



Citation for published version:

Pei, X, Smith, AC & Barnes, M 2017, 'AC Losses measurement and analysis for a 2G YBCO coil in metallic containment vessels', *IEEE Transactions on Applied Superconductivity*, vol. 27, no. 4, 5900605, pp. 1-5.
<https://doi.org/10.1109/TASC.2017.2669141>

DOI:

[10.1109/TASC.2017.2669141](https://doi.org/10.1109/TASC.2017.2669141)

Publication date:

2017

Document Version

Peer reviewed version

[Link to publication](#)

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AC Losses Measurement and Analysis for a 2G YBCO Coil in Metallic Containment Vessels

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Abstract—AC losses in high temperature superconductors (HTS) are an important design parameter for large scale power applications. It is often necessary to have a metallic containment vessel to house the superconducting element in a closed loop cryogenic system. This however produces additional AC losses due to induced eddy currents in the walls of the vessel.

This paper focuses on the investigation and understanding of the induced eddy current loss in the containment vessel. The total AC losses of a one meter YBCO coil was experimentally measured in three different containment vessels. The predicted eddy current loss from FE modeling combined with the measured superconductor hysteresis loss demonstrated good agreement with the experimental results. This paper also includes the implications for practical design of commercial cryostat containment vessel for superconductor power applications to minimize AC losses.

Index Terms—AC losses, containment vessel, eddy current loss, hysteresis loss, skin effect.

I. INTRODUCTION

AC losses in superconductor materials is a critical design variable for superconducting power applications such as fault current limiters, cables and electric machines [1]. Second generation (2G) yttrium barium copper oxide (YBCO) high temperature superconductor (HTS) tape has shown great potential and benefits in power applications due to its high critical current density [2, 3]. AC losses in the YBCO tape include hysteresis loss in the superconductor, eddy current loss in the metal parts of the superconductor tape, coupling loss between two or more superconducting filaments and ferromagnetic loss in magnetic substrates [1]. A large amount of research has been carried out on the measurement and computation of losses for HTS applications [1, 4-7]. In commercialized applications, a metallic containment vessel to house the superconducting element is almost inevitable for a closed loop cryogenic system. Copper is commonly used as the containment vessel material because of its good thermal conductivity. Copper however suffers from induced eddy current loss in the walls of the vessel. Investigation of the eddy current loss in the containment vessel is vitally important for HTS power application since the design of the cooling

system needs to take into account the thermal loads. Little research however has been undertaken on the eddy current loss in the surrounding containment vessel for HTS applications.

This paper investigates the effect of the eddy current loss in the containment vessel and explores solutions to minimize it. A superconductor coil made of one meter YBCO tape was experimentally investigated. The YBCO coil was placed into three different containment vessels including a non-metallic plastic bucket, a stainless steel bucket, and a copper bucket that was placed within a commercial cryostat. The total AC losses were measured with the YBCO coil immersed in a liquid nitrogen bath. The copper bucket temperature was subsequently reduced to 40 K by a cryocooler and the AC losses were measured again. This paper reports on the experimental results of the AC losses in the YBCO coil under the above four conditions, which will be explained in detail in Section II. Theoretical analysis is used to explain the trend of the eddy current loss. An axisymmetric finite element (FE) model was also built to estimate the eddy current loss in the surrounding containment vessel.

The paper includes a detailed analysis of the experimental results and comparison with predictions of the eddy current loss in the containment vessels. The understanding of the eddy current loss mechanism helps to find solutions for loss reduction. The implications for the practical design of commercial cryostat containment vessel are also discussed.

II. EXPERIMENTAL SETUP

A one meter YBCO tape sample with a width of 12 mm was supplied by Fujikura Ltd. The specification of the YBCO tape is listed in Table I. Copper stabilizers were soldered on both sides of the tape. The YBCO tape was wound onto a clear perspex tube, as shown in Fig. 1. The copper braid connections were fixed onto the perspex tube and then soldered to both coil ends using low temperature solder.

