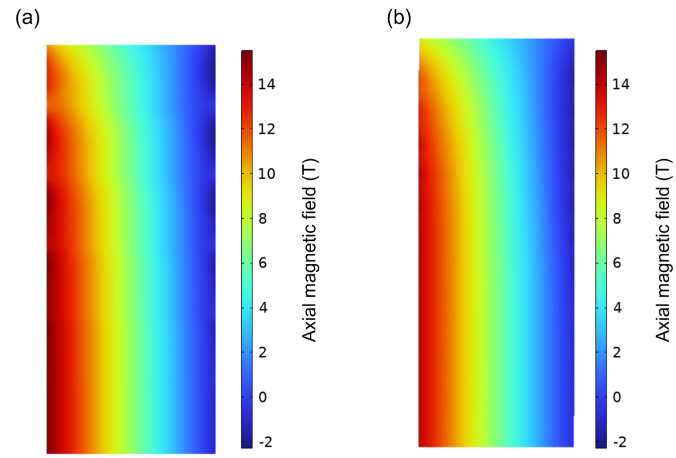

Fig. 4. Axial field distribution displayed in the upper half section of two REBCO coils: (a) a pancake-wound coil and (b) a quasi-layer-wound coil.

show the same direction of screening current induction along the radial direction. However, the screening current induction shows a pattern in which positive (red coloured) and negative (blue coloured) alternate sequentially in the quasi-layer-wound coil case. The magnitudes of the calculated radial and axial fields of the quasi-layer-wound coil are lower than the pancake-wound coil. The peak values of radial and axial fields are 6.7 and 15.4 T for the pancake-wound coil, and 5.7 and 14.3 T for the quasi-layer-wound coil. This results from the lower energy density (or overall current density) due to the void spaces of the quasi-layer-wound coil. One intriguing comparison in the peak magnetic fields is that the difference in the axial field at the coil center is about 7%, but that in the radial field at the coil top or bottom is about 15%; for both fields, the quasi-layer-wound coil simulation results show lower values. This finding explains that the quasi-layer-wound coil could allow less radial field and thus less screening currents at the coil top and bottom.

In the SCS simulation work, we selected a particular location near the top of both coils for this hoop stress comparison since such areas of a pancake-wound coil show the peak hoop stresses, mainly due to the peak radial field penetration and thus large screening current induction, compared to the other areas. One thing we should note here is that the top turns of the quasi-layer-wound coil include Hastelloy tapes, thus lower overall current density, so we selected the area 2 mm below the top surface for a better comparison. To sum up, we selected the area of the top pancake of the pancake-wound coil for both, but the body force resulting from the fields (the background field included) and currents is different.

Fig. 5 shows the calculated hoop stresses and compares the peak hoop stresses. As shown in this figure, there is a notable difference in the hoop stress distribution. For instance, the calculated stress distribution of the quasi-layer-wound coil shows better uniformity than the pancake-wound coil, which notes that the quasi-layer winding option could help spread concentrated (highly amplified) electromagnetic stresses, thus mitigating peak stresses. The peak hoop stress of the quasi-layer-wound coil (990 MPa) is 14% lower than the pancake-wound coil (1150 MPa). Despite this benefit, however, one potential concern is the wider spread of conductor damage where the stress exceeds the transition point from elastic to plastic conductor

