Transport AC Loss Measurements of a Triangular, Epoxy-Impregnated High Temperature Superconducting (HTS) Coil

Di Hu, *Student Member, IEEE,* Mark D. Ainslie, *Member, IEEE,* Jozef Kvitkovic, Jingeun Kim, Chul Kim, Sastry Pamidi, Difan Zhou, Jordan P. Rush, and John H. Durrell

***Abstract*—In this paper, the transport AC losses in a triangular, epoxy-impregnated high temperature superconducting (HTS) coil made from YBCO coated conductor, intended for use in a prototype axial flux HTS electric machine, are measured using two different electrical techniques at 77 K. The first set of AC loss measurements of the coil are carried out at the University of Cambridge using a technique based on a lock-in amplifier. The coil is then measured at the Center for Advanced Power Systems (CAPS), Florida State University, using a technique based on a high accuracy data acquisition (DAQ) measurement system. The two different methods show consistent results, validating the accuracy of these two techniques for transport AC loss measurements of superconducting coils. Multiple voltage taps are utilized within the coil to study the details and distribution of the AC loss in different sections of the coil. Losses are also measured with a flux diverter made of ferromagnetic material to analyze its effect on the AC losses.**

***Index Terms*—AC loss, critical current density (superconductivity), high-temperature superconductors, superconducting coils, transport ac loss.**

I. Introduction

TRANSPORT AC loss is an important problem in high temperature superconducting (HTS) devices supplied with a time-varying current. Such losses increase the refrigeration load and, therefore, decrease the device efficiency consequently increasing the complexity of the design required in applications such as HTS machines [1]-[3]. Detailed measurements of the transport AC loss can help better interpret the physical mechanisms of the loss, investigate loss mitigation methods for the superconducting wire at an application design level, and help design an appropriate cryogenic system. A four-point measurement technique using voltage taps is commonly used to measure the transport AC loss, which is suitable for short samples of wire [4]. AC loss measurements on HTS coils have been studied by several groups [2], [5]-[10]. Calorimetric and electromagnetic methods can yield consistent transport AC loss results for superconducting coils [8], but compared with calorimetric methods, electrical methods are generally faster, having greater sensitivity [11], [12]. However, the key problem when applying the electrical technique to a superconducting coil is the compensation of the much larger inductive component of the coil's voltage, compared with the in-phase component that gives the AC loss.

We are investigating the design of an axial gap-type superconducting machine using HTS materials in both bulk and wire forms [3], [13]-[15] and evaluating the performance of test coils for this. In [14], the DC characterization of a triangular, epoxy-impregnated HTS coil showed that non-uniformity exists along the length of the coil. The next step in characterizing the coil is to measure the transport AC loss.

In addition, in [16]-[18], it is shown that magnetic materials can be used to modify the magnetic flux profile of the conductors in an HTS coil to reduce its AC loss without modifying the original conductor, acting as a so-called flux diverter, and avoiding possible degradation of the superconducting properties that can occur with other techniques, such as striation [19]-[26], cutting/punching the conductor into a Roebel cable [27]- [31] or twisting [32], [33]. It is therefore of interest to consider whether the addition of a ferromagnetic layer is effective in reducing the AC loss for this triangular coil with non-uniformity along its length.

In this paper, the transport AC losses in a triangular, epoxy-impregnated HTS coil are measured using two different electrical techniques at 77 K. The first set of AC loss measurements are carried out at the University of Cambridge using a technique based on a lock-in amplifier. The coil is then measured at the Center for Advanced Power Systems (CAPS), Florida State University, using a technique based on a high accuracy data acquisition (DAQ) measurement system [8]. Multiple voltage taps are used to provide more detailed information on the distribution of the AC loss. The AC characterization of the coil, after adding a flux diverter made of ferromagnetic material, is also carried out to analyze its

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D. Hu, M. D. Ainslie, D. Zhou, J. P. Rush, and J. H. Durrell are with the Bulk Superconductivity Group, Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, UK (e-mail: dh455@cam.ac.uk; mark.ainslie@eng.cam.ac.uk; dz286@cam.ac.uk; jpr47@cam.ac.uk; john.durrell@eng.cam.ac.uk).