The schematic diagram of the AC loss measurement circuit is shown in Fig. 2, which includes a network analyzer, a power amplifier, a voltage step-down transformer, a compensation cancelling coil and an oscilloscope. A variable frequency sinusoidal signal was generated using the network analyzer and then amplified using the power amplifier. The voltage step-down transformer was used to increase the current level. The compensation cancelling coil was connected in series with the YBCO coil to cancel the inductive component of the superconductor voltage. The instantaneous voltage and current signals were recorded by the high sampling-rate oscilloscope.

This work was funded as part of the UK EPSRC, FCL/CB: An Integrated VSC-HVDC Fault Current Limiter/Breaker project, EP/L021552/1.

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Table I: Parameters of the YBCO tape sample

Tape parameters	Value
Tape #	Fujikura FYSC-SH12
Tape width (mm)	12
Thickness (μm)	121
Substrate (μm)	75
Copper stabilizer (μm)	20
Tape I_c (A) @ 77 K, self-field	720

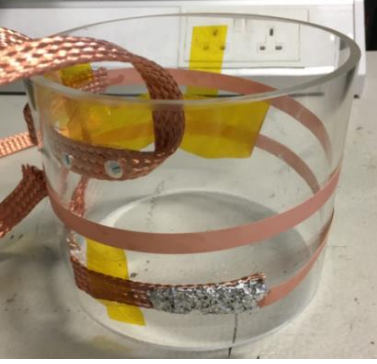


Fig. 1: YBCO tape wound onto a perspex tube.

The objective of this paper is to investigate and analyze the eddy current loss in different containment vessels. The AC losses were measured under four test conditions:

- 1) Liquid nitrogen bath in the non-metallic plastic bucket (77 K);
- 2) Liquid nitrogen bath in the stainless steel bucket (77 K);
- 3) Liquid nitrogen bath in the copper bucket (77 K); and
- 4) Solid nitrogen in the copper bucket (40 K).

The test rig for the AC loss measurement with the YBCO coil immersed in liquid nitrogen in the plastic bucket is shown in Fig. 3. During tests 3 and 4, the YBCO coil was placed into a commercial cryostat which uses a copper containment vessel around the test space. A commercial Gifford-McMahon (GM) cryocooler and an internal heater with a PI controller, which can operate from 20 K to 80 K, were used to set the temperature on the copper containment vessel.

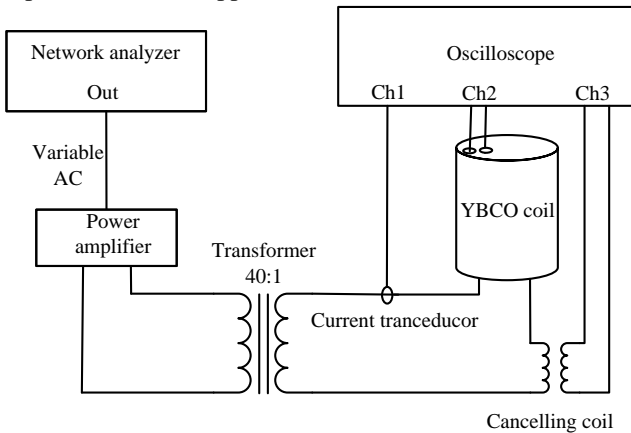


Fig. 2: AC loss measurement circuit diagram.

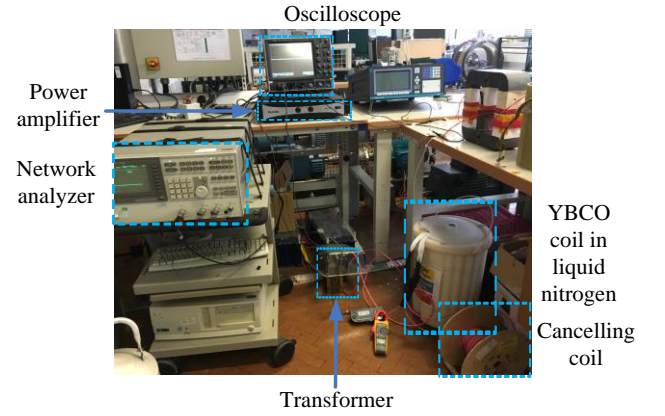


Fig. 3: AC loss measurement test rig.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. AC loss measurement technique

An electrical technique was used to measure the AC loss in the coil. Two electrical test circuits and calculation methods were compared: the current and voltage of the YBCO coil was measured directly; and a cancelling coil was added to eliminate the inductive component of the YBCO coil voltage [8, 9].

