

Designing and Commissioning an Experimental Setup to Evaluate AC Losses in Superconductors Under Transverse Rotating Fields

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Abstract—The development of low AC loss MgB₂ conductors and the increasing interest in a liquid hydrogen-based economy have reignited research into high power density fully superconducting (SC) electrical machines. In these machines, the armature winding experiences rotating fields that generate AC losses, making it essential to estimate these losses during machine design. While analytical and finite element analysis (FEA) models are available in the literature for estimating AC losses, these models for multi-filament MgB₂ superconductors have yet to be experimentally validated for machine operating regions. This article presents a high-precision AC-loss test setup to measure AC losses in SC MgB₂ windings under rotating fields at the air-gap field, frequency, and operating temperature levels relevant to electrical machine applications. The experimentally measured AC losses are then compared with analytical and FEA models. Results demonstrate good agreement between measurements and predictions. The paper discusses the experimental setup, sample preparation, calibration, measurement method, and results. The study provides a significant contribution to the development of high power density fully SC electrical machines.

Index Terms—Armature AC loss, AC loss measurement, fully SC machines, rotating field.

I. INTRODUCTION

EXPERIMENTAL measurement of AC losses in superconducting wires can present significant challenges due to their relatively small magnitude, typically on the order of milliwatts. Despite these difficulties, several successful studies have reported the measurement of AC losses in wires and cables operating under stationary alternating field conditions [1], [2], [3]. These can be measured through the electromagnetic measurements [4], [5], the electric-heater-based calorimetric method [6], or the cryogen boil-off-rate based calorimetric method [7]. Losses must be measured in the transverse rotating field to validate the loss estimation in electrical machines. Adding a

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TABLE I
TRANSVERSE ROTATING FIELDS EXPERIMENTAL SETUP CAPABILITIES

Method Reference	Field [T]	Frequency [Hz]	Temperature [K]
UIUC experimental setup	1	150	20
PM rotor [8]	0.5	400	77
Field winding rotor [9]	0.35	60	77
Alternating field [10]	0.02	90	77

rotating field to the loss measurements increases the complexity of the measurement setup and subsequent loss measurements. A rotating electrical field inside a cryogenic environment can be created by a permanent magnet (PM) rotor [8], field winding rotor [9], specially arranged alternating field coils [10], or by rotating a sample in a uniform field, [11]. As shown in Table I, limitations exist for each method in terms of the field level, frequency, and achievable sample temperature in the applied field. In particular, the majority of experimental setups currently available have measurement capabilities below 0.5 T and above 50-K. However, the experimental setup presented in this article surpasses the capabilities of other experimental setups, as it allows for the testing of samples at a field of 1-T and at sub-20-K temperatures while accommodating frequencies of up to 150-Hz. Fully SC electric propulsion machines operate at the 0.4–1 T air-gap field range and higher electrical frequencies in the 100–300 Hz range [12], [13], [14], [15], [16]. Fully SC direct drive wind turbines operate at low frequencies of 0.1–5 Hz and higher fields in the range of 0.5–1.5 T [17], [18], [19], [20], [21]. These higher fields and electrical frequencies greatly increase the losses in SC wires and pose substantial challenges to using them as armature windings. Recent developments in low-loss MgB₂ wires have promising features for fully SC machines. However, no measured loss data is available for MgB₂ conductors in these temperature, frequency, and magnetic-field regimes relevant to SC machine applications. This article experimentally validates the AC losses in MgB₂ wires for wind turbine applications and compares the results against analytical and FEA prediction. The detail of analytical and FEA models can be found in [22], [23]. The rest of the paper is organized as follows; Section II describes the AC loss measurement experimental setup, section III describes the detail of sample preparation, Section IV describes the calorimetric method, Section V describes the calibration and measurement methods, and Section VI summarizes the measurement results.

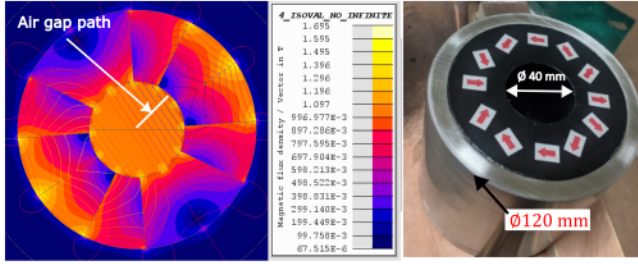


Fig. 1. (a) Flux density variation in the air gap. (b) Fabricated magnet rotor.

