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Total AC loss study of 2G HTS coils for fully HTS machine applications

Min Zhang[1], Weijia Yuan[1], Jozef Kvitkovic[2] and Sastry Pamidi[2,3]

[1] Department of Electronic and Electrical Engineering, University of Bath, BA2 7A1, UK
[2] Center for Advanced Power Systems at Florida State University, Tallahassee, FL 32310, USA
[3] Department of Electrical and Computer Engineering, FAMU-FSU College of Engineering, Tallahassee, FL, USA

E-mail: m.zhang2@bath.ac.uk

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Abstract

The application of HTS coils for fully HTS machines has become a new research focus. In the stator of an electrical machine, HTS coils are subjected to a combination of an AC applied current and AC external magnetic field. There is a phase shift between the AC current and AC magnetic field. In order to understand and estimate the total AC loss of HTS coils for electrical machines, we designed and performed a calorimetric measurement for a 2G HTS racetrack coil. Our measurement indicates that the total AC loss is greatly influenced by the phase shift between the applied current and the external magnetic field when the magnetic field is perpendicular to the tape surface. When the applied current and the external magnetic field are in phase, the total AC loss is the highest. When there is a 90 degree phase difference, the total AC loss is the lowest. In order to explain this phenomenon, we employ H formulation and finite element method to model the 2G HTS racetrack coil. Our calculation agrees well with experimental measurements. Two parameters are defined to describe the modulation of the total AC loss in terms of phase difference. The calculation further reveals that the influence of phase difference varies with magnetic field direction. The greatest influence of phase difference is in the perpendicular direction. The study provides key information for large-scale 2G HTS applications, e.g. fully HTS machines and superconducting magnetic energy storage, where the total AC loss subjected to both applied currents and external magnetic fields is a critical parameter for the design.

Keywords: 2G HTS, AC loss, fully HTS machine, numerical modeling

1. Introduction

In order to drive large electrical aircraft and offshore wind turbines, the power density of current electrical machines must be significantly increased. Recently, fully HTS machines have been proposed as a potential technology to increase machine power density [1, 2]. Existing HTS machines use HTS DC windings in the machine rotors [3, 4]. Fully HTS machines can achieve higher electric loading using HTS AC windings compared to conventional partially HTS machines. In addition, if the AC and DC windings operate at the same temperature, the air gap can be made much smaller than that of partially HTS machines, resulting in a higher magnetic loading and increased machine power density. An HTS AC winding will be in the path of full flux (alternating with the revolution of the rotors), and will have energy dissipation known as AC loss. Due to the heavy cooling penalty, the AC loss of HTS AC windings becomes the key factor limiting the power density of fully HTS machines. Increasing the machine output will result in increased AC loss and cooling penalty. Therefore it is of critical importance to accurately estimate the AC loss of HTS AC windings.

Studies of AC loss in HTS tapes and coils have been carried out throughout the development of HTS devices. Most of the work has been done using short samples of tapes and small coil assemblies [9]. Researchers concentrated on studying AC loss in a uniform magnetic field or in the presence of transport current [12, 13, 20–24]. A lot of effort has

Table 1. Parameters for the double racetrack coil.

Definition	Value
Turns per layer	39
Total turns	78
Total tape length	39.5 m
Tape I_c	96 A
Coil I_c	56 A
Straight part length	0.18 m
Inner diameter R1	0.068 m
Outer diameter	0.09 m

been put into the numerical modelling of AC loss based on both the critical state model and *E–J* power law [6, 8, 10]. The latest modeling progress includes utilizing the homogenization principle to expand the modeling scale from a small number of turns to thousands of turns [5]. Although these published results can be used to understand HTS coils in a complex environment, HTS coils have not been properly modeled and characterized when used as machine AC windings. A machine AC winding is subjected to a combination of a rotational magnetic field and AC current in an electrical machine. There is a phase shift between the AC current and the magnetic field, depending on the machine's torque angle. Up to date, only transport AC loss of HTS AC windings has been studied [7, 11].

Previous studies based on HTS tapes showed that total AC loss of HTS tapes increased when transport current or external magnetic field was increased [25, 26], and it is influenced by the phase shift between the current and the external magnetic field [14, 15–19]. These result indicated that the total AC loss of machine AC windings depends not only on the magnitudes of the magnetic field and transport current, but also on the interaction between the magnetic field and the current. However, previous studies were all based on single HTS tapes under perpendicular magnetic field conditions. In a real machine environment, the magnetic field of HTS AC windings has both perpendicular and parallel components. So it is important to characterize total AC loss of HTS coils considering different magnetic field directions, as well as the phase shift between the current and magnetic field. To the best of our knowledge, no such study has yet been reported.