In the direct method, the instantaneous current and voltage of the YBCO coil is used to produce the instantaneous power. The instantaneous power is then integrated over a cycle to obtain the real power P corresponding to the AC loss.

$$P = \left(\int_0^T v_s \times i_s dt \right) / T \quad (1)$$

where T is the period of the signal, v_s is the voltage across the YBCO coil and i_s is the current through the YBCO coil.

The YBCO coil voltage comprises a resistive component (hysteresis loss) and an inductive component (self-inductance), and can be expressed as follows:

$$V_S = I_S (R_S + j\omega L_S) = I_S R_S + j\omega L_S I_S \quad (2)$$

where R_S and L_S are the equivalent resistance and self-inductance of the YBCO coil, respectively.

The inductive component can be eliminated using the cancelling coil by adjusting the mutual inductance M between the primary and secondary coils. The voltage of the secondary coil V_C is:

$$V_C = j\omega M I_S \quad (3)$$

The voltage of the YBCO coil minus the cancelling coil voltage gives:

$$V_S - V_C = I_S R_S + j\omega (L_S - M) I_S \quad (4)$$

When the mutual inductance of the cancelling coil is equal to the self-inductance of the YBCO coil, the voltage is purely resistive and in-phase with the current. The AC loss can be obtained by multiplying the voltage and the current.

$$P = (V_S - V_C)_{rms} \times I_{Srms} \quad (5)$$

The AC losses of the YBCO coil was measured and calculated using the above two methods with the coil placed in the stainless steel bucket. The AC losses were measured with a supply frequency of 50 Hz and 200 Hz, and are shown in

Fig. 4. It should be noted that the current in all the figures is rms value. The experimental results show that the measured AC losses from these two methods are closely similar when the coil inductance is low. The direct method therefore was selected for the following experimental tests due to its inherent simplicity.

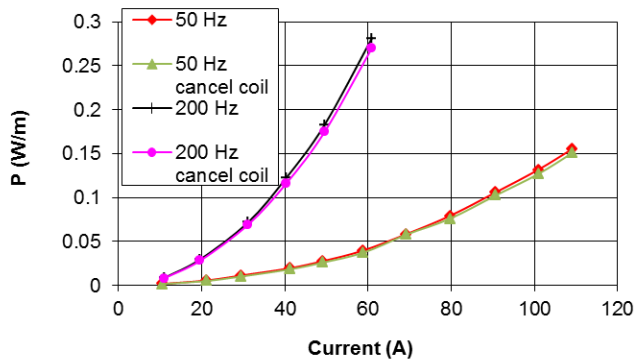


Fig. 4: YBCO coil AC loss when placed in the stainless steel bucket.

B. AC losses in different containment vessels

The AC losses of the YBCO coil were initially measured in the plastic bucket in liquid nitrogen. The AC losses under this condition were dominated by the hysteresis loss of the superconductor because the eddy current loss in the copper stabilizer at power frequencies below 200 Hz is generally low and can be neglected [4, 5]. The AC losses were measured at supply frequencies of 25 Hz, 50 Hz, 100 Hz and 200 Hz and the experimental results are shown in Fig. 5. It is clear that the losses increase as the operating frequency increases, which is consistent with the predication that the hysteresis loss in the superconductor is proportional to the frequency [7].

The YBCO coil was then placed in the stainless steel bucket to observe the total AC losses including the superconductor hysteresis loss and the eddy current loss in the stainless steel bucket. Again the AC losses were measured at the supply frequencies of 25 Hz, 50 Hz, 100 Hz and 200 Hz and are presented in Fig. 6. The AC losses are clearly significantly higher at higher operating frequency. The hysteresis loss is proportional to the frequency and the eddy current loss is proportional to the frequency squared. AC losses in Fig. 5 and Fig. 6 are more significant at the higher frequencies. At 200 Hz the total AC losses including the eddy current loss in the stainless steel bucket is almost 10 times higher than the YBCO hysteresis losses in Fig. 5. This demonstrates that it is difficult to separate the superconductor hysteresis loss from the total AC losses when the superconducting coil is placed in a metallic containment vessel.

