Transport AC Loss Measurements in Superconducting Coils

Jae-Ho Kim, Chul Han Kim, Gopal Iyyani, Jozef Kvitkovic, and Sastry Pamidi

Abstract— **Transport AC loss measurements were performed on several Second Generation (2G) High Temperature Superconducting (HTS) pancake coils. A good agreement was observed between the AC loss values of the coils obtained using two separate techniques. Self-field critical current density of the tape did not have direct effect on the AC losses in coils. Relative orientation of the tapes in 2-tape stack affects AC losses in coils using the stacked conductor. Losses scale with maximum perpendicular field seen by the conductor in the coil suggesting that the magnetization loss is the predominant component of coil losses. Absence of frequency dependence of the losses indicates that the eddy current losses are not significant in the coils up to 400 Hz.**

Index Terms—**AC loss, Stacked tape, Pancake Coil, Magnetic Field, Calorimetric Method, Electrical Method.**

I. INTRODUCTION

INCREASING demand on High Temperature Superconducting (HTS) power applications with commercial availability of HTS has been drawing great interest in understanding alternating current (AC) losses in order to successfully design power system components such as motors, transformers, and generators. Although substantial efforts have been made to understand the complicated interactions of AC with HTS materials in simple tapes and cables [1]-[4], there is still a need for reliable techniques for AC loss measurement in coils which is one of the most common forms of such components. Calorimetric technique has its own advantages in reproducibility and versatility in sample size. However, there are limitations in sensitivity and experimental equipment related to calorimetric measurements. Electromagnetic methods often require relatively simple equipment and are fast in response to AC input. Due to the nature of large inductively coupled signals in electromagnetic methods, there are no dependable techniques available for measurement of ac losses in coils and devices with complex magnetic field profiles.

Electrical methods are widely used for the measurement of short samples which do not impose large inductive signals. The electromagnetic technique used for this study is similar to the one used for short samples but with extended applicability that involves effectively eliminating large inductively coupled signals. In this study, the electromagnetic technique was standardized by using the data from calorimetric liquid nitrogen boil-off method.

One of the benefits of studying AC losses in pancake coils of second generation (2G) HTS tape is their relatively large perpendicular magnetic field component that exists when transport current is passed through the coil. In many applications such as transformers and high field magnets, there is a need for high current carrying cables of 2G HTS tapes. One simple configuration of fabricating high current cables is stacking of multiple 2G tapes. The electromagnetic properties, particularly AC loss behavior of coils made from stacked tapes need to be understood. Electromagnetic properties and AC loss characteristics of coils change depending on the configuration of the tape stacks used for coil fabrication. Optimal stacking configuration to minimize losses has not been known for coil applications. This paper reports result of investigations in the effect of stacking configuration on AC losses of pancake coils made from conductors consisting of stacks of two tapes in three different configurations.

II. EXPERIMENTAL SETUP

A. Electrical Method

Coil was supplied with AC current by a power amplifier controlled by a function generator. The voltage signal from potential taps between the ends of coil is superposed with very high inductive component that can be eliminated using cancellation coil by eliminating any phase difference between the source current and the measured voltage signal. Lussajous pattern was used to indicate the phase difference between two sine waves of the same frequency for fine compensation of inductive component.

Fig. 1 shows the circuit diagram of the transport AC loss measurement by the electrical method and high accuracy data acquisition (DAQ) system. When the AC transport current flows in superconducting coil, the magnetic flux is generated by Ampere's law, and an additional magnetic field is generated in voltage lead by Faraday's law. The two components add together to give the total local induction as follows [5],