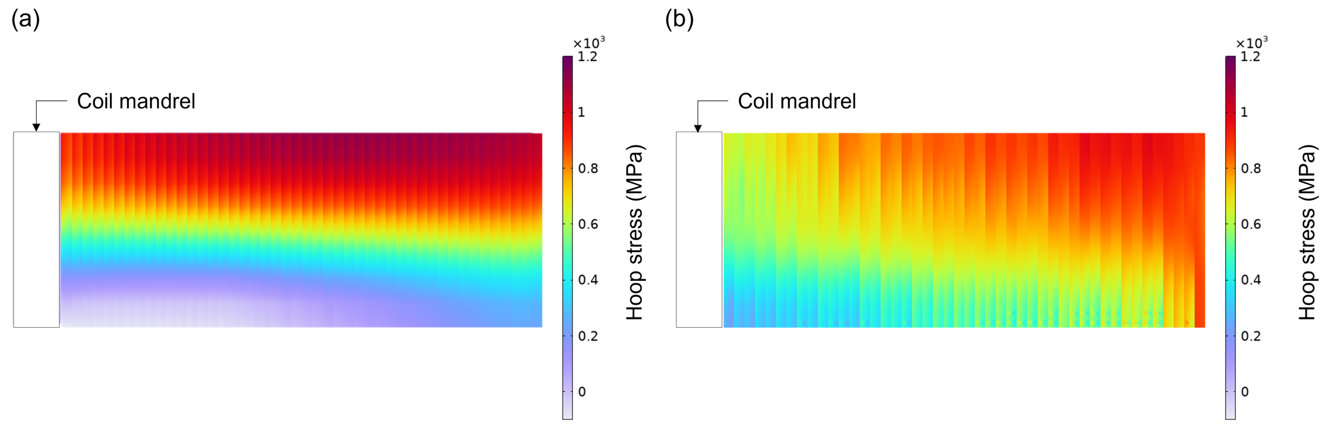

Fig. 5. Hoop stress distribution displayed in the top section of the upper half section of two REBCO coils, where the largest stresses are expected due to excessive SCS: (a) a pancake-wound coil and (b) a quasi-layer-wound coil.

deformation regime if much higher stresses are applied. For instance, pancake-wound coils have a narrow stress concentration area (mostly near to top edges), leading to localized conductor damage, e.g., local kinks or edge waves, but quasi-layer-wound coils may have broader stress amplification and subsequent global conductor damage.

V. Discussion on Quasi-Layer Winding and Cabling Approaches

The simulation work showed SCS mitigation with the quasi-layer winding, so in this section, we explain its feasibility. This approach is implementable with the use of multiple pieces of REBCO tapes and co-winding techniques without large back tension and hard-way bending at the top and bottom of a coil, but a large number of soldering joints are necessary. This requirement leads to a potential concern of heat dissipation, but it could be addressed by reducing joint resistance with advances in conductor technology. For instance, at present, it is possible to make desirable soldering joints having a few nano-ohms within a few-centimeter-long joint [19], [20].

Considering that the key to SCS mitigation presented in this work is to manipulate screening current distribution, a cabling approach with pancake-winding may be an alternative to quasi-layer winding. Fig. 6 shows an example of a cable consisting of three 8 mm wide tapes, a 4 mm wide REBCO tape, and a 4 mm wide Hastelloy tape. Two 8 mm wide tapes on the left side act main current carrier, one 8 mm wide tape does screening current manipulator, thus mitigating SCS. The Hastelloy tape modifies the engineering current density (in this case, 12.5% reduction) while reinforcing mechanical properties. We expect the manipulation of the screening current distribution, referring to our simulation experiences, and SCS mitigation, although further studies are needed.

Our simulation work of a quasi-layer-wound coil is, however, limited in that a 2D-axisymmetric model for a quasi-layer-wound coil is an imperfect representation of the true details of the layer-winding. The current path of a quasi-layer-wound coil cannot be fully described in a 2D-axisymmetric domain due to the winding angle change between odd and even layers, leading to simulation errors in fields and stresses/strains. In addition, conductor rotation [21] and subsequent crystallographic tilt angle change [22] of a quasi-layer-wound coil would differently affect screening current induction and SCS compared to such effects of a pancake-wound coil. The other concern is that the hoop stress is not the principal stress component in the layer-wound coil.

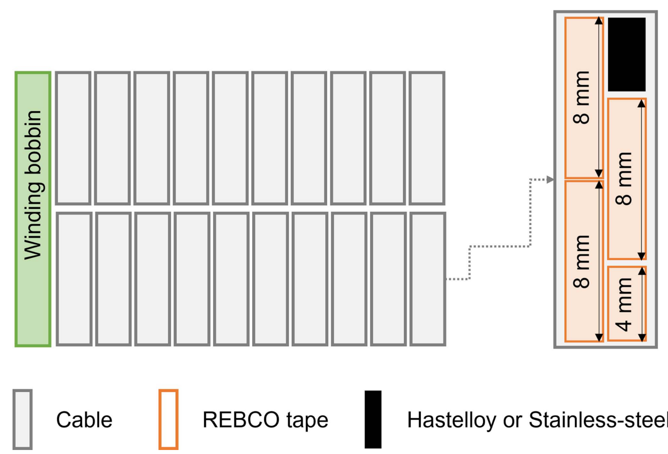

Fig. 6. A cabling option to mitigate excessive stresses for a high-field, high-stress pancake-wound coil.

VI. Conclusion

We compared simulation results of pancake-wound and quasi-layer coils. Two-dimensional axisymmetric simulation models were used for screening current and screening current stress simulations. The key finding is that using the quasi-layer winding method is to manipulate the screening current distribution so as to mitigate screening current stresses. In the chosen case study, over 10% mitigation was evaluated. We discussed a cabling option, considering an alternative to the quasi-layer-winding option, that can realize the manipulation of screening current distribution. However, further studies are needed since some technical challenges and simulation model improvements remain. There will be many other combinations besides the proposed one. We hope to see some simple but effective methods of the layer-winding and cabling approaches for high-field, high-stress superconducting magnets.

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