Fig. 7 shows the total AC losses when the coil was placed in the cryostat copper bucket in liquid nitrogen. The total AC losses with the coil in the copper bucket is lower than in the stainless steel bucket, which indicates that the eddy current loss in the copper bucket is lower than the stainless steel bucket. The eddy current loss is often regarded as being proportional to the conductivity of the material and proportional to the frequency squared [1]. This relationship however is only valid under certain assumptions (uniform

material, uniform magnetic field and no skin effect, etc). The electrical conductivity of copper is much higher compared to stainless steel so simplistically one would expect the eddy current losses AC to be higher than those in the stainless steel bucket if the above assumptions were valid. The experimental results however seem to contradict this so a deeper understanding is needed and will be discussed in the next section.

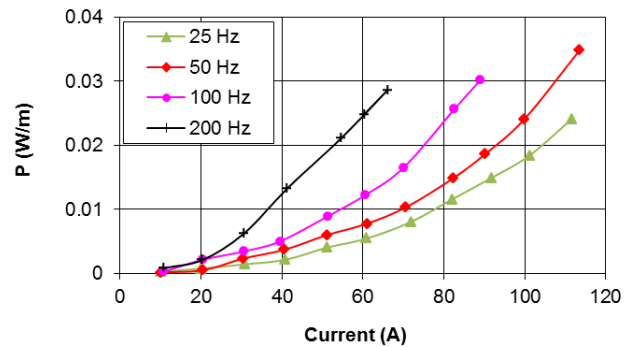


Fig. 5: YBCO coil hysteresis losses at different frequencies.

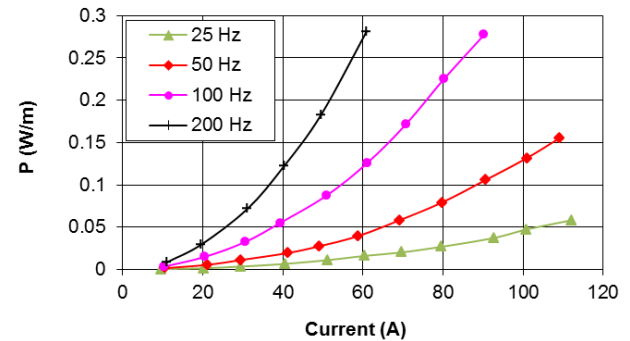


Fig. 6: Total AC losses with the YBCO coil in the stainless steel bucket.

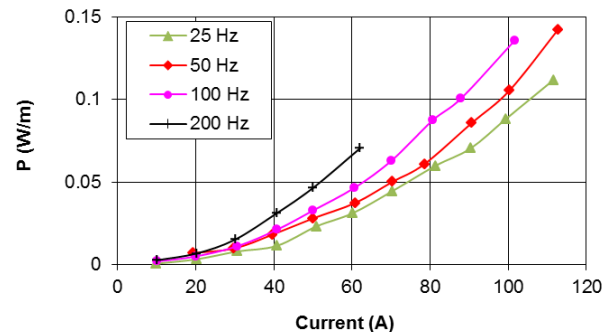


Fig. 7: Total AC losses with the YBCO coil in the copper bucket at 77 K.

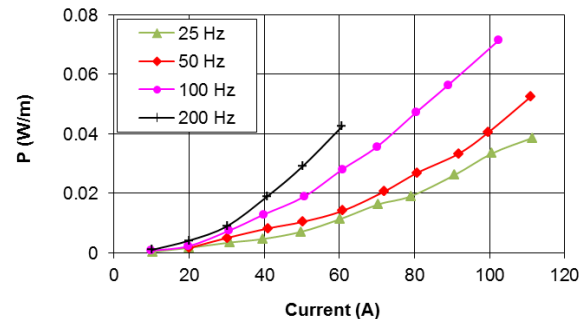


Fig. 8: Total AC losses with the YBCO coil in the copper bucket at 40 K.