So, in this paper, we focus on the total AC loss of 2G HTS racetrack coils. Particularly, we focus on the influence of phase shift between the applied current and external magnetic field for different magnetic field directions. The total AC loss for a HTS racetrack coil was measured by the calorimetric method [28], and the interaction between transport current and external magnetic field was analyzed by finite element modeling (FEM) and H formulation [11, 30]. The paper is organized as follows: the second section introduces the experimental setup and measurements, and the third section presents modeling results from FEM and discusses in detail how the phase difference influences the total AC loss.

2. Experimental setup and results

The experimental 2G HTS coil is a double racetrack coil. It was wound with Kapton insulated Superpower 4 mm tape on a G10 former, and the parameters are shown in table 1.

In our experiment, an external magnetic field induces shielding currents [33] inside the superconductor, leading to a magnetization loss in the racetrack coil. Meanwhile, an applied current leads to a transport loss in the racetrack coil. The applied current and the external magnetic field have the same frequency. The heat generated by the racetrack coil can boil off the surrounding liquid nitrogen in the cryostat. By measuring the flow rate *F* in liters/minute of the nitrogen gas, the total loss of the racetrack coil can be measured.

Figure 1 shows the experimental setup. In our measurement, the external magnetic field and transport current are simultaneously present in the racetrack coil. External AC magnetic fields with variable amplitudes and frequencies were produced using a special double helix dipole magnet which has two sets of tilted copper coils, each consisting of three layers. The tilted coils are connected in series in such a way as to cancel the axial field component and produce a pure transverse field B which is perpendicular to the magnet axis. The HTS coil sample can be rotated in respect to the direction of B so that B is perpendicular to the flat surface of the HTS tapes. The region of homogeneous magnetic field is 30 cm long. The magnet current is supplied from four Techron amplifiers. The inner cryostat is filled with liquid nitrogen, which provides cooling for the HTS coil. The outer cryostat is also filled with liquid nitrogen, which is used to cool the copper magnet. Two pipes from the inner cryostat are connected to two flow meters. The sum of the readings from the two flow meters gives the total flow rate, which corresponds to a loss value. The resistive heater shown in figure 2 is used to calibrate the liquid nitrogen boil-off rate. We plot the flow rate versus input heater power, and the slope of the curve is the calibration flow rate constant *K* (L/min/W). The total AC loss *Q* (J/cycle) can be calculated by $Q = \frac{F}{Kf}$, where *F* is the nitrogen gas flow rate (L/min) and *f* is the frequency (Hz) of the magnetic field.

The main advantage of the calorimetric method is that it can measure the total loss of a coil regardless of the phase difference between the applied current and background magnetic field. However, the sensitivity of the calorimetric method is not as high as that of the electrical method. In our setup, any AC loss lower than 0.5 W is impossible to measure accurately, due to the sensitivity limit of our flow meters. The fluctuation of background flow is usually up to 0.1 L/min. The loss dissipation from the current leads and background flow was subtracted from the total flow. We performed a measurement without the racetrack coil with current leads present, and recorded the flow rate in order to identify the loss from the copper current leads.

