Temperature dependence of critical current and transport current losses of 4 mm YBCO coated conductors manufactured using nonmagnetic substrate

J Kvitkovic¹, R Hatwar¹², S V Pamidi¹³, S Fleshler⁴, C Thieme⁴
¹ Center for Advanced Power Systems, Florida State University, Tallahassee, Florida 32310, USA
² Heat Transfer Lab, Mechanical Engineering Department, Johns Hopkins University, Baltimore, Maryland 21218 USA
³ Department of Electrical & Computer Engineering, FAMU-FSU College of Engineering, Tallahassee, Florida 32310, USA
⁴ American Superconductor Corporation, Devens, Massachusetts, USA

E-mail: kvitkovic@caps.fsu.edu

Abstract. The temperature dependence of the critical current and AC losses were measured on American Superconductor Corporation’s (AMSC) second generation high temperature superconducting (2G HTS) wire produced by Rolling Assisted Biaxially Textured Substrate (RABiTS) and Metal Organic Deposition (MOD) process. Wires manufactured with two types of substrates were characterized. The magnetic substrate with composition Ni5a%W exhibits a magnetic signature and has non-negligible AC losses in AC power applications. A new nonmagnetic substrate with an alloy composition Ni9a%W has been developed by AMSC to address the AC losses in 2G HTS. The data presented show that the performance of the new conductor is identical to the conductor with magnetic substrate in terms of critical current density. The data on AC losses demonstrate the absence of ferromagnetic loss component in the new conductor and significantly reduced AC losses at low to moderate values of I/Ic. The reduced losses will translate into reduced capital costs and lower operating costs of superconducting electrical devices for AC applications.

1. Introduction

Critical current density and AC losses are two of the most important electrical characteristics of superconducting wires critical for their power applications. Recent advances in the production of long lengths of 2G HTS tapes with high critical current values have made it feasible for deploying HTS cables, fault current limiters, transformers, and energy storage systems. AC losses are one of the major heat loads on the cryogenic systems supporting the power devices, and hence, contribute to the capital investments and operating costs of the overall power system. Many studies were carried out to measure the critical current and transport AC losses on variety HTS tapes to understand the relation between them and to develop theoretical models [1–3]. American Superconductor Corporation (AMSC), one of the major manufacturers of 2G HTS wire uses a technology that is based on Rolling Assisted Biaxially Textured Substrate (RABiTS) for the template on which HTS layer is grown via Metal Organic Deposition (MOD) as described elsewhere [4, 5]. The standard RABiTS technology employs a Ni-W alloy with nominally five atomic percent W (Ni5a%W) as it can be readily produced with a high degree
of cube texture and can support HTS layers with high critical current densities. Although wire manufactured with Ni5at%W is suitable for many DC applications, the substrate exhibits a ferromagnetic signature which gives rise to non-negligible AC loss under some AC conditions rendering it less desirable for several AC applications. To reduce the AC loss of the wire and address the magnetic behavior of the substrate, a RABiTS process has been developed for an alloy with composition Ni9at%W [6, 7]. This alloy exhibits a relative permeability slightly above one and reversible magnetic behavior at temperatures accessible with liquid nitrogen.

Superconducting cables are typically operated in sub-cooled liquid nitrogen to take advantage of the enhanced critical current densities at lower temperatures and to prevent nitrogen gas bubble formation to ensure dielectric integrity of the cable system. For application of wire with this nonmagnetic substrate to cable systems, it is necessary to understand the critical current and the AC loss characteristics, the relations between the two parameters of the new non-magnetic conductor in the temperature range accessible by liquid nitrogen. In this study we have measured temperature dependence of critical current and transport AC losses on two 2G HTS wires at frequencies 10–400 Hz in the temperature range of 63 – 78 K. The main emphasis of this study is to compare critical current (Ic) and AC losses of 2G wires produced by AMSC with the original magnetic and newer non-magnetic substrates.

2. Experimental

2.1. Sample description

Two samples of 2G wire used in this study were provided by AMSC. Sample 1 was produced with the Ni5at%W substrate while Sample 2 was manufactured with Ni9at%W substrate. For both samples, the substrate thickness was in the range 62 – 75 μm. HTS layers deposited on the substrates are nominally 1.2 μm thick with both tapes possessing self-field Ic’s around 150 – 160 A at 77 K. The HTS insert strip produced on the manufacturing line was slit to 4 mm in width and laminated to 4.4 mm wide brass stabilizers on each face. This wire configuration with 4.4 mm x 150 μm of brass stabilizers on each side has been deployed in numerous power cables.

2.2. Critical current and AC loss measurement apparatus

The sample ends were soldered on to the current leads of the sample holder with a low temperature Indium solder (66%In and 34%Bi). The voltage taps were soldered on the tape axis and the loop width was maintained at three times the half tape width of the HTS tape before they were twisted. Three Lake Shore Cernox temperature sensors were placed below the sample for precise sample temperature measurement. The sample holder was immersed in liquid nitrogen bath in a vacuum tight cryostat that is suitable for pumping on the liquid nitrogen. The temperature of the liquid nitrogen bath in temperature range 63 – 78 K was controlled by regulating the pressure above the bath with a vacuum pump and valve combination. The temperature of the sample was monitored using a Lake Shore temperature controller model 340. The temperature stability at the set point was better than +/-0.1 K. The DC current–voltage characteristics at different temperatures were measured by the standard four-probe method. A schematic used for the transport current AC loss measurements is shown in Fig. 1. The power amplifier cabinet consists of four blocks of Techron 7782 amplifiers connected in parallel and controlled by a Stanford Research Systems DS360 signal generator. The voltage step-down and isolating transformer was used to achieve the sample current up to 600 A. The transformer also facilitates in minimizing the common mode errors in the measurements.