The cryostat temperature was then reduced to 40 K and the total AC losses were measured again. Fig. 8 shows the total AC losses with the coil in solid nitrogen. It is clear that the total AC losses including the eddy current loss in the copper bucket are further reduced from 77 K to 40 K. It is therefore important to understand the mechanism of the eddy current loss and the experimental results.

IV. EDDY CURRENT LOSS ANALYSIS

The importance of understanding the eddy current loss in the containment vessel lies in two aspects: it is essential for the engineering design of a cryogenic cooling system; and it can be used to explore methods to minimize AC losses.

A. Analytical analysis

When a metal plate is subject to a uniform field parallel to its surface, the loss per unit surface area P_e can be expressed as [10]:

$$P_e = \frac{H_s^2}{\sigma \delta} \frac{\sinh \gamma - \sin \gamma}{\cosh \gamma - \cos \gamma} \quad (6)$$

where H_s is the peak applied field, σ is the conductivity of the metal plate, and γ is the ratio of the thickness $2b$ to the skin depth δ of the metal plate.

Under one extreme condition, when $2b \ll \delta$:

$$P_e \approx \frac{H_s^2}{\sigma \delta} \frac{\gamma^3}{6} = \frac{4}{3} \pi^2 f^2 \sigma \mu_0^2 \mu_r^2 H_s^2 b^3 \quad (7)$$

where f is the frequency of the applied field, μ_0 is the permeability of free space, and μ_r is the relative permeability of the metal plate.

The magnetic field produced by the YBCO coil is taken as the external applied field to the containment vessel. When the conductivity of the containment vessel is very low, e.g. in the stainless steel bucket, the skin depth can be much higher than the wall thickness. The eddy current induced in the bucket is then limited by the high resistivity and it is classified as resistance-limited. Clearly the resistance-limited eddy current loss is proportional to the conductivity of the metal and also proportional to the frequency squared.

Under the other extreme condition, when $2b \gg \delta$:

$$P_e \approx \frac{H_s^2}{\sigma \delta} = H_s^2 \sqrt{\frac{\pi f \mu_0 \mu_r}{\sigma}} \quad (8)$$

When the conductivity is high, e.g. in the copper bucket at cryogenic temperatures, the skin depth can be much smaller than the wall thickness of the bucket. The current distribution is then limited by the effect of its own field and the eddy current is termed inductance-limited. From equation 8, it is clear that the inductance-limited eddy current loss is proportional to the square root of the frequency and inversely proportional to the square root of the conductivity. This can explain why the eddy current loss in the copper bucket reduces as the operating temperature reduces from 77 K to 40 K. It also explains why the increase in the eddy current loss in copper bucket as the frequency increases is not as high as the stainless steel bucket where the eddy currents are resistance-limited.

Equations 7 and 8 are two extreme conditions and the eddy

current loss rises to a maximum between these two conditions [10]. This suggests that to reduce the eddy current loss in the containment vessel, it is recommended to use material that either has an extremely low conductivity, e.g., non-metallic plastic, or has a very high conductivity, e.g. copper. At cryogenic temperatures, copper is considered to have a good thermal conductivity and commonly used as the containment vessel material. The eddy current loss in the copper bucket can be reduced by using copper with a high residual-resistance ratio (RRR). The close proximity of the copper containment system to the coil can also significantly increase the eddy current loss due to the increased magnetic field. The eddy current loss can also be reduced by moving the containment vessel further away from the superconducting coil; this however will be limited by the space available.

B. FE modeling

An axisymmetric FE model was built to estimate the eddy current loss in the containment vessel. The eddy current loss predicted by the FE model was added to the measured hysteresis loss, as shown in Fig. 5, which gives the estimated total AC losses. Fig. 9 shows the comparison of the measured and predicted AC losses with the YBCO coil placed in the stainless steel bucket. It is clear that the estimated AC losses are closely similar to the experimental results. The FE modeling results also confirm that the eddy current loss in the stainless steel bucket is proportional to the frequency squared, as predicted in equation 7.