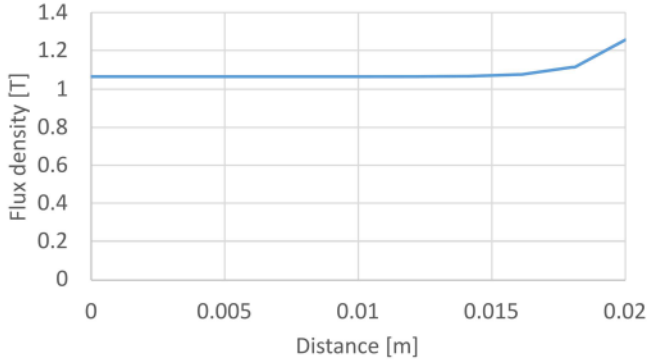


Fig. 2. Flux-density variation along the radius from the center.

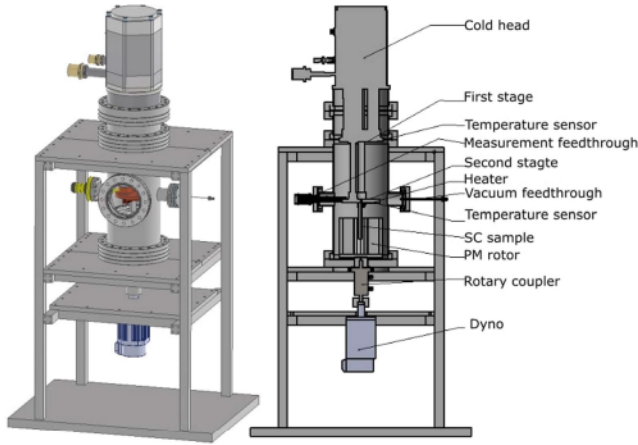


Fig. 3. 3-D CAD model of the AC-loss measurement test setup.

II. AC LOSS MEASUREMENT EXPERIMENTAL SETUP

Fig. 1 demonstrates that a two-pole rare earth PM rotor generates a strong magnetic field of approximately one Tesla (1 T) within a 40 mm air gap. The corresponding flux density variation across the air gap from its center is depicted in Fig. 2. The results reveal that the magnetic field within the air gap is relatively uniform. The field intensity slightly increases as it approaches the magnet, indicating a non-uniform distribution near the edges of the air gap. Samples are placed in the air gap, and the rotating field is applied mechanically, rotating the rotor. The applied electrical frequency can be changed up to 150 Hz. The heater-based calorimetric method measures the losses in the MgB_2 sample conductors. Fig. 3 shows the cross-section of the measurement setup. The PM rotor and the sample are placed

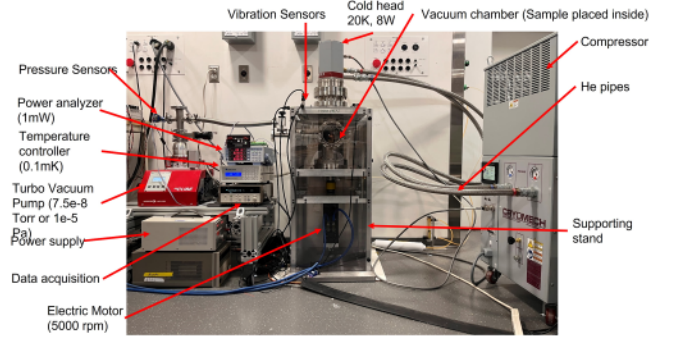


Fig. 4. AC-loss measurement test setup in the lab.

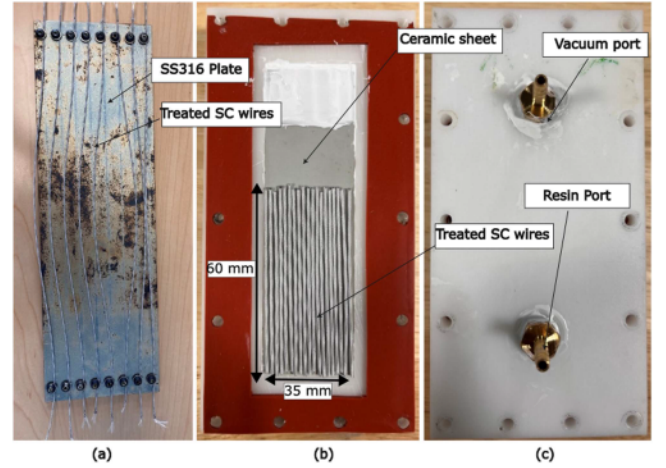


Fig. 5. SC MgB_2 samples preparation (a) Heat-treated MgB_2 wire (b) Samples stacked on the ceramic holder (c) VPI mold.