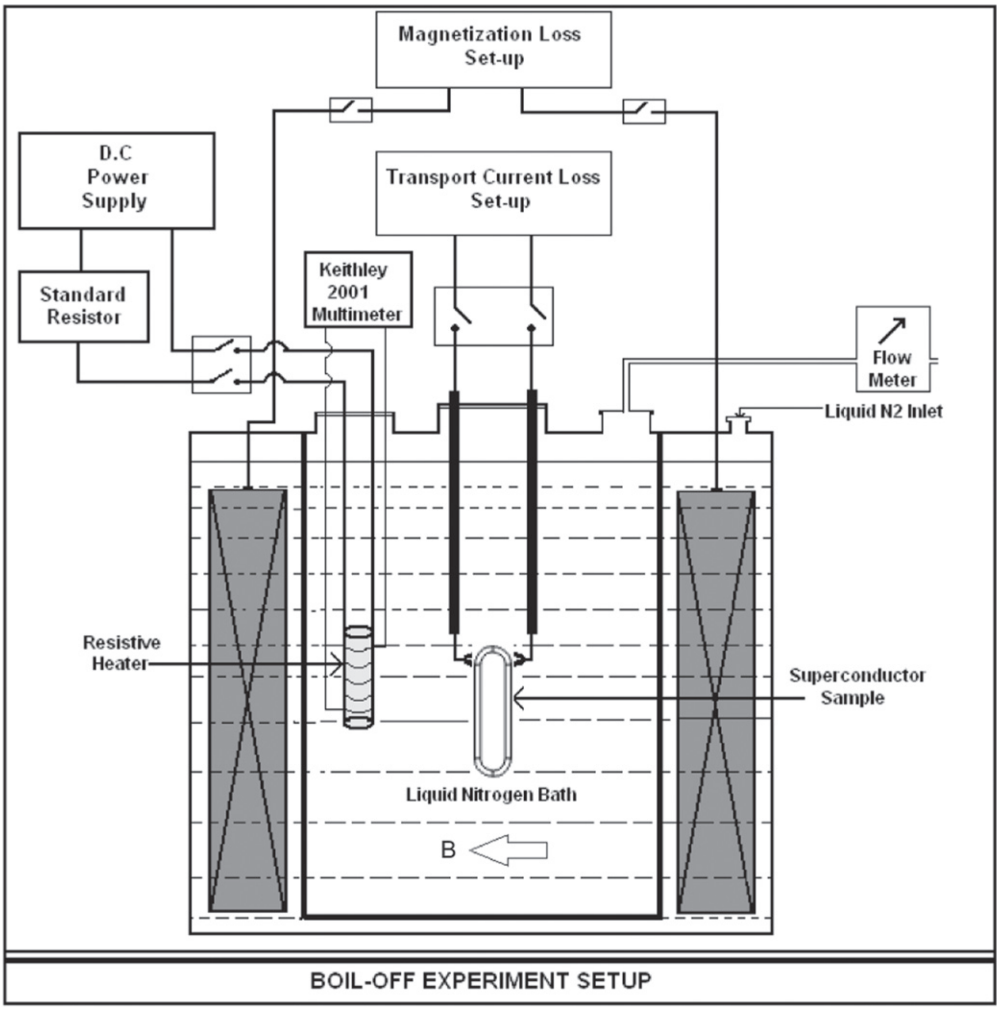

Figure 1. The experimental setup configuration.

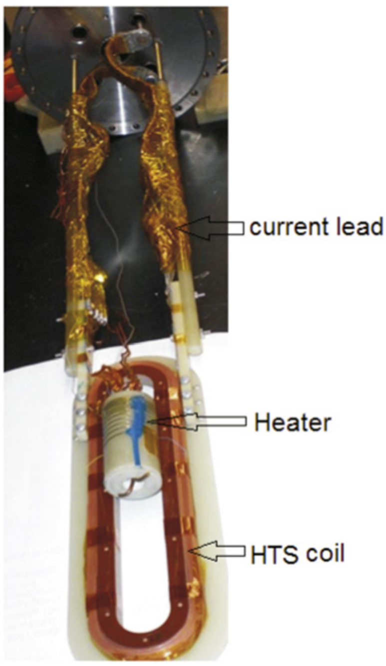

Figure 2. Sample holder with the HTS racetrack and heater mounted.

The total loss measurement was carried out under 180 Hz frequency for two conditions: (1) transport current 15 A (rms) and perpendicular magnetic field 25.28 mT (rms) in the coil center, and (2) transport current 25 A (rms) and perpendicular magnetic field 26.76 mT (rms) in the coil center. There are two Techron amplifier racks, which apply current for the copper magnet and for the HTS coil respectively. The signal generators for the amplifiers are synchronized by a sync signal, which is connected in the rear with a coax cable. In the signal generator controlling current for the HTS coil, the phase was kept constant (0 degrees) and the phase of the second signal generator was adjusted from 0 to 360 degrees. The phase shift α between the external magnetic field and the transport current equals the phase of the second signal generator. Figure 3(a) shows the direction of the magnetic field with respect to the coil'(s) geometry. Figure 3(b) shows the current shapes for the copper magnet with a phase shift α equal to 0°, 90° and 180°.

Figure 4 shows the total AC loss measured for different phase shifts under the two conditions. Estimated error comes from fluctuation of the background flow (±2.8% for condition 1 and ±1.4% for condition 2) plus a flowmeter error (±0.5%).

