

Numerical Electromagnetic Field Analyses of Dynamic Losses and Dynamic Resistances in Multilayered Spiral Copper-plated Striated Coated-conductor Cables

Yusuke Sogabe, *Member, IEEE*, Sho Honda, and Naoyuki Amemiya, *Senior Member, IEEE*

Abstract—Spiral Copper-plated Striated Coated-conductor (SCSC) cables are anticipated to be a game-changer for ac applications of high-temperature superconducting technology due to their low ac losses and high robustness. Experiments and numerical electromagnetic field analyses have confirmed that the structure of SCSC cables is effective in reducing dynamic losses and dynamic resistances, which is a problem in flux pumps and rotating machines. However, these results were confirmed for a single copper-plated multifilament coated conductor in a spiral configuration. It remains unclear whether they hold true for SCSC cables with the multilayer structure required for practical current-carrying capacity. Particularly, there is concern that the effect of reducing the dynamic resistance of SCSC cables may be lost due to tape-to-tape interactions caused by an increase in the number of layers or the number of tapes within a layer. We evaluated this using numerical electromagnetic field analyses.

Index Terms—dynamic loss, dynamic resistance, electromagnetic field analysis, multilayer spiral coated conductor cable, SCSC cable

I. INTRODUCTION

A Spiral Copper-plated Striated Coated-conductor (SCSC) cable features a structure where a copper layer is plated to cover the entire group of filaments of a multifilament coated conductor, which has its superconductor layer divided widthwise, and these are wound spirally onto a cylindrical metal core [1–3]. The SCSC cable is a type of high-temperature superconductor (HTS) cable known as spiral-coated-conductor cables [4–10]. The spiral geometry of coated conductors in the SCSC cables shortens the decay time constants of the coupling currents flowing through the copper layer sufficiently, while also achieving reduction in hysteresis losses by multifilament structure under practical frequencies. Furthermore, SCSC cables can relatively easily increase current capacity through a multilayer structure compared to other HTS cables, and their circular cross-section structure also provides high mechanical flexibility. For these

reasons, SCSC cables are expected to be applied to ac machines and magnets requiring the generation of time-varying magnetic fields.

When an alternating magnetic field is applied to a superconductor carrying a direct current, a loss known as dynamic loss occurs [11–13]. Dynamic resistance is the representation of this dynamic loss as resistance to the direct current, and it poses a problem in applications such as flux pumps and rotating machines.

We have demonstrated through experiments and numerical electromagnetic field analyses that the dynamic losses and the dynamic resistance are reduced in samples featuring a spiral configuration of single copper-plated multifilament coated conductors, which is the fundamental structure of SCSC cables [14, 15]. However, since actual SCSC cables are not single wires but rather cables composed of multiple coated conductors assembled into a multilayer structure, there is concern that the dynamic resistance reduction effect may deteriorate or be lost due to electromagnetic interactions among the coated conductors.

To address this concern, numerical electromagnetic field analyses were performed on SCSC cables with varying numbers of layers and coated conductors per layer. The shape of the dynamic region, as well as the magnetic field dependence of dynamic loss and dynamic resistance, were investigated. The influence of electromagnetic interaction among coated conductors on these properties was examined.

II. NUMERICAL ELECTROMAGNETIC FIELD ANALYSIS MODEL

A. *T*-formulation and Thin-strip Approximation [16]

As a numerical electromagnetic field analysis model for SCSC cables, we adopted the *T*-formulation, in which the current vector potential *T* is an unknown variable. We solve the equation derived from Faraday's law, Biot-Savart's law, Ohm's law, and the definition of the current vector potential. In the actual analyses, these equations are combined with the thin-strip approximation, and the following equation is solved using the finite element method:

$$\nabla \times \left(\frac{1}{\sigma} \nabla \times \mathbf{n}T \right) \cdot \mathbf{n} + \frac{\partial}{\partial t} \frac{\mu_0 t_{sc}}{4\pi} \left(\int_{S'} \frac{(\nabla \times \mathbf{n}'T') \times \mathbf{r} \cdot \mathbf{n}}{r^3} dS' + \mathbf{B}_{ext} \cdot \mathbf{n} \right) = 0. \quad (1)$$

This work was supported by JST-ALCA-Next Program Grant Number JPMJAN24G1, Japan. (*Corresponding author: Naoyuki Amemiya*).