The measured and predicted AC losses with the YBCO coil placed in the copper bucket with liquid nitrogen and solid nitrogen are shown in Fig. 10 and Fig. 11, respectively. Again the estimated AC losses show the same trend as the experimental results. The modeling results also confirm that the eddy current loss in the copper bucket with a high electrical conductivity is proportional to the square root of the frequency, as predicted by equation 8. The eddy current loss in the copper bucket is also shown to reduce further with the increasing conductivity as the temperature reduces to 40 K, which also confirms that the eddy current loss is inversely proportional to the square root of conductivity.

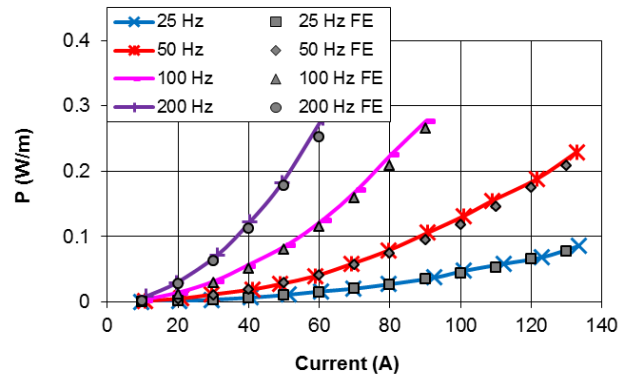


Fig. 9: Comparison of measured and predicted AC losses with the YBCO coil in the stainless steel bucket.

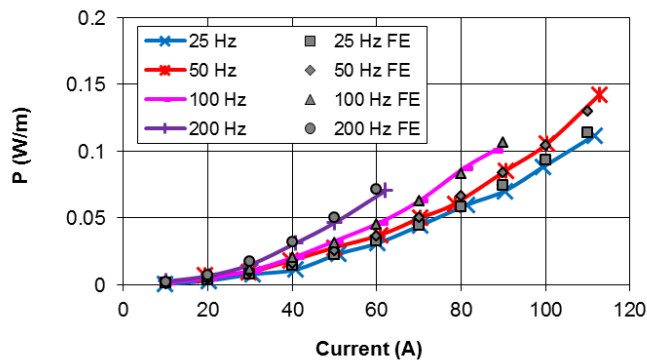


Fig. 10: Comparison of measured and predicted AC losses with the YBCO coil in the copper bucket at 77 K.

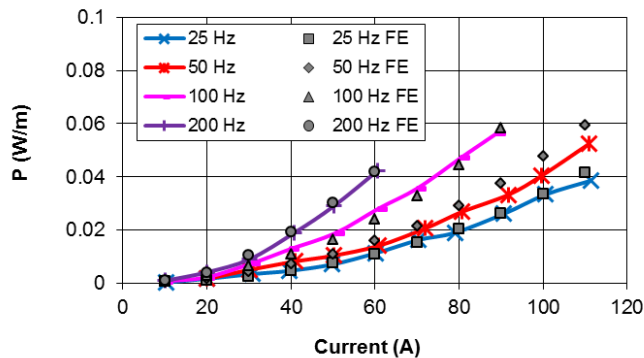


Fig. 11: Comparison of measured and predicted AC losses with the YBCO coil in the copper bucket at 40 K.

V. CONCLUSION

The eddy current loss in the containment vessel to house the superconducting coil is examined in this paper. The direct measurement of the superconductor voltage and current gives similar results to the compensation circuit when the coil inductance is low. The AC losses of the YBCO coil were experimentally measured in three different containment vessels. The analytical analysis and FE modeling confirms the eddy current loss can be categorized as resistive-limited or inductive-limited.

When designing a containment vessel for commercial cryostats, a non-metallic material would be the first option because this removes the additional eddy current losses. If a metallic material is used, a material which has a high conductivity would be recommended to minimize the eddy current loss. This paper helps to understand eddy current losses in containment vessels and provides general guidelines on how to minimize it.

ACKNOWLEDGMENT

The authors would like to thank Fujikura Ltd. for providing the YBCO tape sample.

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