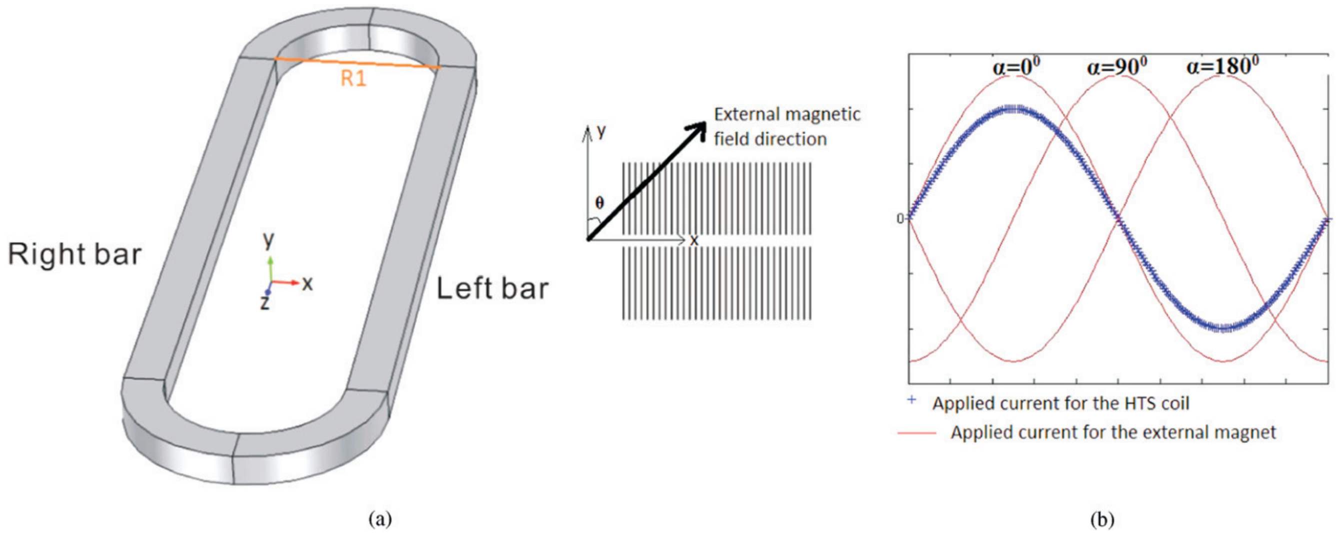

Figure 3. (a) θ defines the direction of external magnetic field. $\theta = 90°$gives a perpendicular magnetic field; (b) current phase shifts for different α values (not to the scale).

Figure 4(a) illustrates that for both conditions, there is a modulation of total AC losses in terms of the phase shift α. Near zero phase shift, total AC loss is maximum; near 90° phase shift, total AC loss is minimum. The normalized loss $Q_{\text{total}}(\alpha)/Q_{\text{total}}(\alpha = 0°)$ as a function of α is plotted in figure 4(b).

3. Numerical modeling and results

3.1. Perpendicular magnetic field

To understand the influence of phase shift and to explore this topic further, finite element modeling is employed for the total AC loss calculation. In our previous studies, we reported the finite element modeling for 2G HTS racetrack coils to calculate transport loss [11]. It has been demonstrated extensively that finite element modeling using H formulation can be effective in AC loss estimation [9, 11, 30].

Our model consists of two stacks of HTS tapes, each stack having 39 tapes. Each HTS tape is 0.004 m wide and 1 μm thick. The gap between the two stacks is 0.001 m. The external magnetic field is assumed to be uniform, and the applied current is the same in each tape. More information about the model setup can be found in [11, 31]. H formulation is applied to the 2D infinitely long model. The model contains two variables, defined as $\mathbf{H} = [Hx; Hy]$. Maxwell's equation is solved together with Ampere's Law to calculate $\mathbf{H} = [H_x; H_y]$:

$$\mu_0 \frac{\partial H}{\partial t} = -\nabla \times (\rho \nabla \times H) \quad (1)$$

where ρ for the HTS coil is defined by the E-J power law.

We simplify the problem into two stacks of infinitely long 2G HTS tapes, the tape arrangement of which is identical to the cross section of a bar of the racetrack coil. This simplification has been used previously in both transport loss and magnetization loss estimation of 2G HTS racetrack coils [11, 29]. In order to concentrate on the analysis of phase shift, the AC loss values below are normalized by dividing the loss value by the loss value at zero phase shift. Anisotropic characteristics of 2G HTS tapes ($J_c(B)$) are included in the model using the interpolation method in [31, 33].

Figure 5 illustrates the comparison between calculation and measurement for condition 1. The calculation shows a periodic pattern: the highest AC loss appears when the applied current and magnetic field are in phase, while the lowest AC loss appears when there is a 90-degree phase shift between the applied current and the magnetic field.

The magnitude of loss modulation can be described by two parameters: $\omega = \frac{Q(\alpha = 90°)}{Q(\alpha = 0°)}$, $\sigma = \frac{Q(\alpha = 180°)}{Q(\alpha = 0°)}$. When ω and σ are less than one, it suggests that the total AC loss is highest with zero phase shift. The smaller the two values are, the greater the magnitude of the total AC loss modulation.