The authors are with the Department of Electrical Engineering, Kyoto University, Kyoto 615-8510, Japan (e-mail: amemiya.naoyuki.6a@kyoto-u.ac.jp).

Color versions of one or more of the figures in this article are available online at <http://ieeexplore.ieee.org>

Here, T and T' are current vector potentials at field point and source point, respectively. $\mathbf{n}$ and $\mathbf{n}'$ are the normal vector of the coated conductor at field point and source point, respectively. $\mathbf{r}$ and r are the vector from the source point to the field point and their distance, respectively. t_{sc} is the thickness of the superconductor layer, and σ is the equivalent conductivity of the analyzed region. $\mathbf{B}_{ext}$ is the external magnetic flux density.

When applying the thin-strip approximation to copper-plated multifilament coated conductors, normal-conducting strips were placed between superconductor filaments. The thickness of these normal-conducting strips was made equal to that of the superconductor filaments, and their conductivity was determined by comparing coupling time constant measurements with numerical analyses [17].

B. Definition of Dynamic Regions, Losses, and Resistances

When an alternating magnetic field is applied to a superconductor carrying a direct current, it is known that a region forms at the center of the superconductor where the current density always aligns with the direction of the applied current during the period of the magnetic field [15]. This region is called the dynamic region.

Dynamic loss Q_d is the loss occurring in the dynamic region. In this paper, the loss occurring in regions other than the dynamic region is referred to as magnetization loss Q_m . Q_d and Q_m can be calculated from the current density J distribution and electric field E distribution in each region, obtained from the results of the numerical electromagnetic field analysis described earlier. Furthermore, dynamic resistance R_d is defined by the following equation:

$$R_d = Q_d / I_{t,cable}^2. \quad (2)$$

Here, $I_{t,cable}$ is the transport current of the cable.

III. ANALYZED SCSC CABLES AND ANALYSIS CONDITIONS

To clarify the reduction effects of dynamic loss and dynamic resistance in multilayer SCSC cables, we performed numerical electromagnetic field analyses on the four types of cables listed in Table 1. As an example of a practical multilayered SCSC cable, the SCSC cable named as 4L-3T was analyzed. Additionally, to separately investigate the effects of electromagnetic interactions among HTS tapes within the same layer and HTS tapes in

different layers, cables with impractical structures—namely 1L-1T, 1L-3T, and 4L-1T—were also analyzed.

All these cables were composed of the same HTS tapes. The width and thickness of the tape were 2 mm and 54 μm , respectively. The plated copper layer around the HTS tape was 10 μm thick, and the thickness of the superconductor layer was 2 μm . The superconductor layer was divided into 10 filaments with the width of 155 μm each. The parameters of these HTS tapes conform to those of HTS tapes used in actual SCSC cables [2]. For the electric field E –current density J characteristics of the coated conductors, the power-law model incorporating the magnetic field and its angle dependence of $I_{c0,tape}$ and n -value was employed [18]. The dataset of E – J characteristics of a coated conductor manufactured by SuperPower Inc. from the Robinson Research Institute HTS Wire Critical Current Database [19] were used for parameter fitting of E – J characteristics in the analyses.

The analyses were performed by varying the load ratio $i = I_{t,cable} / (I_{c0,tape} \times n_t)$ and the external magnetic field amplitude B_{ext} . Note that the analyses assume equal current flow through each coated conductor. This is because the cables analyzed here are short in length, and current distribution is dominated by terminal resistance. The frequency of the external magnetic field f was set to 200 Hz, and the temperature was set to 77 K. In aircraft motors, a potential application for SCSC cables, the cables are expected to be exposed to an alternating magnetic field of approximately 200 Hz. On the other hand, it is generally known that dynamic losses and dynamic resistance do not exhibit frequency dependence, and this holds true for SCSC cables as well. Furthermore, considering that this analysis involves large degrees of freedom and is relatively large-scale, this paper fixed the external magnetic field frequency at 200 Hz for evaluation. Note that for the analysis of 4L-3T, due to the extremely large degrees of freedom, B_{ext} and i were fixed at $B_{ext} = 100$ mT and $i = 0.6$.