$$B = \mu_0 \mu_r H = \mu_0 H + \mu_0 M \qquad (1)$$

The induced voltage can be represented as following expression [6],

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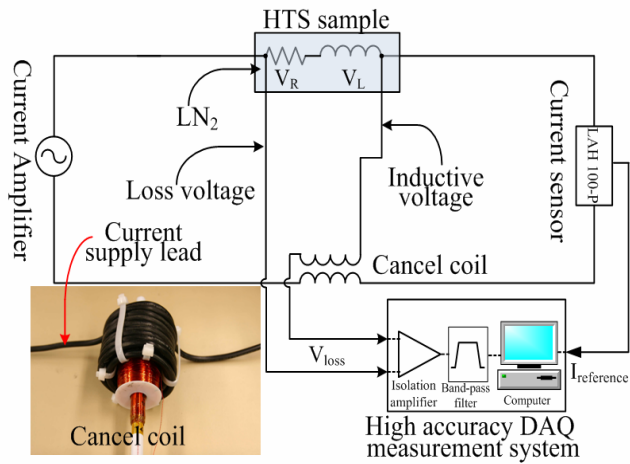
Fig. 1. Circuit diagram of electrical method showing the cancellation coil used to eliminate the inductive component for AC loss measurement.
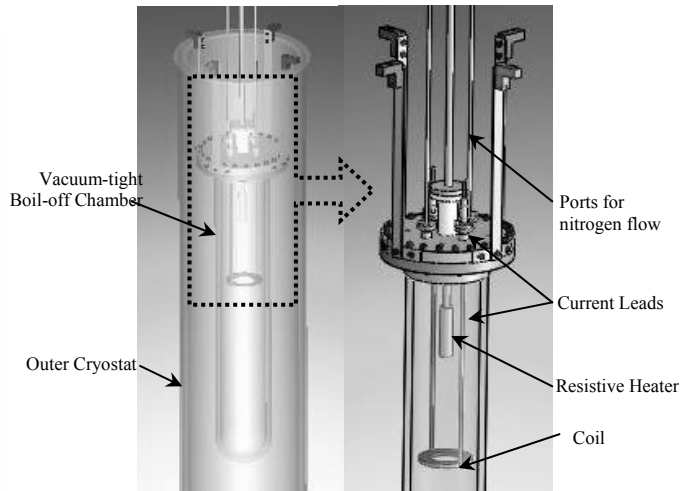

Fig. 2. Schematic of the experimental apparatus used for AC loss measurements in superconducting coils using calorimetric liquid nitrogen boil-off technique.

$$V = \frac{d}{dt} \int_s (\mu_0 H + \mu_0 M) ds \qquad (2)$$

where, B : magnetic induction, μ_0 : magnetic permeability of free space, μ_r : relative magnetic permeability, H : magnetic intensity, M : magnetization density, V : induced voltage of voltage lead, ds : vector area of an infinitesimal element of surface.

The first term of the integrand in the right hand of (2) is inductive component and second one is resistive component. Only the resistive component of the voltage represents the ac loss. The loss voltage was measured by canceling the inductive voltage and the effect of magnetic field from self-inductance of the coil with a cancelation coil. The signal from the cancelation coil was connected in anti-series with the signal from the voltage taps of the superconducting coil to compensate the inductive component. The magnitude of the cancelation voltage was adjusted to minimize the phase difference between the input current (to the coil) and the voltage signal from the coil and cancellation coil combination. The resulting voltage represents the resistive component and hence was recorded as the loss voltage.

The voltage signal of pancake coil were amplified by an amplifier and passed through a band-pass filter in order to enhance the signal-to-noise ratio and remove the harmonic component using High accuracy DAQ measurement system with LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) program. The transport AC loss per unit length per cycle is given as:

$$Q_t = I_{rms} V_{rms} / lf \qquad (3)$$

Where, l is coil length, f is frequency, I_{rms} and V_{rms} are in-phase current and voltage, respectively.

B. Calorimetric Method

Self-filed AC loss in the coils was measured in boil-off chamber as seen in Fig. 2. The liquid nitrogen boil-off measurement technique is based on enclosing the HTS coil in a sealed experimental chamber filled with liquid nitrogen. The heat caused by the AC losses boils the corresponding amount of liquid nitrogen. The resulting rate of gas evolution is measured using a standard nitrogen gas flow meter in standard liters per minute (SLPM). The measured nitrogen gas flow rate can be used to directly to infer the extent of AC losses. To minimize the heat leak from outside, the experimental chamber is immersed in liquid nitrogen contained in an external Dewar. The liquid nitrogen in the external container intercepts heat from the current leads in addition to maintaining zero temperature gradient between the inside and outside of the experimental chamber.

The nonmagnetic stainless steel cryostat (Dewar flask) is 181 cm in height and 31 cm in inner diameter. The experimental calorimetric chamber is made of fiber glass which is 91 cm in length and 14 cm in inner diameter. It has a stainless steel ConFlat flange and hangs inside the outer cryostat concentrically. The top flange of the experimental chamber was sealed with copper gasket creating a cryogenic and vacuum tight seal when the experimental chamber is immersed in liquid nitrogen in the outer cryostat during experiments, Fig.2. For measurement of nitrogen boil-off rate, the flow rate of the evaporated gas was measured at room temperature in units of standard liters per minute (SLPM). For large flow rates, two flow meters were used in parallel to prevent pressure build up in the chamber.

A resistive heater was used to check the accuracy and linearity of the liquid nitrogen boil-off measurement set up. Calibration was performed using a heater with around 13 ohm resistance and a constant current source. The system was tested for accuracy up to 180 W. The slope of flow rate versus heat input line was found to be 0.249 SLPM/W, agreeing well with the theoretical value of 0.25 SLPM/W [7].