inside a stationary ultra-low vacuum chamber to eliminate the convection losses. The radiation shield, magnetic shield, and windage loss shield are placed inside the AC loss setup to minimize the error. The radiation shield is thermally grounded to the second stage of the cryocooler, and 15 layers of multi-layer insulation (MLI) are added outside the shield to reduce radiation losses further. A ferrofluid rotary vacuum feedthrough rotates the magnets inside the chamber. Samples are attached to a cold head using a thick copper disk to maintain them at the required temperature. A picture of the measurement experimental setup in the lab is shown in Fig 4.

The heater-based calorimetric method is employed to measure the AC losses. The cryocooler is operated in constant power mode. A heater is attached to the sample to control the heat load on the cryocooler and the cold-head temperature.

III. SC SAMPLES

The react and wind method is utilized to make SC MgB_2 samples. Un-reacted SC wire (0.52 mm OD, 24 μm filament OD, 57 filaments, 10 mm twist pitch) triplets supplied by HyperTech are used in the test. Sample wires are first cut into 45 cm length wires and attached to an SS316 steel plate as shown in Fig. 5(a) and heat treated for one hour at 650 degrees Celsius inside an Argon-filled oven. Then, the treated wires are cut into 6 cm samples and attached to a ceramic sheet totaling around 100 cm,

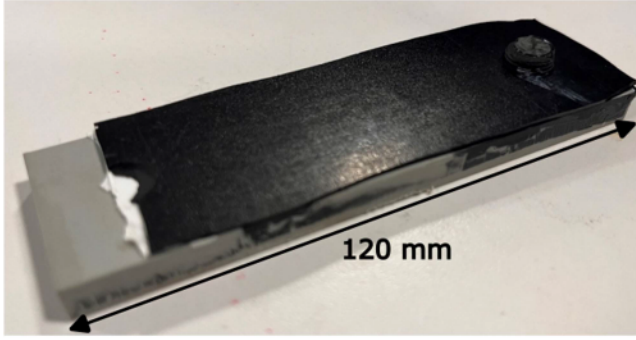
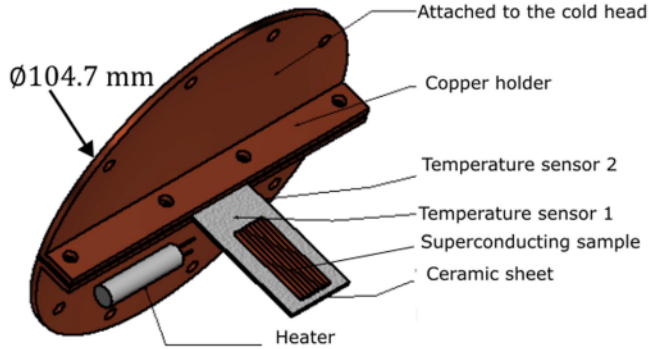
Fig. 6. SC MgB₂ samples after VPI.

Fig. 7. Calorimetric measurement arrangement inside the vacuum chamber.

as illustrated in Fig. 5(b). The ceramic holder is used instead of a metal holder to eliminate eddy current losses in the holder while providing excellent heat conduction to the SC samples. Aluminum nitride (AlN) and Boron (BN) nitride ceramic sheets are used as sample holders.

In order to achieve a high-quality resin fill and sufficient thermal conductivity, the samples were impregnated with resin using a vacuum pressure impregnation (VPI) method. Fig. 5(c) shows the vacuum and resin ports. The SC sample is placed inside the mold, and resin (STYCAST) is filled inside the mold against gravity using a vacuum pump. This reduces the entrapped air bubbles inside the sample and provides better thermal conduction between the SC wires and the ceramic holder. Fig. 6 shows a final AC loss measurement sample.