IV. ANALYSIS RESULTS

A. Dynamic regions in SCSC cables

Fig. 1 illustrates the dynamic regions for the 1L-1T, 1L-3T, and 4L-1T cables under the conditions $B_{ext} = 60$ mT and $i = 0.6$. In this paper, the analysis results are compared when the load ratio i of the cables is made the same to standardize the transport current conditions across different cables. Note that this does not mean the current flowing through the cables, $I_{t,cable}$ is identical. The dynamic region of 1L-1T, as previously reported in [15], was distributed in each filament. This is because, at $f = 200$ Hz in this analysis, the electromagnetic coupling among the filaments was completely decoupled due to the shortening effect of the coupling time constant resulting from the spiral configuration of copper-plated multifilament coated conductors in SCSC cables.

The distribution of the dynamic region within each coated conductor in 1L-1T and 1L-3T was nearly identical. This indicates that the number of coated conductors present within the same layer does not affect the shape of the dynamic region; therefore, the electromagnetic field distribution within the coated conductors is also not affected. Furthermore, the distribution of the dynamic region in 1L-1T and 4L-1T was similarly nearly

TABLE I
SPECIFICATIONS OF ANALYZED SCSC CABLES

Cable Name	1L-1T	1L-3T	4L-1T	4L-3T
No. layers	1	1	4	4
No. tapes / layer	1	3	1	3
No. tapes / cable n_t	1	3	4	12
Cable length	100 mm			
Winding angle	55°			
Core diameter	3 mm			
$I_{c0,tape}$	57.6 A			

2-LP-AC.44

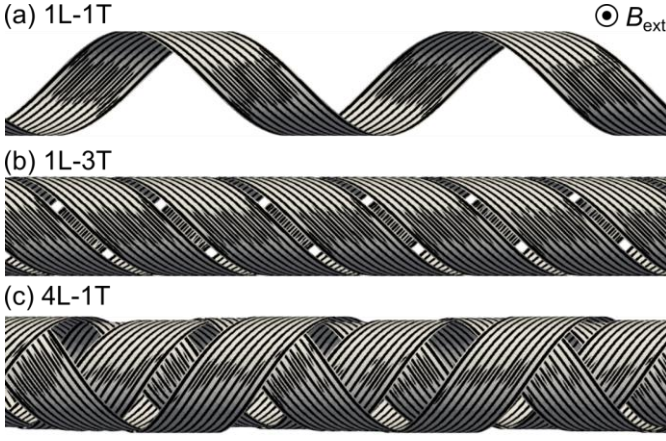


Fig. 1. Dynamic regions of (a) 1L-1T, (b) 1L-3T, and (c) 4L-1T, when $B_{\text{ext}} = 60$ mT and $i = 0.6$. Black parts are dynamic regions, and white parts are the other regions.

identical. This result indicates that electromagnetic interactions among layers also have negligible effects on the electromagnetic field distribution within the coated conductor. Magnetization in coated conductors occurs perpendicular to their flat-wise surface. Therefore, interlayer electromagnetic interactions are thought to be more influential than electromagnetic interactions among coated conductors within the same layer. However, in practice, both are found to be negligible. This is attributed to the extremely low magnetization of copper-plated multifilament coated conductors under the condition which the filaments were completely decoupled, rendering them negligible in response to external magnetic fields.

B. Dynamic Losses and Magnetization Losses

Fig. 2 shows the magnetic field amplitude dependence of dynamic losses in the three cables (1L-1T, 1L-3T, and 4L-1T) whose dynamic regions were indicated in the previous section with different i values. In this figure, note that Q_d is plotted as dynamic loss per tape for the purpose of comparing electromagnetic phenomena within the tapes. As expected from the nearly identical shapes of the dynamic regions, the dependence of dynamic losses on magnetic field amplitude was nearly identical for all these cables. The ratio of B_{ext} to the tape's magnetization $\mu_0 M$ governs whether electromagnetic interactions among tapes affect dynamic losses. Namely, the electromagnetic interactions among coated conductors can be more pronounced in the low magnetic field conditions; however, no clear difference was observed. This is because the magnetization of copper-plated multifilament coated conductors in a state where the filaments are completely decoupled is extremely small (e.g., on the tape surface, $\mu_0 M$ is of the order of 0.01 mT).

