A Simplified Model of the Field Dependence for HTS Conductor on Round Core (CORC) Cables

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***Abstract* — This article presents a simplified mathematical model of the anisotropic magnetic field dependence (AMFD) for simulating the High-temperature superconducting (HTS) Conductor on Round Core (CORC) Cables. All these simulations of HTS CORC Cable were performed based on the finite-element method (FEM) *H*-formulation model merged into the numerical platform COMSOL Multi-physics. The simplified model of AMFD was implemented into both the 2-dimension (2D) and 3-dimension (3D) *H*-formulation models of HTS CORC cables. Their results were studied with different conditions, such as the increasing transport current, as well as the gap angle between the superconducting tapes in a single layer. This new simplified AMFD model can give a proper approximation of the actual electromagnetic behaviours of the HTS CORC, but also establish the upper limit of the AC loss calculation, which can be fairly useful for designing future HTS CORC cables.**

***Index Terms* —High-temperature superconductor (HTS), HTS cable, Conductor on Round Core (CORC), Anisotropic magnetic field dependence (AMFD), Finite element method (FEM), AC loss.**

I. Introduction

In the 21th century, the 2nd Generation (2G) High-temperature superconductor (HTS) has been extensively tested for the scientific research purpose, but also started to contribute for the real life of human beings . The HTS exhibits the superiors in various power applications as its extraordinary high current density and almost zero loss operation [1-3]. The HTS cable for electrical power transmission is no doubt an excellent example which takes both of these advantages, and there are several types of HTS cables which have been vastly investigated in the superconductivity community: the twisted stack cables, Roebel cables, and Conductor on Round Core (CORC). CORC owns its great advantages on the easy fabrication, good mechanical stability, proper isotropic field characteristics, and the potential for the long distance cabling [4].

Experiments and simulations have proved that CORC cables possess the superiority of the comparably low AC loss when they are in the presence of AC magnetic field or transporting AC current [5]. It is understandable that the field shielding effect can be created by each HTS tape in a single layer, and this effect can theoretically cause the AC loss per tape to be even less than the AC loss of an isolated single tape carrying the same AC transport current [6]. However, this is very difficult to achieve in the reality, because the 2G HTS tape possess the strong anisotropic magnetic field dependent behavior, and it can give rise to more AC loss.

For the modeling of CORC, it is fairly challenging to implant the model of anisotropic magnetic field dependence (AMFD), because the superconducting tapes laying on the CORC central former are not in the perfectly straight line, and it is very difficult to define the perpendicular and parallel magnetic flux components (usually called $\boldsymbol{B}_{perp}$ and $\boldsymbol{B}_{para}$) in the bending parts of superconducting tapes. Nevertheless, without the proper AMFD, the numerical model will underestimate the value of AC loss.

In this paper, therefore, we demonstrate a new simplified model of AMFD for simulating HTS CORC cables. The field dependent model was evaluated by both the 2D and 3D CORC model, with various transport currents and the gap angles between the HTS tapes in a single layer. By using this new AMFD model, following results show the reasonable electromagnetic characteristics of HTS CORC cables can be well simulated, and the upper boundary of the AC loss can be calculated. This simplified model is efficient and helpful for designing future superconducting CORC cables.

II. Model Explanation

As shown in Fig. 1, for the purpose of verifying the feasibility of the simplified model of AMFD, a relatively basic geometry of CORC cable was modeled: A single layer CORC has 4 HTS tapes on it. The 2G HTS tape, 4 mm width, with the critical current 100 A in the field-free condition, was used to model the CORC cable. In order to investigate the details inside each superconducting tape, the