J. Kvitkovic, J. Kim, C. Kim, and S. Pamidi are with the Center for Advanced Power Systems, Florida State University, Tallahassee, FL 32310 USA (e-mail: kvitkovic@caps.fsu.edu; jkim@caps.fsu.edu; ckim@caps.fsu.edu; pamidi@caps.fsu.edu).

S. Pamidi is with the Department of Electrical and Computer Engineering, FAMU-FSU College of Engineering, Tallahassee, FL 32310 USA (e-mail: pamidi@caps.fsu.edu).

effect on the coil's performance. The specific experimental details are described in Section 2. In Section 3, the experimental results and discussions are presented, highlighting the consistency of the AC loss results using different techniques and the effect of the flux diverter. The results show some unique AC loss characteristics particular to this epoxy-impregnated HTS coil, which has a degraded region of non-uniform I_c most likely caused by the epoxy impregnation.

II. AC Characterization of the Test Coil

A. Coil Properties and Flux Diverter

The triangular HTS coil under test with the flux diverter is shown in Fig. 1. The DC characterization of this coil was carried out in [14] and its manufacturer specifications are listed in Table I. As a flux diverter, ferromagnetic sheets can be placed over the edges of the superconducting tapes in the coil. The ferromagnetic material used in this study, Vacoflux 50, was provided by Vacuumschmelze [34]. Each sheet of Vacoflux 50 was 0.35 mm in thickness and was machined into three flux diverter sheets with a shape to match the dimensions of the coil, such that three sheets could be layered to produce a single sheet with effective thickness 1.05 mm.

To achieve the best performance, the sheets should be added on both sides of the coil [16]-[18]; however, in this case, it could only be added on one side of the coil because of the voltage taps and current contact on the other side. A Teflon sheet of thickness 0.25 mm, shown in Fig. 1, is placed between the coil and the flux diverter as an insulation layer to avoid any current flow between the two.

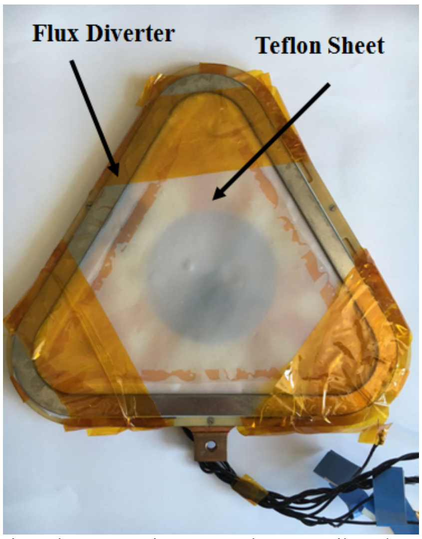

Fig. 1. The triangular, epoxy-impregnated HTS coil under test with flux diverter (Vacoflux 50, manufactured by Vacuumschmelze).

Ten voltage taps were utilized within the coil to help provide further detailed information on the AC loss of the coil. By pairing the voltage taps, there are 13 voltage sections used for the measurements, as shown in Fig. 2. The voltages V_1-V_9 are the voltages between the individual taps, which are spaced approximately every 2 m along the tape length (approx. every four turns), except for the final voltage tap, which is located 1.4 m from its preceding tap (approx. three turns). The first voltage tap is located 1 m from the coil's inner copper current contact and the final voltage tap is located 0.2 m from the outer current contact to prevent an anomalous measurement due to localized heating of the tape near the coil terminals [35]. Hence, V_1 corresponds to the voltage across the innermost section of the coil and V_9 corresponds to the outmost section. V_{10}, V_{11} and V_{12} correspond to the voltages along each third of the coil, where $V_{10} = V_1 + V_2 + V_3$, $V_{11} = V_4 + V_5 + V_6$, and $V_{12} = V_7 + V_8 + V_9$, and V_{13} is the total coil voltage across the 17.4 m tape length.