Although this digresses slightly from the main focus of this paper, we will also discuss magnetization loss Q_m , which occurs in regions outside the dynamic region. Fig. 3 shows the magnetic field amplitude dependence of Q_m per tape for $i = 0.6$ in 1L-1T, 1L-3T, and 4L-1T. The Q_m values for these cables were nearly identical for all magnetic field amplitudes, consistent with the matching shapes of the dynamic regions and characteristics of dynamic losses.

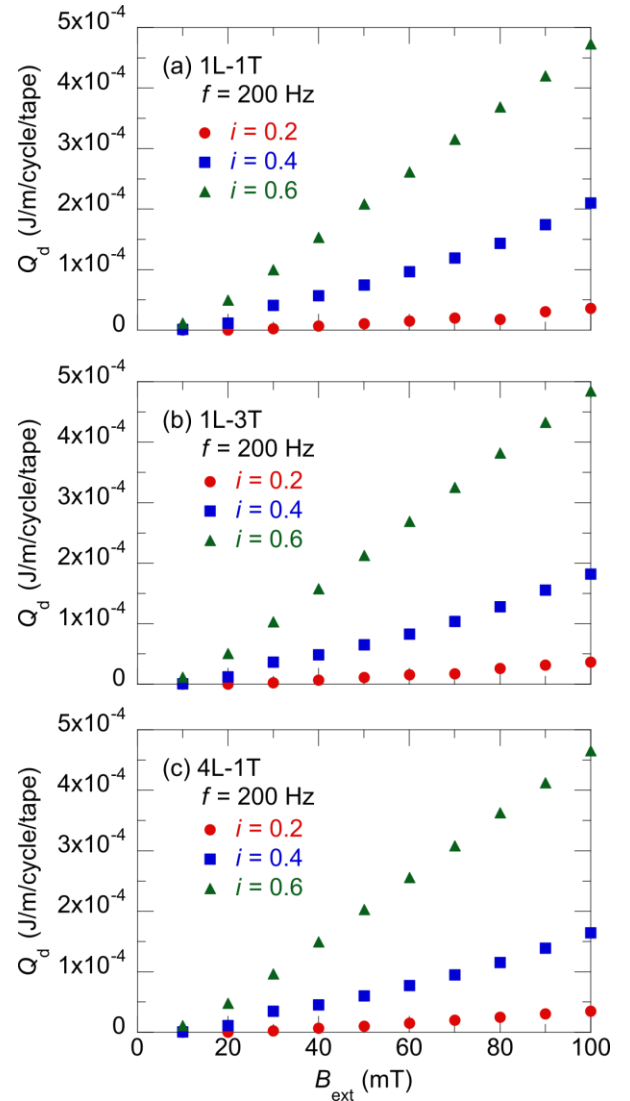


Fig. 2. Magnetic field amplitude dependence of dynamic losses Q_d in (a) 1L-1T, (b) 1L-3T, and (c) 4L-1T for different i . Note that in this figure, Q_d is plotted as dynamic loss per tape.

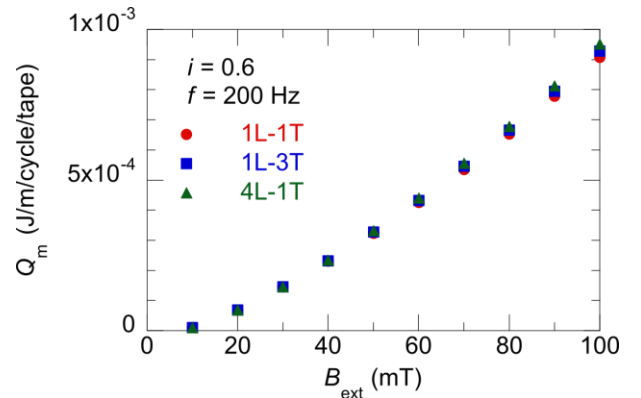


Fig. 3. Magnetic field amplitude dependence of magnetization losses Q_m in (a) 1L-1T, (b) 1L-3T, and (c) 4L-1T for $i = 0.6$. Note that in this figure, Q_m is plotted as magnetization loss per tape.