The loss modulation is influenced by the magnitude of the applied current and magnetic field; therefore ω, σ are functions of B_{rms} and I_{rms}. We calculated ω, σ for varied applied currents and magnetic fields. Figure 6 shows how the external magnetic field influences the values of ω, σ. $\omega \leqslant 1$, $\sigma \leqslant 1$ suggest that the highest AC loss exists when the applied current and magnetic field are in phase ($\alpha = 0°$). Notice that minimum values exist for both ω and σ when the magnetic field increases. For ω, when the magnetic field is 25 mT, it reaches a minimum value of 0.65, which means that when there is a 90-degree phase difference between the current and the magnetic field, the total AC loss is only 65% of that when the current and magnetic field are in phase. For σ, when the magnetic field is 15 mT, it reaches a minimum value of 0.9, which means that when there is a 180-degree phase difference between the current and the magnetic field, the total AC loss is only 90% of that when the current and magnetic field are in phase. When the magnetic field increases further, the differences between $Q(0)$, $Q(90°)$ and $Q(180°)$ decrease. In other words, the effect of phase shift on total AC loss is stronger for

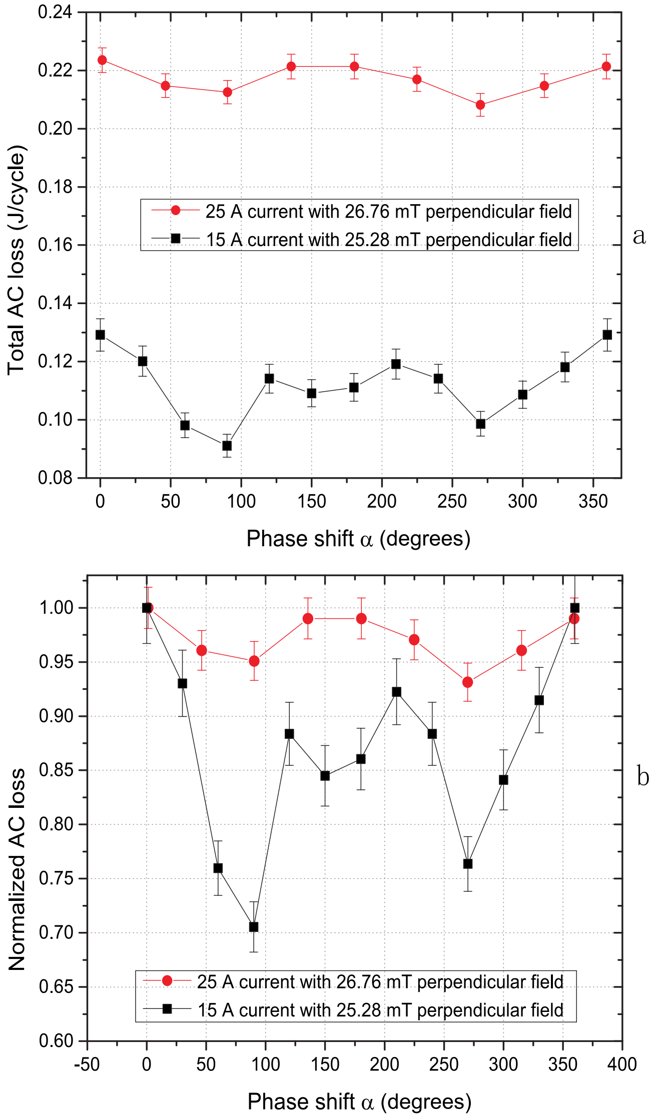

Figure 4. (a) Calorimetric measurements of total AC loss; (b) normalized calorimetric measurements of total AC loss. The external magnetic field is in the x direction, perpendicular to the wide surface of the 2G HTS tapes. f = 180 Hz.

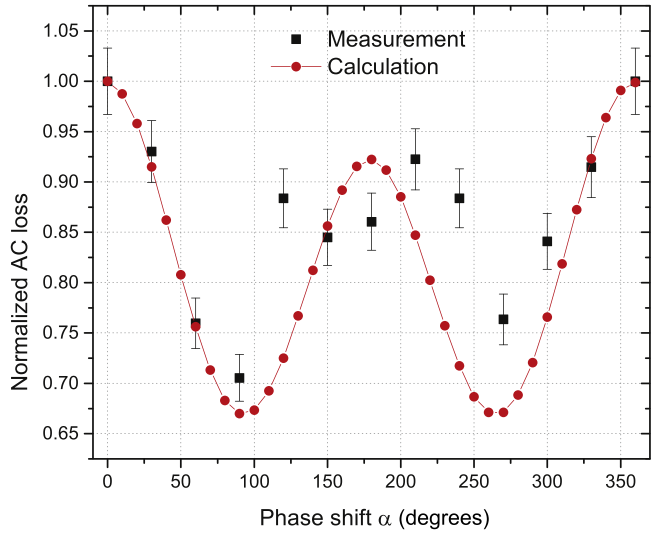

Figure 5. Comparison between calculation and measurement for the total AC loss. Applied current 15 A, magnetic field 25.28 mT. The magnetic field is perpendicular to the HTS coil. f = 180 Hz.