TABLE I
Specifications of the Coated Conductor and Triangular HTS Coil

Parameter	Triangular pancake coil
Tape manufacturer	SuperPower
Tape type	SCS4050-AP
Conductor width, w	4 mm
Conductor thickness, d_c	0.1 mm
YBCO layer thickness, d_{sc}	1 µm
Distance between YBCO layers	Approximately 220 µm
Length of conductor used	18.6 m
Coil turns, n_c	37
Coil measured inductance	465 µH

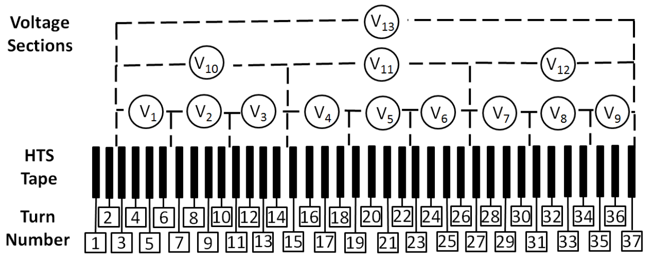

Fig. 2. The specific voltage tap locations and measured voltages for the triangular, HTS coil. The numbers at the bottom of the diagram represent the turn numbers of the coil.

B. Transport AC Loss Measurement with a Lock-in Amplifier

A schematic diagram of the experimental setup for measuring the transport AC loss of the triangular HTS coil is shown in Fig. 3. The setup includes a lock-in amplifier to extract the voltage corresponding to the transport AC loss, a signal generator to provide a stable sinusoidal waveform to the power amplifier, a Rogowski coil to provide a reference signal to the lock-in amplifier to set the phase accurately, a clamp meter to measure the current in the circuit, and an oscilloscope (not shown) to observe the signals in real time. The signal generator is the internal oscillator of the lock-in amplifier, which also acts as the lock-in amplifier's reference signal. The coil is cooled in a liquid nitrogen bath, the same procedure as that used in the DC characterization experiments in [14]. A compensation coil with a variable mutual inductance is used to compensate the HTS coil's large inductive voltage.

The compensation coil is similar to the one used in [2], [7] with some turns removed appropriate for the comparatively lower inductance of this test coil. By adjusting the displacement of the secondary coil of the compensation coil with respect to the primary coil, the inductive component of the combined voltage of the superconducting and compensation coils can be minimized. It can help reduce the out-of-phase component of the measured voltage, which can increase the tolerance of the phase error [36].

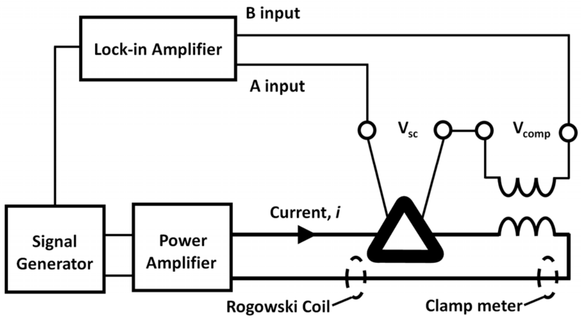

Fig. 3. Schematic diagram of the experimental setup for measuring the transport AC loss of an HTS coil using an electrical measurement method with a lock-in amplifier.

The Rogowski coil assists in obtaining an accurate phase of the current with respect to the voltage, which is one of the main sources of error in such AC loss measurements. The coil provides a purely inductive signal 90° out of phase with the circuit current, but at same frequency. It can be used to accurately set the phase of the lock-in amplifier [37] when combined with the output from the signal generator. In addition, the Rogowski coil is immune to electromagnetic noise if wound with evenly spaced windings.