Loss measurements using the electrical method were carried out at a wider range of transport current values compared to that of the calorimetric method. As explained later, because of the
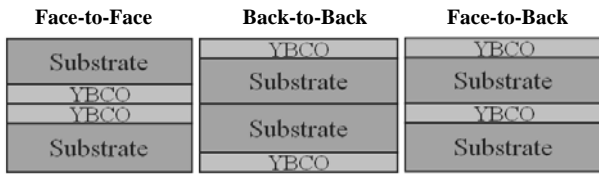
Face-to-Face	Back-to-Back	Face-to-Back

Fig. 3. Schematic diagram of stacking configurations of HTS tape for coils.

TABLE 1 SPECIFICATIONS OF COILS

Coil Name	A1	B1	B2-FF	B2-BB	B2-FB
Configuration	Single stack	Single stack	Face-to-Face	Back-to-Back	Face-to-Back
No. of Turns	40	40	20	20	20
Length (m)	7.49	7.49	3.75 ×2	3.75 ×2	3.75 ×2
Coil I_c (A) [a]	38	66	137	138	135
Tape I_c (A) [a]	102	115	115	115	115

All coils have identical dimensions of ID = 57 mm and OD = 70 mm.

"Face" represents superconductor (YBCO) side and "Back" represents substrate and stabilizer side.

[a] Measured at 77 K with 1 μV/cm criterion.

good agreement between the two techniques, majority of the data presented in the paper are from the electrical method.

C. Coil Specification

Specifications of the pancake coils used for this study are summarized in Table 1. The coils were wound using insulated tape. Coils were made from two different batches of 2G conductor, A and B, noted by first letter in coil label. Number of tapes in the stack used for coil winding is either 1 or 2 and represented by the second character in the label. For the two tape stack, there are three possible stacking configurations as denoted by the last two letters of the label (FF, BB or FB). Coils wound from single-tape have 40 turns each and the coils wound with 2-tape stack have 20 turns each. Thus, the total length of the conductor, the inner diameter, and outer diameter are identical for all the 5 coils. The stacking configurations are shown schematically in Fig. 3. The two tapes in 2-tape stack of each turn of coil are electrically isolated except at the current leads at both ends.

III. EXPERIMENTAL RESULTS

A. External Magnetic Field Effect on Critical Current

The 2G HTS tape used for coils A1 has slightly higher self-field critical current compared to that used for B1 has. However, the tape used for B1 has significantly higher critical current in external perpendicular magnetic field than conductor that used for A1. Fig. 4 shows effect of external magnetic field perpendicular to the conductor tape. Critical current decreases as perpendicular magnetic field increases. However, tape B (for coil B1) shows smaller reduction in external magnetic field. This difference between the tape A and B affects the coils A1 and B1 resulting in the critical current of A1 and B1 to be 38 A and 66 A, respectively.
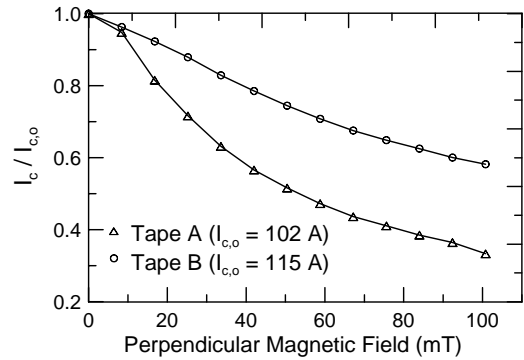

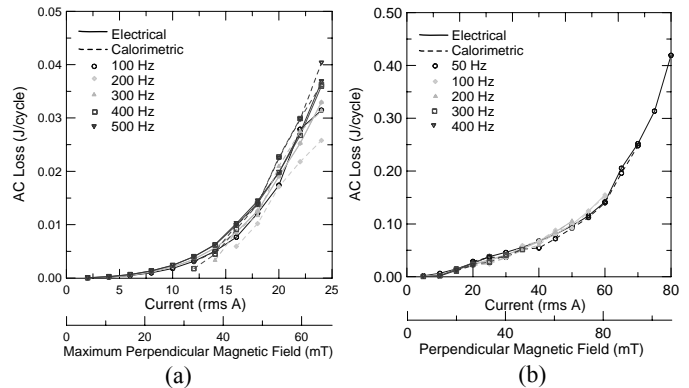Fig. 4. Effect of external perpendicular magnetic field on critical current of HTS tapes