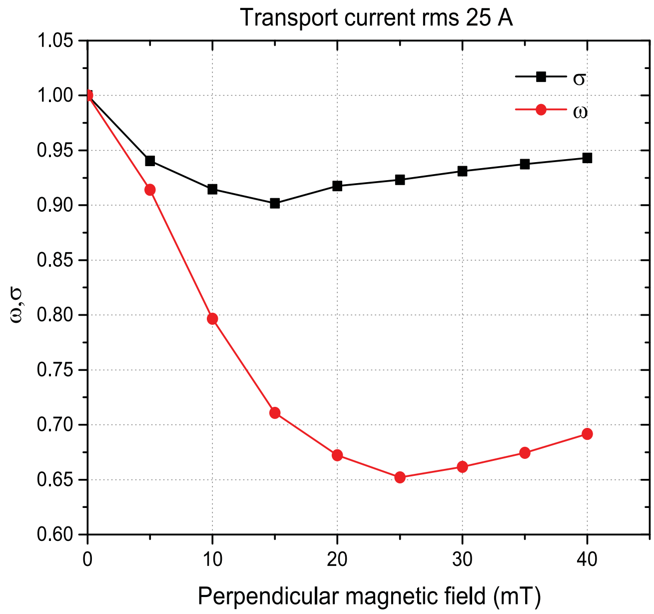

Figure 6. Calculated different ω, σ values for different external fields. Applied transport current is 25 A.

smaller perpendicular fields, which are comparable to self magnetic fields (peak 18 mT for 15 A rms applied current).

A similar situation can be seen in figure 7, where the external magnetic field is kept constant and the applied current varies. There are applied current values corresponding to minimum values for ω and σ respectively. When the applied current is further increased, the differences between $Q(0)$, $Q(90°)$ and $Q(180°)$ decrease. The reduction of AC loss modulation can be understood from the fact that when the AC loss component from either applied current or external magnetic field dominates the total AC loss, the interaction of the current and magnetic field is weakened by the dominant source.

3.2. External magnetic field with various directions

The previous section discussed how the phase shift between the applied current and the magnetic field affects the modulation of the total AC loss. The external magnetic field for both the experiment and the calculation is perpendicular to the 2G HTS tape. In this section, we discuss the total AC loss modulation with regard to the phase shift, when the direction of the external magnetic field varies. This is very important for machine applications, especially air-cored HTS AC winding designs, because the magnetic field direction varies depending on the depth of the windings.

Figure 3(a) shows the cross section of the racetrack coil and the direction of the external magnetic field. When the angle θ is 90 degrees, the magnetic field is perpendicular to the HTS tape. When θ is 0, the magnetic field is parallel to the HTS tape. The normalized total AC loss results for $\theta = 0°$, 45°, and 90° are shown in figure 8. When $\theta = 90°$, the total

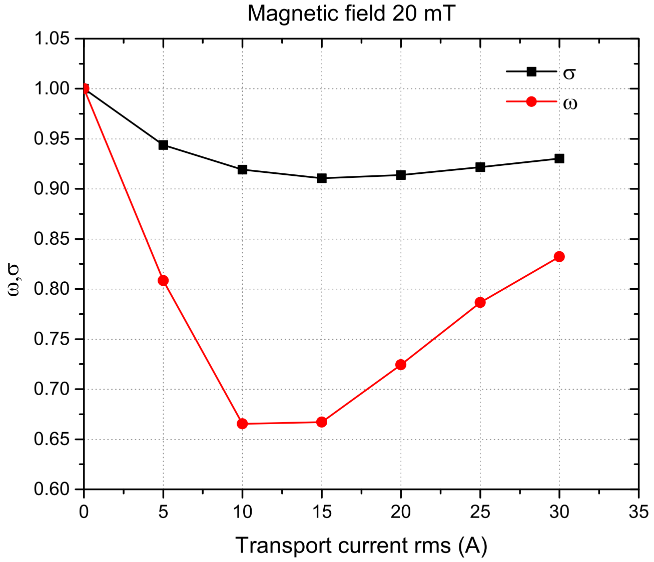

Figure 7. Calculated different ω, σ values for different transport currents. External magnetic field is 20 mT.

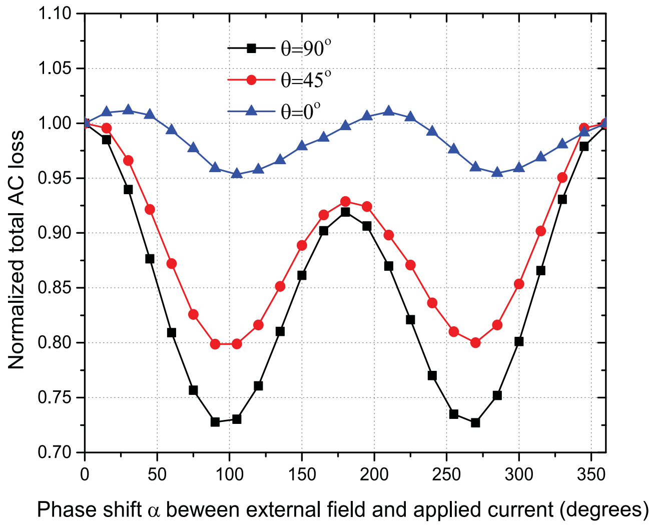

Figure 8. Calculated normalized total AC loss for three different θ values. Applied current is 30 A (rms). Magnetic field is 20 mT (rms).