The measured AC loss in J/cycle is calculated using V_{rms} I_{rms}/f, where V_{rms} represents the voltage in phase with the current of the HTS coil, as measured by the lock-in amplifier, I_{rms} represents the current flowing through the coil, which is measured by the clamp meter, and f is the frequency. The applied current in Figs. 6, 7, 9-11 is given in terms of its peak value.

C. Transport AC Loss Measurement with a High Accuracy Data Acquisition (DAQ) Measurement System

In order to verify the accuracy of the AC loss measurement technique using a lock-in amplifier, as described in the previous section, AC loss measurements were also carried out at CAPS using a DAQ measurement system [8]. A schematic diagram of the experimental setup for measuring transport AC loss using this system is shown in Fig. 4. The setup includes a high accuracy DAQ measurement system to extract the AC loss voltage and current, a signal generator to provide a stable sinusoidal current to the power amplifier, a current sensor to measure the current signal in the circuit and send the signal to the high accuracy DAQ measurement system, and an oscilloscope (not shown) to observe the signals in real time. The coil is cooled to 77 K in a liquid nitrogen bath. A compensation coil, providing a variable mutual inductance, is used to compensate the HTS coil's large inductive voltage.

The main difference between the setup in Fig. 3 is the use of the high accuracy DAQ measurement system, which consists primarily of an amplifier, a band-pass filter, an analogue to digital converter and a computer. The compensated voltage signal of the HTS coil (using the compensation coil) is amplified by the amplifier and passes through the band-pass filter to improve the signal-to-noise ratio and remove harmonics [8] using LabVIEW.

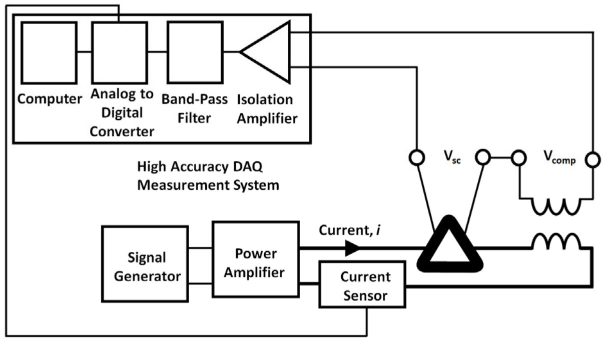

Fig. 4. Schematic diagram of the experimental setup for measuring transport AC loss of an HTS coil using an electrical measurement method with a high accuracy data acquisition (DAQ) measurement system.

III. RESULTS AND DISCUSSION

The critical current of the coil, measured by the method presented in [14], is 17 A, not 38 A as published in [14]. Between the DC characterisation in [14] and the ac loss measurements presented here, several preliminary experiments were carried out to calibrate the experimental equipment. At some point during this process, some further degradation occurred, resulting in a reduction in the coil's I_c. However, the I_c did not further degrade and retained this I_c after all the AC loss measurements in this paper. It is difficult to ascertain the exact cause of the degradation, but it is believed that the epoxy impregnation is the main cause, as described in [38]. The further degradation may have occurred to due overcurrent during preliminary testing; since the coil was thermally cycled many times, both here and in [14], this is not believed to be the cause.

Similar to the results in [14], V_3 dominates the voltage of the whole coil and there are almost no voltage drop in the V_{13}–V_3 region (the remainder of the coil), which can be seen in Fig. 5.

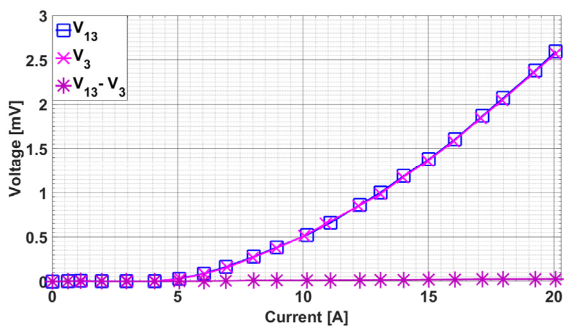

Fig. 5. Experimental results for the DC characterization of the triangular HTS coil, including voltages V_{13}, V_3, and V_{13}–V_3.