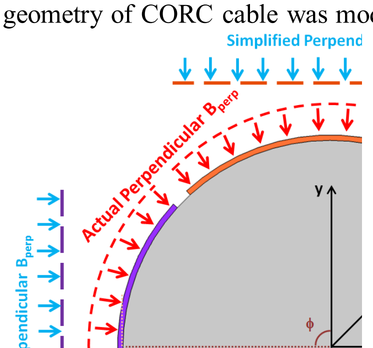

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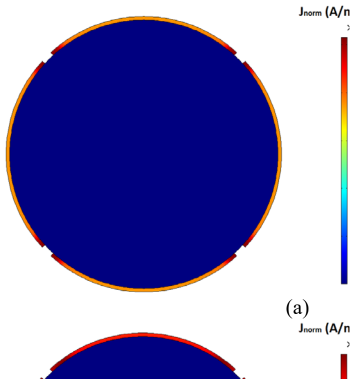
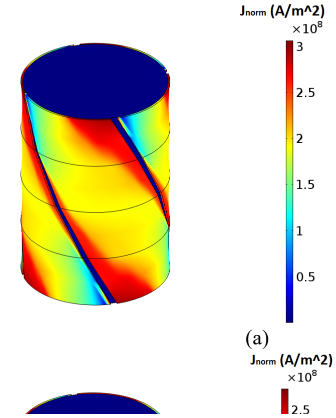
TABLE I. PARAMETERS OF CORC CABLE MODEL

Parameters
Number of HTS tapes per layer
Number of layer
Tape gap
Radius of former
Pitch
HTS Tape width





homogenization method was used to artificially expand 100 times of the thickness of the HTS tape to 100 μm. The gap angle between each HTS tape changed from 5° to 20°. The central former was modeled as the copper with a radius of 4.63 mm. Other parameters of this CORC cable modeling can be seen in Table I.

For both the 2D and 3D CORC models, their geometry parameters matched each other. For the 3D CORC model, the degree of twist, pitch, was fixed at 45.2 mm. Only a quarter of the entire pitch was modeled for the 3D CORC model, which can efficiently reduce the computation time.

The *H*-formulation partial differential equation (PDE) was implanted into the FEM software COMSOL Multi-physics, which was used throughout the 2D and 3D CORC modeling. The detailed explanation on how to derive *H*-formulation for both the 2D and 3D modeling can be seen in [7, 8]. As the only one variable ***H***, the magnetic field intensity, the general form of *H*-formulation is [9, 10]:

$$\frac{\partial(\mu_0\mu_r\boldsymbol{H})}{\partial t}+\nabla\times(\rho\nabla\times\boldsymbol{H})=0 \qquad (1)$$

Equation (1) was implemented into the FEM software COMSOL as the governing equation [11].

The transport currents were injected into the terminal cross-sections of the CORC cable, which was realized by the "Global Constraint" physics in COMSOL software. The Ω is the chosen domain of HTS materials, and the *T* is the time period of one cycle. The power loss per cycle was calculated using the integration of the ***E*** Electric Field, and the ***J*** Electric Current Density, over the HTS domain [12, 13]:

$$Q=\frac{2}{T}\int_{0.5T}^{T}\int_{\Omega}\boldsymbol{E}\cdot\boldsymbol{J}\quad d\Omega dt \qquad (2)$$

The frequency in this study was set as 50 Hz. the power index for the *E-J* resistive power law was set as a typical value of 25. The anisotropic ***B***-dependent critical current model (with magnetic field component $\boldsymbol{B}_{perp}$ in the perpendicular direction, and $\boldsymbol{B}_{para}$ in the parallel direction) was merged into the basic ***H***-formulation model [14]:

$$J_c(B)=\frac{J_{c0}}{\left(1+\frac{\sqrt{(k\boldsymbol{B}_{para})^2+\boldsymbol{B}_{perp}^{\;2}}}{\boldsymbol{B}_c}\right)^b} \qquad (3)$$

where the $B_c = 0.035$, $k = 0.25$, and $b = 0.6$ were set for this study.