The actual current through the sample was measured by a low inductance Hall probe current sensor and a digital multimeter Keithley model 2001. The loss voltage was measured using a Lock-in amplifier Stanford Research Systems SR830. The auto-gain and auto-phase procedure was performed at sample current of 5 A using a Rogowski coil output connected to the Lock-in input A. After measuring the phase shift between sample current and Rogowski signal, the phase was changed by 90 degrees to measure the resistive component of the sample loss voltage. The directly measured sample voltage was connected to input A of the Lock-in amplifier. The inductive component of the sample voltage was
compensated by a variable voltage, generated in compensation coil, connected input B of the Lock-in amplifier. Lock-in amplifier was set to differential input A-B in float configuration with the time constant of 0.3 s. The AC loss measurements were performed in frequency range 10 - 400 Hz.

3. Results and discussion

Critical current was measured on samples of 16 cm in length with soldered current contacts of 5 cm long on both sides. The potential taps were placed in the center of the sample with 2 cm between them. The temperature dependence of the critical current in self-field was measured with the electric field criterion of 1 μV/cm. Critical currents of both samples were measured in the temperature range of 63 – 78 K, the results of the critical current measurements are shown in Fig. 2. It can be seen that both samples have approximately the same critical current of 160 A at 77 K and the temperature dependence of Ic of both samples is identical with a slope of ~ -15 A/K. As is typical with 2G HTS, the critical current doubles as temperature is lowered from 77 K to 67 K. We fit the measured data with Onnes formula: \( I_c(T) = I_c(0)(1 - T/T_c) \) with \( T_c = 88 \) K and \( I_c(0) = 1310 \) A.

The transport current losses per cycle and unit length of Sample 1 and Sample 2 at 78 K as function of the transport current amplitude are shown in Fig. 3. At currents well below the temperature dependent \( I_c \), the superconductor losses are negligible for Sample 1 and the ferromagnetic loss dominates the loss signal. As current is increased, the superconductor losses increase non-linearly while the ferromagnetic loss tends to saturate. The level of current at which the superconductor losses become significant relative to the ferromagnetic loss depends on the temperature dependent \( I_c \). Loss is a mixture of superconducting loss and a saturated ferromagnetic loss. It can be noticed for Sample 1 that the frequency dependence of AC loss is weak. Sample 2 had ~ 10 times lower losses at 10 A peak.
To further analyze the impact of the magnetic component to the AC loss in Sample 1, the loss data is normalized by $I_c^2$ and plotted against normalized transport current (by $I_c$) in Fig. 4 in the temperature interval of 63 – 68 K at 100 Hz. As seen in the figure, the losses at different temperatures do not scale with normalized current due to the ferromagnetic losses from the magnetic substrate. Ferromagnetic
losses do not change with the temperature while the critical current increases with decreasing temperature.

The results of AC loss measurements on Sample 2 at 78 K and 64 K are shown in Fig. 5. The temperature dependence behavior of AC losses in Sample 2 is different than in Sample 1. The measured AC losses are significantly smaller in Sample 2 compared to Sample 1 over the entire transport current interval. The frequency dependence of the losses in Sample 2 at 78 K is weak.

![Figure 4](image4.png)

**Figure 4.** Normalized transport current losses versus normalized current of Sample 1.

![Figure 5](image5.png)

**Figure 5.** Transport current losses versus transport current of Sample 2 at 64 and 78 K.

Fig. 6 shows the normalized losses versus transport current of Sample 2 in temperature interval 64 – 78 K at 100 Hz. It can be seen that that the AC loss data at various temperatures scales perfectly. The perfect scaling of the normalized losses clearly indicates that the losses depend just on the current and there is no ferromagnetic loss component present. The loss data of Sample 2 demonstrates that the substrate in Sample 2 is nonmagnetic.
Comparison of normalized transport current losses versus normalized transport current of both samples at 100 Hz is presented in Fig. 7. One could observe that normalized AC losses of Sample 2 are minimum three times lower for normalized current, $I/I_c$ from 0 to 0.3 while the normalized losses on both samples are almost identical at higher currents.

Figure 6. Normalized transport current losses versus normalized current of Sample 2.

Figure 7. Comparison of normalized transport current losses versus normalized transport current of Sample 1 and Sample 2 at 100 Hz.
The data presented demonstrates that the 2G HTS conductor fabricated using the nonmagnetic substrate performs similar to that fabricated from the magnetic substrate in terms of critical current density values and temperature dependence of critical current density. The benefit of the nonmagnetic substrate is clearly demonstrated with lower losses, particularly at the normalized critical current, $I/I_c$ values of < 0.6. Typical superconducting cables and other devices are designed to operate below $I/I_c$ of 0.6 to have operating and safety margin. Hence use of the nonmagnetic substrate significantly reduces the heat load on the cryogenic systems of superconducting cables and other devices for AC applications.

4. Conclusions
Temperature dependence of the critical current and transport current losses were measured on samples from two different batches of 2G HTS wire manufactured by AMSC. One of the samples is fabricated using the magnetic substrate with ferromagnetic properties and the second sample is fabricated with a nonmagnetic substrate. It was demonstrated that the conductor produced with the nonmagnetic substrate performs similar to the conductor with the magnetic substrate in terms of critical current and its dependence on operating temperature. Loss measurements in the temperature range 63 – 78 K have shown that the conductor with the nonmagnetic substrate does not have any magnetic loss component and the AC losses are significantly lower than in the conductor with the magnetic substrate for current values lower than 60 % of the critical current at the given operating temperature. The reductions in the AC losses represent a significantly reduced cryogenic capacity needed and lower operating costs of the cryogenic equipment for power applications.

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