The AC loss of the triangular coil is measured separately using the lock-in technique and the high accuracy DAQ measurement system for three frequencies (44, 66 and 88 Hz). A comparison of the AC loss measurement results using these two techniques is shown in Fig. 6 and the AC loss measurements at different frequencies (44, 66 and 88 Hz) using the two different measurement techniques at different places (UK and US) are consistent. This validates the accuracy of these two techniques for transport AC loss measurements of superconducting coils. AC loss measurements are difficult to carry out and experimental verification using different techniques is extremely important. It is even more important in this case, where the measured ac loss is significantly different from ideal behavior, that such measurements should be verified to show the measurements are accurate, and can be trusted.

To provide more detail on the AC characterisation, the AC loss is measured for each third of the coil: V_{10}, V_{11}, and V_{12}, (see Fig. 2), and the results for three different frequencies (44, 66 and 88 Hz) are shown in Fig. 7. The sum of $V_{10} + V_{11} + V_{12}$, as well as V_{13} (Fig. 6), is also included in Fig. 7 for 88 Hz. It can be seen from Fig. 7 that the sum of $V_{10} + V_{11} + V_{12}$ is consistent with the result for V_{13}, and from Fig. 2, we expect that $V_{13} = V_{10} + V_{11} + V_{12}$. By investigating the AC loss characteristics in different regions of the coil, as carried out for the DC characterization in [14], more detailed information on its performance can be attained. It is clear from Fig. 7 that for the three different frequencies, the AC loss in J/cycle in each third of the coil are the same. In the DC characterization, V_3 dominates the measured voltage of the coil, and for the other regions, there is almost no voltage increase (see Fig. 5, for example), and V_3 belongs to V_{10}. One might initially assume that the region corresponding to V_{10} should have a higher measured AC loss in comparison to other regions, but this is not observed in Fig. 7, where the AC loss has a uniform distribution. The specific reason for this interesting uniform distribution requires careful investigation, including numerical simulations, which will be useful to further investigate both local and global superconducting properties, including the magnetic field profile and the current flow characteristics, particularly in the degraded region, and their influence on other regions of the coil. In the case of degraded I_c, if it were a single HTS tape being measured, we would expect the AC loss to increase for a given transport current, in comparison to a non-degraded tape [39]. In an HTS coil, the contribution of the magnetization from the self-field can dominate the AC loss, so although it is counter-intuitive, we might not expect an increased loss even with a region of low I_c, if the transport loss is not dominant [40]. The loss would also depend on the size of the degraded region along the tape length. From the DC characterization shown in Fig. 5, an ohmic loss of approximately 2 mW can be estimated for I = 7 A. This is dominated by the total AC loss (Fig. 7), which can be estimated as 176 mW for 88 Hz for I = 10 A_{peak}, corresponding to $I \approx 7$ A_{rms}.

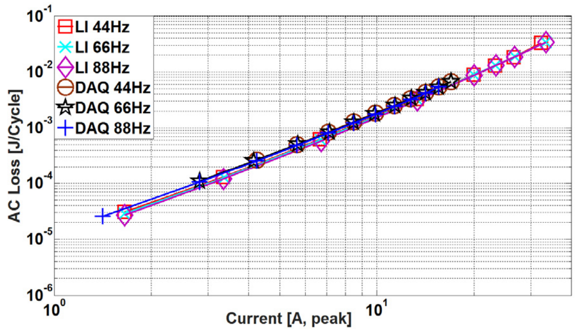

Fig. 6. Comparison of the experimental results for the transport AC loss measurement of the triangular HTS coil, corresponding to V_{13}, for three frequencies (44, 66 and 88 Hz) using the two electrical measurement techniques: (1) with the lock-in technique (LI) and (2) the high accuracy DAQ measurement system (DAQ).