IV. CALORIMETRIC METHOD

The heater-based calorimetric method is employed to measure the generated AC losses. Fig. 7 presents the cold-head arrangement inside the vacuum chamber. A cryocooler is operated in a constant power mode to cool the sample. A heater is attached to the sample to control the heat load on the cold head and the cold-head temperature. A temperature controller monitors the cold head temperature and controls the heater. Fig. 8 shows the proportional–integral–derivative (PID) controller implemented to maintain a constant sample temperature. No losses are generated in the wire at stable conditions and idle operation. The heat load on the cryocooler equals the heat load put into the heater and the system's thermal losses. When the rotating field is administered, the external disturbance is applied to the system

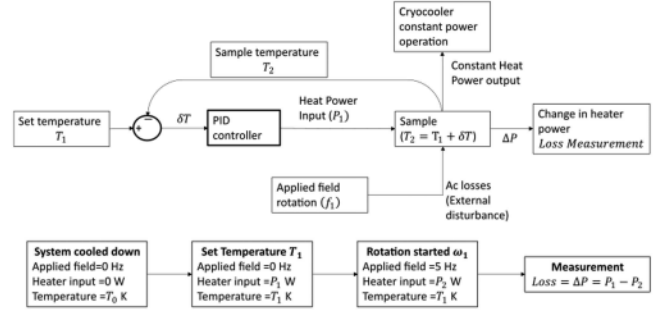


Fig. 8. Measurement control flow chart.

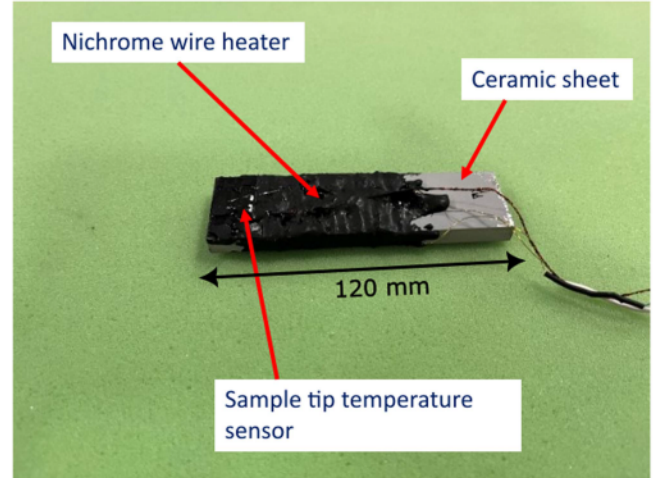


Fig. 9. Calibration sample.

as AC losses. The heat load will increase due to the additional AC losses, and because of that, the cold-head temperature will increase. The PID controller maintains a constant temperature by reducing the heat dissipated in the heater. This reduction is equivalent to the AC losses generated in the sample.

V. CALIBRATION AND MEASUREMENTS

First, rotating fields are generated inside the vacuum chamber without attaching samples to the cold head, and the temperature is monitored. This guarantees that no additional losses are generated inside the chamber due to the mechanical movements. The following tests are performed to calibrate the setup before measuring AC losses in SC samples.

- Epoxy Sample: Ceramic holder with an epoxy layer is used to estimate the windage losses in the system
- Copper wires: Copper wire with the same OD is used to validate the measurement technique
- Untreated SC wires: Estimate the eddy current losses and validate the heat treatment process
- Treated SC wires: Measuring AC losses

The measurement setup is calibrated to measure up to 10 mW of losses at 1 mK accuracy. Epoxy samples, copper wires, and untreated SC wires did not provide significant losses at low frequencies. Therefore, a special sample shown in Fig. 9 is made for calibrating the setup under low-frequency AC loss measurements. This sample is made with the same ceramic

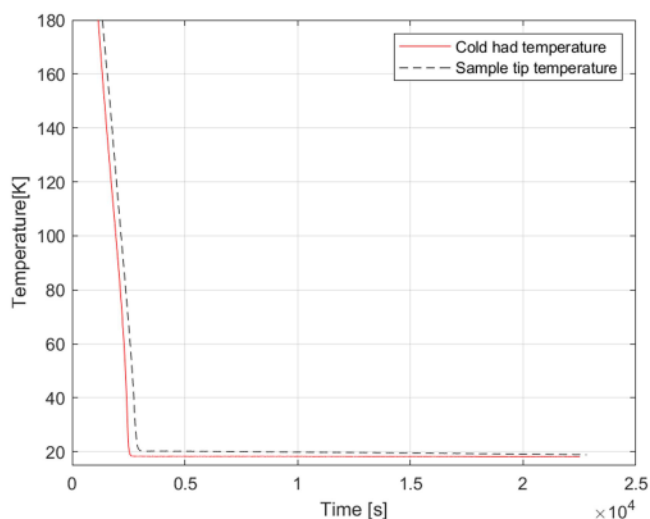


Fig. 10. Cold head temperature and Sample temperature versus time.