C. Comparison between 1L-1T and 4L-3T

Fig. 4 shows a comparison of the losses per layer at $B_{\text{ext}} = 100$ mT and $i = 0.6$ in the 4L-3T cable. Layer 1 is the innermost layer of the cable, while layer 4 is the outermost layer. While Q_d remained nearly constant across all layers, Q_m tended to be slightly greater in the outer layers. This is presumably due to the dynamic region disappearing in the area where the coated conductors become parallel to the external magnetic field, and only magnetization loss occurs. This area expands in the outer layer where the spiral winding diameter increases. Although magnetization loss occurring in this area is relatively small, the area size difference could cause the Q_m difference in each layer. Considering that the results obtained with the cables discussed in IV.A. and IV.B., and that the dynamic losses have not changed across each layer, it can be said that the electromagnetic interaction among coated conductors in 4L-3T is also negligible.

Fig. 5 shows the dynamic loss per cable $Q_{d,\text{cable}}$ and dynamic resistance of cable $R_{d,\text{cable}}$ for 1L-1T and 4L-3T for $B_{\text{ext}} = 100$ mT and $i = 0.6$. Under these conditions, $Q_{d,\text{cable}}$ of 4L-3T was approximately 10 times that of 1L-1T. This difference can be understood as stemming from the ratio of n_t included in the SCSC cables. As pointed out previously, there is nearly no increase in dynamic losses per coated conductor in cables formed by assembling multiple coated conductors due to electromagnetic interactions among them. Therefore, $Q_{d,\text{cable}}$ can be expressed as $Q_{d,\text{cable}} = Q_{d,\text{tape}} \times n_t$, here, $Q_{d,\text{tape}}$ is the dynamic loss when a single tape is wound spirally. The ratio $Q_{d,\text{cable}}$ of in 1L-1T to those in 4L-3T is close to the ratio of n_t , suggesting that this prediction is correct.

Next, the relationship between $R_{d,\text{cable}}$ and $Q_{d,\text{cable}}$ is expressed as shown in equation (2). Since the current flowing through the cable is proportional to the number of coated conductors when their critical currents are all identical, namely $I_{t,\text{cable}} = I_{t,\text{tape}} \times n_t$. Based on this and considerations regarding $Q_{d,\text{cable}}$, equation (2) can be rewritten as follows:

$$R_{d,\text{cable}} = \frac{Q_{d,\text{cable}}}{I_{t,\text{cable}}^2} = \frac{Q_{d,\text{tape}} \times n_t}{(I_{t,\text{tape}} \times n_t)^2} = \frac{1}{n_t} \frac{Q_{d,\text{tape}}}{I_{t,\text{tape}}^2}. \quad (3)$$

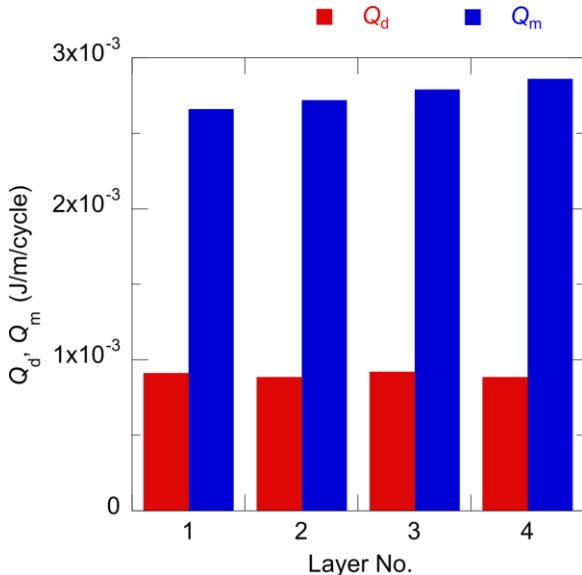


Fig. 4. Dynamic losses Q_d and magnetization loss Q_m per layer in 4L-3T for $B_{\text{ext}} = 100$ mT and $i = 0.6$.