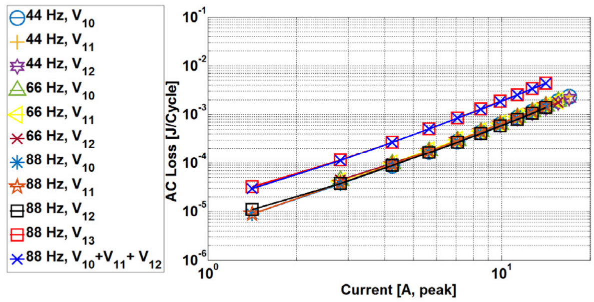

Fig. 7. Experimental results for the transport AC loss measurement of the triangular HTS coil for three frequencies (44, 66 and 88 Hz) for each third of the coil: V_{10}, V_{11}, and V_{12}, using the DAQ system. Additionally, the sum $V_{10} + V_{11} + V_{12}$ is compared with V_{13} (Fig. 6) is compared for 88 Hz.

The properties of the triangular HTS coil with one and three ferromagnetic sheets were measured separately. The experimental results of the DC characterization of the triangular coil without flux diverter, and with one ferromagnetic sheet and three ferromagnetic sheets, are presented in Fig. 8. It can be seen that the critical current of the coil in all cases is the same, around 17 A. It can be concluded that the application of flux diverter has not changed the critical current of the coil, regardless of the thickness of the ferromagnetic sheet.

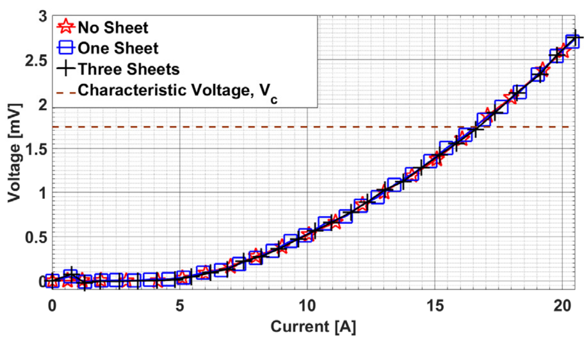

Fig. 8. Experimental results for the DC characterization measurements of the triangular HTS coil without the flux diverter, and one ferromagnetic sheet and three ferromagnetic sheets.

The experimental results for the transport AC loss of the coil with one and three ferromagnetic sheets are shown in Figs. 9 and 10, respectively, for three frequencies (44, 66 and 88

Hz). It can be seen that the transport AC loss in J/cycle for the coil with one or three ferromagnetic sheets at different frequencies (44, 66 and 88 Hz) are consistent, which is expected as both the AC loss and ferromagnetic loss are hysteretic.

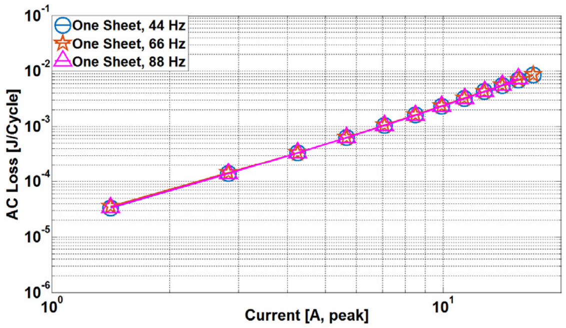

Fig. 9. Experimental results for the AC loss measurements of the triangular HTS coil with one ferromagnetic sheet for 44, 66 and 88 Hz, using the DAQ system.