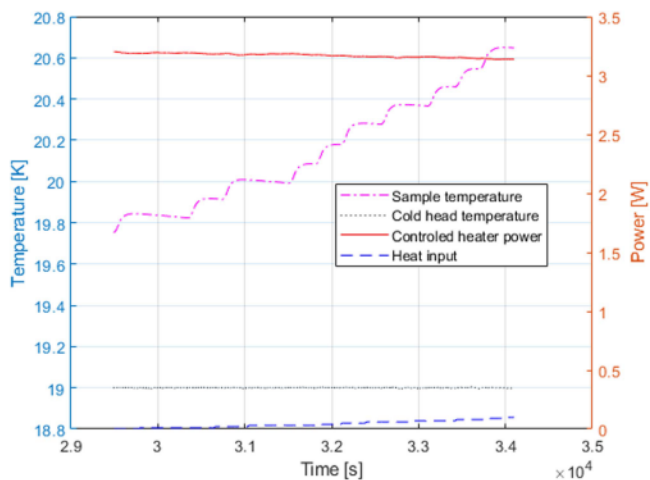


Fig. 11. Measurements taken during the calibration process.

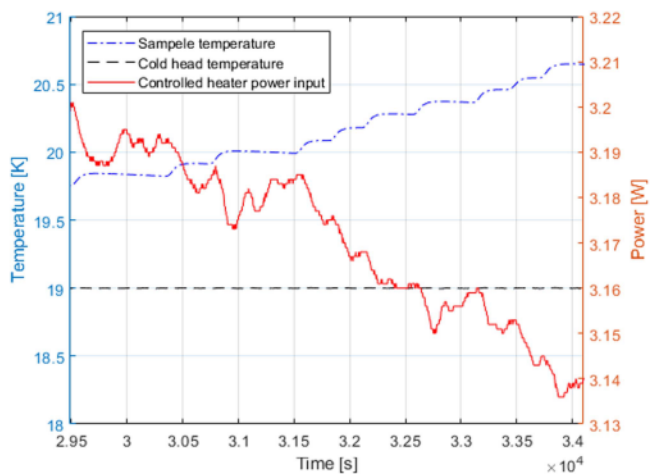


Fig. 12. Calibration procedure: Sample temperature and control heater input.

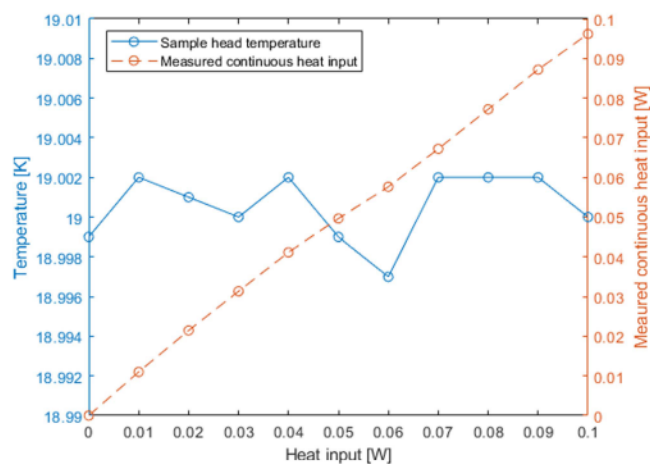


Fig. 13. Input heat versus measured heat.