The model of the AMFD is crucial to the success of AC loss calculation for HTS. How to define the magnetic field component $\boldsymbol{B}_{perp}$ in perpendicular direction, and $\boldsymbol{B}_{para}$ in parallel direction, can be really challenging for the CORC modeling, as the shape of each HTS tape laying on the CORC former is curving. One method could be dividing each HTS tape into much smaller pieces, and setting each piece using different models of the anisotropic magnetic field dependence. However, this method is very time consuming, particularly for the 3D model, and will add much more complications to the model and might cause extra calculation errors.

Fig. 1 demonstrates a simplified model of AMFD. The actual perpendicular components of magnetic field on each HTS tape are radial. In the CORC design, the perimeter of former is generally much greater (usually at least 3-4 times) than the width of HTS tapes. The real bending perpendicular magnetic flux components $\boldsymbol{B}_{perp}$ are close to the ideational straight HTS tape in the tangential line position to the central former. Therefore, an approximation can be used that assuming perpendicular magnetic flux components $\boldsymbol{B}_{perp}$ are all in the orientation perpendicular to the tangential line where the center point of each HTS tape locates, as shown in Fig. 1.

This approximation can be used for any numbers of HTS tapes in a single layer of a CORC cable. In Fig.1, it is a 4-tape CORC cable, which could be an easiest example for the demonstration. Assume the angle ϕ between the y-axis and the radius was perpendicular to the tangential line of a HTS tape (central point). In the 2D CORC model, the approximated perpendicular field components $\boldsymbol{B}_{perp}$ and parallel field components $\boldsymbol{B}_{para}$ can be derived:

$$B_{perp}=B_x\sin(\varphi)+B_y\cos(\varphi) \qquad (4)$$

$$B_{para}=B_x\cos(\varphi)+B_y\sin(\varphi) \qquad (5)$$

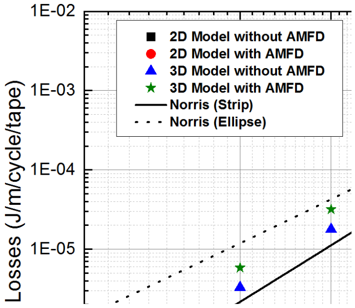
If in the 3D CORC model, both the approximated perpendicular field components $\boldsymbol{B}_{perp}$ and parallel field components $\boldsymbol{B}_{para}$ will be revolving while the HTS tapes twisting with an angle α:

$$\alpha=\frac{2\pi z}{l_{pitch}} \qquad (6)$$

$$B_{perp}=B_x\sin(\varphi)\sin(\alpha)+B_y\cos(\varphi)\cos(\alpha) \qquad (7)$$

$$B_{para}=B_x\cos(\varphi)\cos(\alpha)+B_y\sin(\varphi)\sin(\alpha) \qquad (8)$$

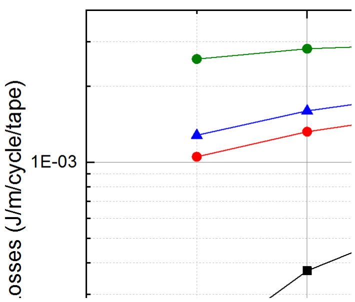
where z is the depth of location in the z-direction, and the l_{pitch} is the length of an entire pitch of CORC cable. These approximated perpendicular field components $\boldsymbol{B}_{perp}$ and parallel field components $\boldsymbol{B}_{para}$ were implanted into equation (3) for both the 2D and 3D CORC modeling.



III. Results and Analysis

A. Current Density Distribution

Fig. 2 shows the current density distribution from the 2D CORC model at the moment that the CORC cable was carrying the peak current of 80% I_c, (a) without the model of AMFD, (b) with the J_cB model of AMFD. In Fig. 2(a), the relatively high current density was located in the two sides of each HTS tape while relatively low current density was located in the middle, but in Fig. 2(b) this phenomenon of extreme was much less obvious with the J_cB model of AMFD: current density was relatively uniform throughout the cross-section of HTS tape. This could be due to the J_cB model of AMFD could expel the biggest current density in the edge of HTS tapes, where strongest magnetic fields generally appeared.