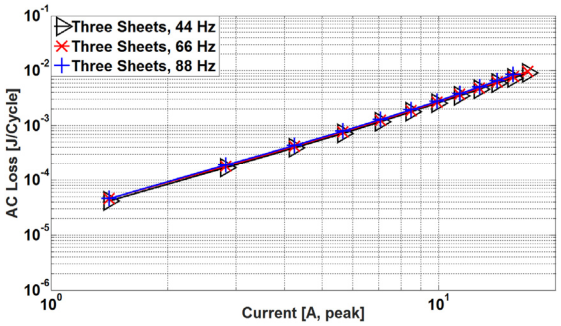

Fig. 10. Experimental results for the AC loss measurements of the triangular HTS coil with three ferromagnetic sheets for 44, 66 and 88 Hz, using the DAQ system.

Fig. 11 compares the measured AC loss of the coil without the flux diverter, and with one and three sheets as a flux diverter at 88 Hz. The use of the ferromagnetic sheet increases the measured AC loss of the coil, and increasing the number (or, correspondingly, the thickness) of sheets increases the AC loss. It should also be noted that with increasing current, the difference in the measured AC loss between each case is reduced.

Therefore, in this particular case, the use of ferromagnetic sheets as a flux diverter for this coil with a degraded region of I_c was not helpful in reducing the transport AC loss. Ordinarily, and as investigated numerically in [17], the AC loss could be reduced by using a flux diverter by changing the magnetic field profile in the coil, even when including the hysteretic loss of the diverter, and this was our main motivation for adding the ferromagnetic sheets in this study. It was also found in [17] that although the AC loss could be reduced, the use of a flux diverter could reduce the I_c by increasing the local magnetic field near the inner turn of the coil, where the highest magnetic field is seen and hence the lowest I_c. However, it has also been shown in recent work, which investigated the difference in AC loss in small HTS coils due to the presence of an iron core, that the AC loss can increase significantly due to the presence of a higher magnetic field when the core is present [41].

As the results show in Fig. 8, the flux diverter doesn't affect the I_c (negatively or positively) because the degraded region corresponding to V_3 dominates the I_c and appears to be unaffected by the presence of the flux diverter. The increase in the measured loss has a component from the increased volume of ferromagnetic material, resulting in a higher ferromagnetic hysteresis loss; however, it is difficult to separate the two components (AC loss and hysteretic ferromagnetic loss) from the measurement. The aid of numerical simulations will also be useful here to further investigate both local and global superconducting properties with the addition of the flux diverter, but including reasonable assumptions regarding the degraded region.

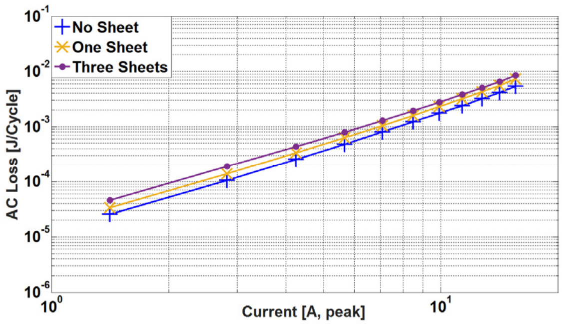

Fig. 11. Comparison of the AC loss for the coil without the flux diverter, and using one and three sheets as a flux diverter, for a frequency of 88 Hz, using the DAQ system.

IV. Conclusion

The transport AC losses in a triangular, epoxy-impregnated high temperature superconducting (HTS) coil were measured at 77 K using two different electrical techniques: one based on a lock-in amplifier (Cambridge) and the other based a high accuracy DAQ measurement system (Florida State University). The two different methods show consistent results, validating the accuracy of these two techniques for measuring the transport AC loss of HTS coils. Multiple voltage taps were utilized within the coil to study the details of the coil, and it was found that although a non-uniform region dominates the measured voltage of the coil from its DC characterization, the transport AC loss of the coil has a uniform distribution. The use of ferromagnetic sheets as a flux diverter is investigated experimentally for this coil with non-uniformity, and it was found that the flux diverter was not effective in reducing the AC loss in the coil, but also did not change the critical current of the coil.

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