AC loss modulation is greatest; when $\theta = 0°$, the total AC loss modulation is smallest. This can be understood in terms of the distribution of the magnetization current. When the external magnetic field is parallel to the tape surface, $\theta = 0°$, the induced magnetization current is minimized because the YBCO layer is only 1 μm thick and there are insulation layers between neighboring HTS tapes, which stop magnetization current from flowing between turns. In this scenario, the total AC loss shows only a slight modulation in regard to the phase angle α ($\omega = 0.95$, $\sigma = 0.99$). When the external magnetic field is perpendicular to the tape surface, the induced magnetization current flows in the 4 mm width of the tape surface, which contributes to the total AC loss. In this scenario, the total AC loss shows the strongest modulation in regard to the phase angle α ($\omega = 0.72$, $\sigma = 0.91$). When $\theta = 45°$, the modulation of total AC loss is medium ($\omega = 0.8$, $\sigma = 0.92$).

It is suggested that the existence of a magnetization current which is induced by the external magnetic field is the main reason for the modulation of total AC loss in regard to the phase angle. Figure 9 shows how the existence of the magnetization current affects the total current distribution within the coil subjected to a perpendicular magnetic field. Figure 9(a) shows the current distribution of the innermost turn of the racetrack coil subjected to an applied current (30 A peak value) and zero external magnetic field. The left image of figure 9(a) illustrates three time points (A, B, C) at which current distributions A, B, and C of figure 9(a) are plotted. The current distributions can be predicted by Brandt'(s) model [32] with a proper $J_c(B)$ assumption [31, 33]. The current distributions are bilaterally symmetrical, due to the absence of magnetization current. Figure 9(b) shows the current distributions of the innermost turn of the single racetrack coil subjected to an applied current (30 A peak value) and an in-phase perpendicular magnetic field (20 mT peak value). The left image of figure 9(b) illustrates three time points (AA, BB, CC) at which current distributions AA, BB and CC of figure 9(b) are plotted. A magnetization current is induced in this case by the change of the perpendicular magnetic field, so the current distribution is no longer bilaterally symmetrical. A comparison between current distributions A and AA shows that for current distribution AA, the critical region penetrates more on the left of the tape and penetrates less on the right of the tape, because the magnetization current is positive on the left of the tape and negative on the right of the tape. Figure 9(c) shows the current distributions of the innermost turn of the racetrack coil subjected to an applied current (30 A peak value) and a perpendicular magnetic field with a 90-degree phase shift (20 mT peak value). The left image of figure 9(c) illustrates three time points (AAA, BBB, CCC) at which current distributions AAA, BBB and CCC of figure 9(c) are plotted. Current distribution AAA is identical to current distribution A, because the magnetic field only starts to take place at 0.005 s. Current distributions BB and BBB (and, likewise, CC and CCC) are different, suggesting that the phase difference between the applied current and the magnetic field is affecting total current distribution. The total AC loss that is influenced by the change of phase shift is due to the changes in the current distribution in the tape. The current distributions for zero phase shift in figure 9(b) result in higher AC loss than the current distributions for 90-degree phase shift in figure 9(c). One possibility is that the greater penetration of critical regions (e.g. current distribution AA) involves more flux movement, resulting in higher AC loss.

In terms of a fully HTS machine, the HTS AC winding is subject to two magnetic fields. The radial magnetic field B_r produces the useful torque. In existing HTS AC winding arrangements [34] where racetrack coils are used to form concentrated windings, the B_r field stands for the parallel field. According to our results, the phase shift between the HTS coils' current and the B_r field is very small, so it can be ignored. However, there is also a tangential magnetic field B_θ. B_θ is perpendicular to the HTS flat surface. So the phase difference between B_θ and the HTS coils' current must be