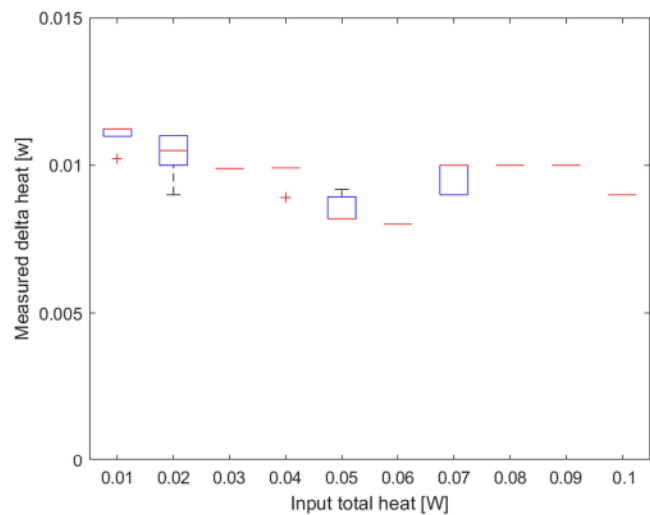


Fig. 14. Box plot of measured heat input.

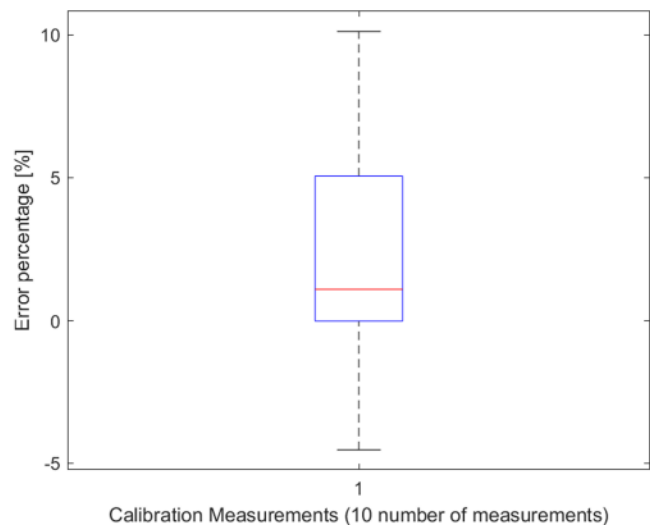


Fig. 15. Box plot of measurement error.

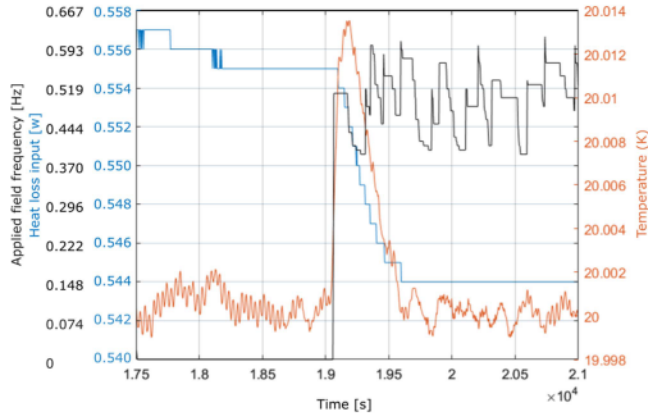


Fig. 16. Calorimetric method measurement.

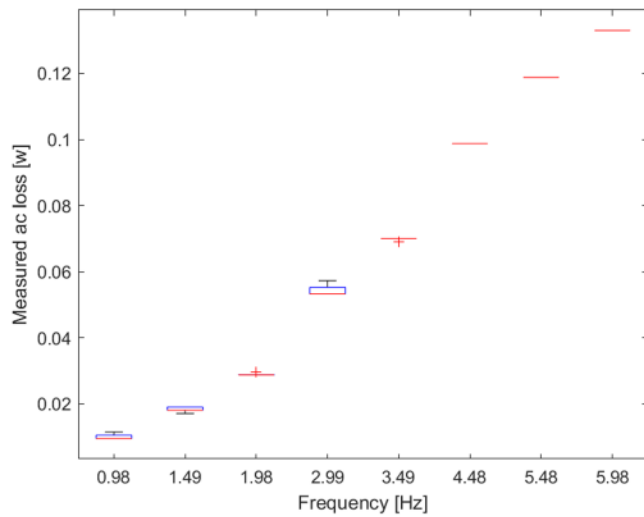


Fig. 17. Measured losses with varying frequency.