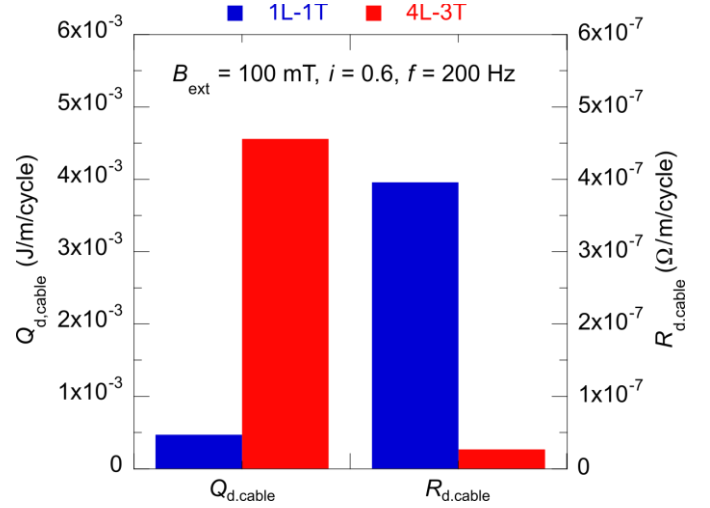


Fig. 5. Comparison of dynamic losses Q_d and dynamic resistance R_d between 1L-1T and 4L-3T for $B_{\text{ext}} = 100$ mT and $i = 0.6$.

Here, if we define the dynamic resistance of a single tape wound spirally as $R_{d,\text{tape}} = Q_{d,\text{tape}} / I_{t,\text{tape}}^2$, $R_{d,\text{cable}} = R_{d,\text{tape}} / n_t$. That is, in this case, $Q_{d,\text{cable}}$ is proportional to n_t , while $R_{d,\text{cable}}$ is inversely proportional to n_t . The relationship between $R_{d,\text{cable}}$ and n_t can similarly be derived by considering the following. In an SCSC cable where the same current flows through all tapes, the dynamic losses in the tapes constituting the cable are equal, and the dynamic resistance in all tapes becomes equal. Since these tapes are connected in parallel electrically, the resistance seen across the entire cable (corresponding to $R_{d,\text{cable}}$) is inversely proportional to n_t . The result of R_d in Fig. 5 is consistent with these discussions.

V. CONCLUSION

Numerical electromagnetic field analyses were performed on multiple multilayered SCSC cables under conditions of direct current energization and applied alternating external magnetic fields to investigate electromagnetic phenomena within the cables. The electromagnetic interactions among the coated conductors composing the cable had little effect on the electromagnetic field distribution within the coated conductors, and the dynamic losses and magnetization losses were nearly identical for each coated conductor. As a result, the dynamic losses of the multilayered SCSC cables were proportional to the numbers of coated conductors contained within the cable, while the dynamic resistances were inversely proportional to them.

Future challenges include investigating the effects of dynamic losses and dynamic resistance under more practical conditions, specifically when cables are longer and current distribution among coated conductors becomes non-uniform due to inductance imbalance. Additionally, further evaluations will be needed for cables with an increased number of coated conductors, as well as when operating temperatures are lower and the applied current and/or magnetic field is greater.

REFERENCES

- [1] Y. Sogabe, Y. Mizobata, and N. Amemiya, "Coupling time constants and ac loss characteristics of spiral copper-plated striated coated-conductor