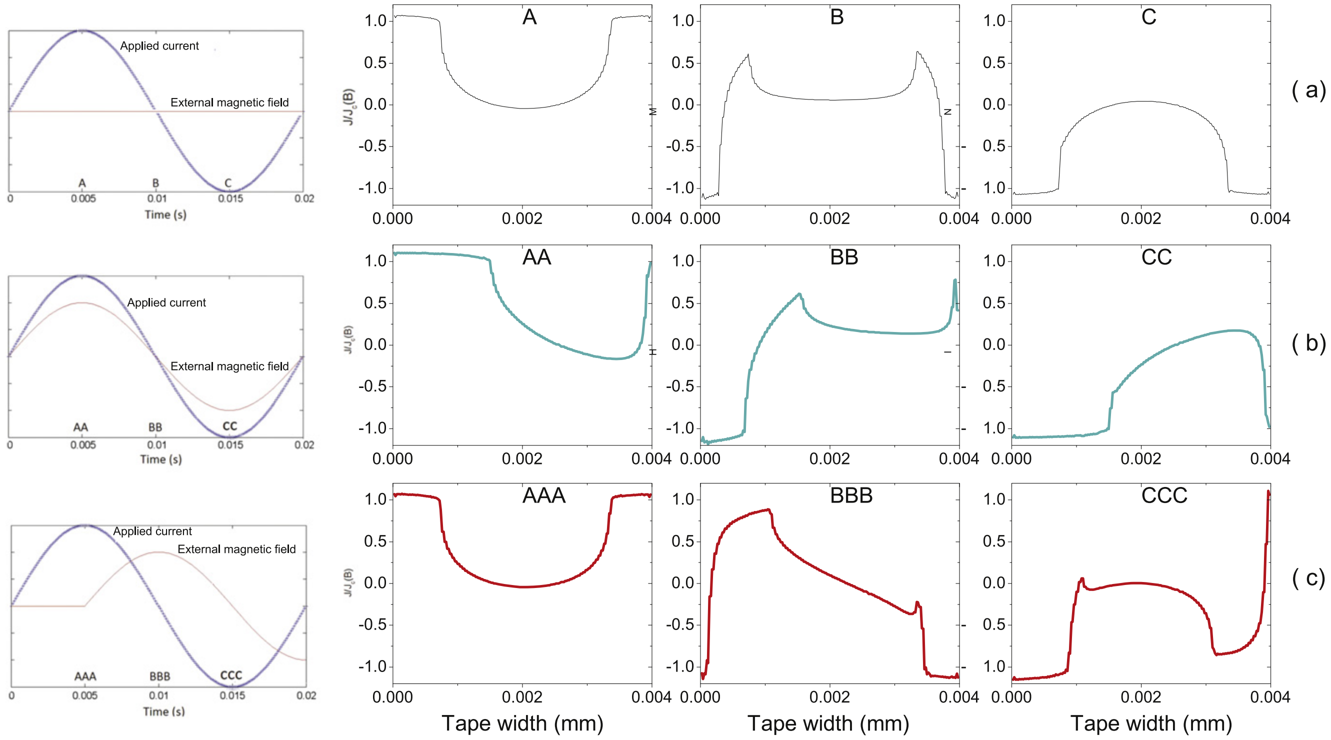

Figure 9. $J/J_c(B)$ at 0.005 s, 0.01 s and 0.015 s for the innermost turn of the single racetrack coil. (a) There is zero external magnetic field; (b) the applied current and the magnetic field are in phase; (c) there is a 90-degree phase difference between the applied current and the magnetic field. $J_c(B)$ is calculated according to [31, 33]. The applied current (30 A peak) and magnetic field (20 mT peak) are 50 Hz (not to scale).

considered while estimating total AC loss. Strategies must be proposed to minimize B_θ in order to reduce AC loss.

4. Conclusion

We designed and performed a calorimetric measurement in order to understand the total AC loss of a 2G HTS racetrack coil subjected to both an applied current and an external magnetic field. When the external magnetic field is perpendicular to the tape surface, the total AC loss show a modulation in regard to the phase shift between the applied current and external magnetic field. We then performed finite element modeling for the racetrack coil, and studied the relationship between the phase shift and total AC loss in detail. Here is a summary of our findings for the perpendicular magnetic field case:

- The modeling results and the measurements showed a similar pattern of total AC loss. When the applied current and external magnetic field are in phase, the total AC loss is the highest; when the applied current and external magnetic field have a 90- or 270-degree phase shift, the total AC loss is the lowest.
- The modulation of the total AC loss can be expressed by two parameters ω and σ, respectively indicating the total AC loss ratio between zero and 90-degree phase shifts, and zero and 180-degree phase shifts. Further study showed that ω and σ are functions of the magnitudes of the applied current and magnetic field. There exist minimum values for both parameters when the applied field or the magnetic field is increasing.
- When the external magnetic field is perpendicular to the tape surface, the influence of phase shift is the greatest in terms of the modulation of total AC loss; when the external magnetic field is parallel to the tape surface, the influence of phase difference is relatively small. This can be explained by the existence of magnetization current contributing to the total AC loss.

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