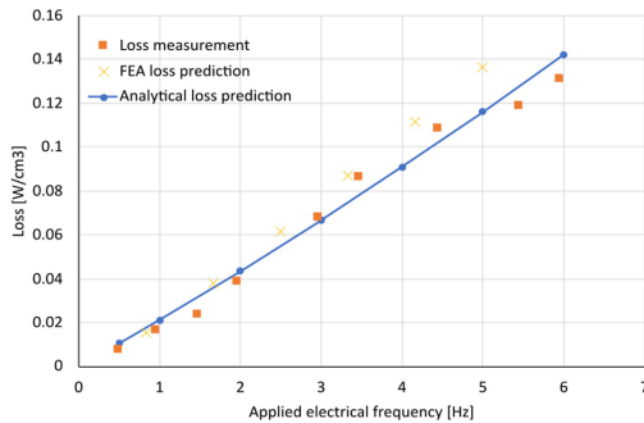


Fig. 18. Comparison of measured losses with analytical and FEA prediction.

sheet used in SC samples. As shown in Fig. 9, nichrome wire is wrapped around the ceramic sheet, and an additional temperature sensor is attached to the tip of the sample. Fig. 10 shows the sample and cold temperatures during the initial cooling down. This shows that the sample temperature and the cold-head temperature closely match.

The nichrome heater is powered by another power supply to heat the sample. Power input to the sample and the sample temperature is measured. Heat input is increased in 10 mW steps and then measured using the calorimetric method. Fig. 11 shows the calibration procedure. It can be seen that, as the heater input is increased in 10 mW steps, the sample temperature also increases, but the cold head temperature is maintained at 19 K set temperature. It can also be seen the sample heat load is increased while the controlled heat load is decreased. This can be further demonstrated in Fig. 12. Losses are measured from when step heat change is applied to when the first steady-state temperature is achieved.

Fig. 13 shows the input heat vs. measured heat with zoomed-in cold head temperature measurements. Cold head temperature is maintained within 2 mK accuracy while heat input is increased from 0-W to 100 mW in 10 mW steps. A box plot of the measurement is shown in Fig. 14. Calibration showed that the losses could be measured with five percent accuracy. Error percentage based on the mean of the measured loss is shown in Fig. 15. The mean error was 1.39%, and the median error was 0.52% with one outlier of 10%. This shows that the measurement setup accurately measures AC losses at low frequencies where total losses are under 10 mW. Fig. 16 presents the calorimetric measurement conducted at 0.5 Hz applied frequency. Initially, the sample is maintained at 20 K, and the rotating field is applied at around 19,000 s. Increasing sample temperature indicates additional AC losses generated in the sample. The PID controller decreases the heater input power to maintain the sample temperature at 20 K. This heat reduction is equal to the AC losses in the sample.

VI. RESULTS

Wind turbines operate at a low-frequency range. For example, a 10 rpm wind turbine generator with 10 to 60 pole count arrangements will have electrical frequencies varying from 0.8 Hz to 5 Hz. Experimental AC-loss measurements are conducted in this range and compared against analytical and FEA loss estimation. Fig. 17 gives the measured AC losses on a reacted MgB₂ SC sample at wind turbine frequencies. Using the total wire length used in the sample loss in conductors can be evaluated in W/cm³. Fig. 18 compares the results in W/cm³ between measurement and prediction. The analytical and FEA prediction closely matches the experimental measurements.

VII. CONCLUSION AND FUTURE WORKS

Fully superconducting (SC) electrical machines hold significant potential for high-power density applications, such as large wind turbines and electric propulsion systems. To measure AC losses in SC wire samples, a high-precision AC-loss test setup was designed and commissioned, which is the first of its kind to measure AC loss in SC MgB₂ windings under a rotating field at the air-gap field, frequency, and operating temperature levels relevant to electrical machine applications. This article provides a detailed description of the construction, operation, calibration procedure, methods for making the SC AC loss samples, and measurement procedure of the experimental setup. The AC losses were measured at low frequencies within the direct drive

wind turbine operating range and compared against analytical models. The results show that the AC loss predictions from the analytical and FEA models closely match the experimental results. Currently, upgrades are being carried out on the test setup to measure losses at high frequency, such as strengthening the rotor shaft and mounting a magnetic shield on the rotor to replace the stationary iron shield. These upgrades aim to increase the rotor speed and improve the accuracy of results at frequencies where eddy currents in stationary shields pose a problem. The AC loss experimental setup developed in this article has the potential to validate loss models for other SC wires and tapes. It would be interesting to conduct a future test campaign to compare the loss predictions and test results for high-temperature superconducting (HTS) tapes and cables under conditions representative of an electrical machine operation.

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