- cables (SCSC cables),” *Supercond. Sci. Technol.*, vol. 33, no. 5, May 2020, Art. no. 055008.
- [2] N. Amemiya, *et al.*, “Effective reduction of magnetisation losses in copper-plated multifilament coated conductors using spiral geometry,” *Supercond. Sci. Technol.*, vol. 35, no. 2, Feb. 2022, Art. no. 025003.
- [3] M. Shigemasa, *et al.*, “Impact of Number of Layers on Magnetization Losses of Spiral Copper-Plated Multifilament Coated Conductors,” *IEEE Trans. Appl. Supercond.*, vol. 33, no. 5, Aug. 2023, Art. no. 5901406.
- [4] D.C. van der Laan, J.D. Weiss, and D.M. McRae, “Status of CORC® cables and wires for use in high-field magnets and power systems a decade after their introduction,” *Supercond. Sci. Technol.*, vol. 32, no. 3, Mar. 2019, Art. no. 033001.
- [5] D.C. van der Laan, *et al.*, “CORC® wires allowing bending to 20 mm radius with 97.5% retention in critical current and having an engineering current density of 530 A mm⁻² at 20 T,” *Supercond. Sci. Technol.*, vol. 37, no. 11, Nov. 2024, Art. no. 115007.
- [6] R. Teyber, *et al.*, “Numerical investigation of current distributions around defects in high temperature superconducting CORC® cables,” *Supercond. Sci. Technol.*, vol. 35, no. 9, Sep. 2022, Art. no. 094008.
- [7] M.D. Sumption, *et al.*, “AC losses of Roebel and CORC® cables at higher AC magnetic fields and ramp rates,” *Supercond. Sci. Technol.*, vol. 35, no. 2, Feb. 2022, Art. no. 025006.
- [8] S. Kar, *et al.*, “Optimum Copper Stabilizer Thickness for Symmetric Tape Round (STAR) REBCO Wires With Superior Mechanical Properties for Accelerator Magnet Applications,” *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, Aug. 2019, Art. no. 6602605.
- [9] M. Solovyov, *et al.*, “Magnetization AC losses in multilayer superconducting round cables with coinciding and opposite lay angles,” *Supercond. Sci. Technol.*, vol. 36, no. 3, Mar. 2023, Art. no. 034001.
- [10] F. Gömöry, *et al.*, “Design and Testing of Coils Wound Using the Conductor-On-Round-Tube (CORT) Cable,” *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. no. 4600305.
- [11] B. Taquet, “Superconducting Coil Degradation,” *J. Appl. Phys.*, vol. 36, no. 10, Oct. 1965, pp. 3250–55.
- [12] H. Zhang, *et al.*, “Dynamic resistance and dynamic loss in a ReBCO superconductor,” *Supercond. Sci. Technol.*, vol. 35, no. 11, Nov. 2022, Art. no. 113001.
- [13] Y. Qiao, *et al.*, “Simulation of Dynamic Resistance and Total Loss of HTS CORC Cables,” *IEEE Access*, vol. 11, pp. 797–807, 2023.
- [14] Y. Sogabe and N. Amemiya, “Effect of dynamic resistance reduction in spiral copper-plated multifilament coated conductors,” *Supercond. Sci. Technol.*, vol. 38, no. 1, Jan. 2025, Art. no. 015002.
- [15] Y. Sogabe, S. Honda, and N. Amemiya, “Numerical Electromagnetic Field Analyses of Spiral Copper-Plated Striated Coated-Conductor (SCSC) Cables Carrying DC Current Subjected to AC Magnetic Fields,” *IEEE Trans. Appl. Supercond.*, vol. 35, no. 5, Aug. 2025, Art. no. 5901205.
- [16] T. Mifune, *et al.*, “Large-scale electromagnetic field analyses of coils wound with coated conductors using a current-vector-potential formulation with a thin-strip approximation,” *Supercond. Sci. Technol.*, vol. 32, no. 9, Sep. 2019, Art. no. 094002.
- [17] N. Amemiya, *et al.*, “Shielding current in a copper-plated multifilament coated conductor wound into a single pancake coil and exposed to a normal magnetic field,” *Supercond. Sci. Technol.*, vol. 32, no. 11, Nov. 2019, Art. no. 115008.
- [18] Y. Sogabe, *et al.*, “AC Loss Characteristics in REBCO Coil Assemblies With Different Geometries and Conductors,” *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, Apr. 2018, Art. no. 4700150.
- [19] The Robinson Research Institute HTS Wire Critical Current Database, <https://htsdb.wimbush.eu/dataset/4256624>.