As shown in the Fig. 3, the current density distribution from the 3D CORC model was plot at the moment that the CORC cable was carrying the peak current of 80% I_c, (a) without the model of AMFD, and (b) with the J_cB model of AMFD. Similar pattern from Fig. 2 can be seen in Fig. 3 that current density from the CORC model with the AMFD model was more evenly distributed than that from the CORC model without the AMFD model. By comparing Fig. 3(a) and Fig. 3(b), the difference was the symmetry of current density from the cable top and cable bottom: good symmetry appeared in the CORC model (a) without the AMFD model, but asymmetry was not obvious in the CORC model (b) with the AMFD model. These reveals the 3D CORC model with the AMFD model could produce more realistic results.

B. AC Loss

To carry out a more precise analysis, Fig. 4 presents the AC loss calculation (per tape, and per unit length) of the 2D and 3D CORC models, with or without the model of AMFD, with the gap angle 5° and AC transport current increasing to the full critical current, and with the references of Norris strip and Norris ellipse. It can be seen that the AC loss calculation from 2D model without the model of AMFD was always far below other three cases and Norris strip/ellipse. The AC loss calculation from 2D model with the AMFD model was firstly not far away from the 2D model without it, but was approaching the AC loss result of 3D model without the AMFD model, when the transport current was in the greater level. The AC loss from 3D model without the AMFD model was above the Norris strip if transport current was below 50% I_c, but was smaller than the Norris strip soon from this point onward. The AC loss calculation from 3D model with the AMFD model was slightly lower than Norris ellipse where the transport current was below 40% I_c, but the increasing trend was gradually less steep and finally approaching the Norris strip analytical result, which presents the most reasonable loss results among four cases.

Fig. 5 illustrates the AC loss calculation (per tape, and per unit length) of the 2D and 3D CORC models, with or without the model of AMFD, with AC transport current at peak I_c, and with increasing gap angle from 5° to 20°. Similar to Fig. 4, compared with other 3 cases, the loss curve from the 2D model without the model of AMFD was still always far below. The loss curve from the 3D model without the AMFD model was slightly higher than the AC loss curve of 2D model with the AMFD model, and their rising trends with the increasing gap angle were similar. The AC loss calculation from the 3D model with the AMFD model kept the highest among all these cases. It can be discovered that the increasing rate from the CORC model with the AMFD model was less sensitive than the increasing rate from the CORC model without the AMFD model, for both the 2D and 3D models. That could be due to the AMFD model had the effects on uniforming the high current density.

IV. Conclusion

A new simplified model of AMFD was established, which was used for the modeling of HTS CORC (both the 2D and 3D). The model was validated using the ***H***-formulation based on the FEM software COMSOL Multiphysics (using Intel(R) Xeon(R) CPU E5-1620 v4 @ 3.50GHz, 32.0 GB RAM). The current density distribution was studied by comparing the CORC models with or without the model of AMFD. Later the AC losses from the CORC model with or without the AMFD model were simulated with the increasing current, and different gap angles between the HTS tapes.

To summarize, the 2D model without the AMFD model could not simulate the AC loss from a CORC cable in a relatively acceptable range, and the 2D model with the AMFD model could only calculate the AC loss for reasonable values with the higher transport current close to critical current. The 3D CORC model with this new simplified AMFD model could simulate the AC loss in a reasonable range, whose simulated loss values could slightly greater than the experimental ones, but it has the advantage of predicting the upper limit of the loss, and with a faster computation speed. This novel simplified model and the analytical method are valid for different structures of CORC cables, which will be fairly useful for the future design of superconducting CORC cables.