Fig. 5. AC loss of (a) single stacked coil (A1) and (b) double stacked coil (B2-FF) measured by both calorimetric and electrical methods.
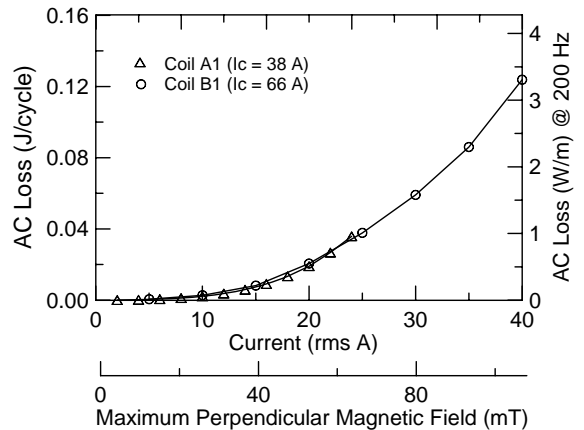

Fig. 6. AC losses of single stacked coils (A1 and B1).

B. Consistency between Calorimetric and Electrical Methods

Fig. 5 shows AC loss results obtained by calorimetric and electrical methods as a function of transport current for coils A1 and B2-FF. The maximum perpendicular magnetic field seen by the tape in the coil is also shown on the x-axis. Solid lines represent the AC losses measured by electrical method and dotted lines are the results by calorimetric method. Losses at various frequencies up to 500 Hz are presented in the figure. No distinguishable or systematic difference between the results by calorimetric and electrical methods was found. All the other coils showed similar agreement between the data obtained using the two independent techniques.

It is also noted that AC losses per cycle are independent of frequency up to 500 Hz. This suggests that the measured loss
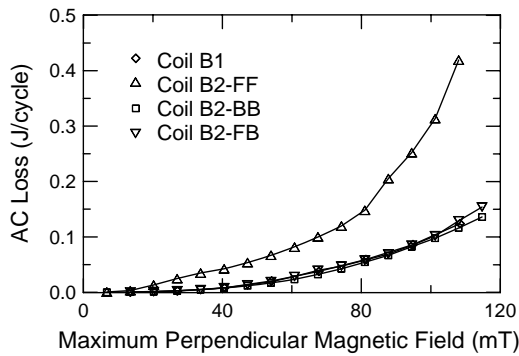
Fig. 7 AC losses of single and double stacked coils as a function of maximum perpendicular magnetic field.

was predominantly hysteretic and came from the superconducting material. The eddy current losses in the metallic substrate or the stabilizer layer are not significant.

C. Effect of Critical Current on AC Losses

As discussed in III-A, critical current of coil B1 is much higher than that of coil A1. However, as seen in Fig. 6, the losses in the coils are independent of the critical current of the coils. This implies that the magnetization loss due to self-field is the dominant component of the measured losses.

D. Influence of Stacking Configuration

For coils wound with 2-tape stacks, three different possible stacking configurations were used. Stacking configuration changes the separation between the superconducting layers in the stack. Face-to-face configuration has the least separation between the superconducting layers while the back-to-back configuration has the most separation between the superconducting layers. Fig. 7 shows the AC losses by averaging over frequencies for clear presentation of each coil since little frequency dependence on AC losses was found for each coil.

The coil wound with single tape, B1 has essentially same configuration with face-to-back configuration of 2-tape stack coil (B2-FB). As expected the two coils showed similar losses over the complete range of applied current. Face-to-face configuration of double stacked coil (B2-FF) shows the highest losses at all frequencies, possibly due to the strongest local magnetic field at the superconducting layers. The smallest losses were measured in the coil with back-to-back

configuration. However, the difference between the face-to-back and back-to-back configurations is within experimental uncertainty.

IV. SUMMARY

Calorimetric and electrical methods were used to measure transport losses in 2G coils made from tapes with different self-field critical currents values. Coils were made with 2-tape stacks with varying stacking configurations. The losses measured by calorimetric and electrical methods agreed well giving confidence in the techniques used for the measurements.

AC loss is independent of self-field critical current of the tape indicating magnetization loss is the dominant component of the coil losses. Little frequency dependence was observed in all coils made from single tape and 2-tape stacks, suggesting no significant eddy-current losses were present. AC losses in coils made from 2-tape stacks depend significantly on the stacking configuration. The face-to-face stacking configuration generates the largest losses. The data presented in the paper advocate the need for further need for detailed AC loss measurements on bundles and cables of 2G tapes fabricated using various potential cabling techniques and the corresponding coils to understand the implications of cable configuration on coils in practical applications.

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