V. References

[1] D. Larbalestier, A. Gurevich, D. M. Feldmann, and A. Polyanskii, "High-Tc superconducting materials for electric power applications," *Nature,* vol. 414, pp. 368-377, 2001.

[2] J. X. Jin, Y. J. Tang, X. Y. Xiao, B. X. Du, Q. L. Wang, J. H. Wang, S. H. Wang, Y. F. Bi, and J. G. Zhu, "HTS power devices and systems: Principles, characteristics, performance, and efficiency," *IEEE Trans. Appl. Supercond.,* vol. 26, no. 7, 2016.

[3] J. X. Jin, Y. Xin, Q. L. Wang, Y. S. He, C. B. Cai, Y. S. Wang, and Z. M. Wang, "Enabling high-temperature superconducting technologies toward practical applications," *IEEE Trans. Appl. Supercond.,* vol. 24, no. 5, 2014.

[4] J. D. Weiss, T. Mulder, H. J. ten Kate, and D. C. van der Laan, "Introduction of CORC® wires: highly flexible, round high-temperature superconducting wires for magnet and power transmission applications," *Supercond. Sci. Technol.,* vol. 30, no. 1, 2016.

[5] J. Sheng, M. Vojenčiak, R. Terzioğlu, L. Frolek, and F. Gömöry, "Numerical study on magnetization characteristics of superconducting conductor on round core cables," *IEEE Trans. Appl. Supercond.,* vol. 27, no. 4, 2016.

[6] B. Shen, J. Li, J. Geng, L. Fu, X. Zhang, H. Zhang, C. Li, F. Grilli, and T. A. Coombs, "Investigation of AC losses in horizontally parallel HTS tapes," *Supercond. Sci. Technol.,* vol. 30, no. 7, 2017, Art. no. 075006.

[7] B. Shen, F. Grilli, and T. Coombs, “Review of the AC Loss Computation for HTS using H formulation,” *Supercond. Sci. Technol.,* vol. 33, no. 3, 2020, Art. no. 033002.

[8] Z. Hong, A. Campbell, and T. Coombs, “Numerical solution of critical state in superconductivity by finite element software,” *Supercond. Sci. Technol.,* vol. 19, no. 12, pp. 1246-1252, 2006.

[9] B. Shen, F. Grilli, and T. Coombs, “Overview of H-formulation: a versatile tool for modelling electromagnetics in high-temperature superconductor applications,” *IEEE Access,* vol. 8, pp. 100403-100414, 2020.

[10] R. Brambilla, F. Grilli, and L. Martini, “Development of an edge-element model for AC loss computation of high-temperature superconductors,” *Supercond. Sci. Technol.,* vol. 20, no. 1, pp. 16-24, 2007.

[11] B. Shen, C. Li, J. Geng, X. Zhang, J. Gawith, J. Ma, Y. Liu, F. Grilli, and T. A. Coombs, “Power dissipation in HTS coated conductor coils under the simultaneous action of AC and DC currents and fields,” *Supercond. Sci. Technol.,* vol. 31, no. 7, 2018, Art. no. 075005.

[12] C. Kan, Y. Wang, X. Yuan, Y. Li, and Y. Hou, “AC loss analysis on a quasi-isotropic strand stacked by 2G wires by numerical simulation in cryogenic temperature,” *IEEE Trans. Appl. Supercond.,* vol. 28, no. 3, 2017, Art. no. 8200206.

[13] B. Shen, T. Coombs, and F. Grilli, “Investigation of AC Loss in HTS Cross-Conductor Cables for Electrical Power Transmission,” *IEEE Trans. Appl. Supercond.,* vol. 29, no. 2, 2019, Art. no. 5900205.

[14] F. Grilli, F. Sirois, V. M. Zermeno, and M. Vojenčiak, “Self-consistent modeling of the Ic of HTS devices: How accurate do models really need to be?,” *IEEE Trans. Appl. Supercond.,* vol. 24, no. 6, 2014, Art. no. 8000508.