AC loss measurements in a hybrid REBCO/BSCCO coil assembly

Z. Jiang, M. Staines, N. J. Long, R. A. Badcock, C. W. Bumby, R. G. Buckley, W. Song, and N. Amemiya

Abstract— Wire cost and AC loss are paramount issues for the future uptake of HTS AC machines. In particular, new approaches which reduce the total manufacturing cost of HTS coils are critical to the future commercial uptake of HTS technology. Here, we present the results of AC loss measurements of a hybrid HTS coil assembly comprising end windings (EWs) wound with BSCCO wire and a central winding (CW) wound with REBCO wire. As a cost mitigation measure, we have chosen to use REBCO wire which possesses a relatively low self-field I_c at 77 K, equating to approximately half that of the BSCCO wire.

Transport AC loss measurements were made on the total coil assembly at both 77 K and 65 K, using a recently developed lock-in amplifier approach. We show the AC losses in the assembly at these temperatures scale with the overall transport critical current threshold of the hybrid coil assembly. The results are then compared with a reference coil assembly having similar geometrical dimensions, and in which both the EWs and CW were wound with identical BSCCO wire. Surprisingly we observe that the AC loss of the hybrid coil is lower than that of the BSCCO coil, despite the CW of the hybrid coil employing wire a lower overall average I_c . We attribute this effect to the lower AC loss of coated conductor REBCO wire under parallel field, which is the dominant field orientation in the CW region.

Based on this observation we conclude that hybrid assembly design is a good design strategy for HTS coil assemblies, enabling both wire cost and AC loss to be balanced.

Index Terms— AC loss, HTS, Coil assembly.

I. INTRODUCTION

Reducing the AC loss of coil windings is a prime consideration in many AC applications of high temperature superconductor (HTS) wire, for example power transformers or fast-ramping DC magnets [1-5]. For a given AC transport current, the loss can be reduced by using wire with higher critical current, or by using a larger quantity of wire operated at a lower fraction of its critical current (to achieve the same amp-turns with fewer amps and more turns). However, both of these approaches incur substantially higher manufacturing costs, as HTS wire is typically marketed on a \$ per kAm basis, and the cost of HTS wire increases rapidly with self-field I_c . This is a major obstacle to technology uptake in cost-sensitive commercial applications.

Two main types of HTS wire are commercially available for HTS coil applications: BSCCO filamentary wire and REBCO coated conductor wire. At the moment, the price of BSCCO wire remains significantly lower than the REBCO price for the same self-field I_c performance at 77 K, even though there is future potential to attain lower manufacturing costs for the latter. Therefore HTS coils manufactured from BSCCO wire can generally be produced at lower cost than equivalent coils manufactured from REBCO wire. On the other hand, by using REBCO wire rather than BSCCO in a coil winding, there is the potential to reduce the AC loss in the coil winding. As a result, the literature is replete with reports of experimental and modelling studies on windings using either BSCCO or REBCO wire [2-10]. However, there are far fewer reports of hybrid coil assemblies employing either mixed wire types, or separate wires with different critical current, that are deliberately apportioned within the winding assembly.

Fig. 1(a) shows a schematic view of a typical HTS coil assembly. The local magnetic field experienced by the wire depends on its position within the coil. Wire near the ends of the winding is subjected to relatively high radial magnetic fields which are perpendicular to the face of the conductor, whilst the wire in the central section of the winding sees magnetic fields which are approximately parallel to the conductor face. The substantial difference in magnetic environment along the coil suggests that the optimal choice of wire for each region may not be the same. The aim of the present study is to investigate the potential for reducing both losses and manufacturing cost by judicious mixing of BSCCO and REBCO wire types.

FIG. 1 HERE

Recently we have reported measurements of the critical current and AC loss of three different HTS winding assemblies made of stacks of six double pancake coils (DPCs) [11]. Each set of double pancakes were fabricated from approximately 4 mm BSCCO and REBCO wires possessing distinctly different self-field I_c values at 77 K. The assembly could be divided into three sections: two identical end windings (EWs) and a central winding (CW) as shown in Fig. 1(b). Each end winding consisted of a single DPC. The central winding was made up of four double pancake coils. One assembly was wound solely from a single type of BSCCO wire with self-field I_c at 77K of

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Z. Jiang, M. Staines, N. J. Long, C. W. Bumby, R. A. Badcock, R. G. Buckley are with the Robinson Research Institute, Victoria University of Wellington, PO Box 33436, Lower Hutt 5046, New Zealand. (e-mail: zhenan.jiang@vuw.ac.nz).

W. Song is with School of Electrical Engineering, Beijing Jiaotong University, Beijing 100044, China, currently is visiting the Robinson Research Institute, Victoria University of Wellington.
N. Amemiya is with Graduate School of Engineering, Kyoto University, Kyoto, 615-8510, Japan.

156 A (All-BSCCO). A second assembly was wound with REBCO wire (All-REBCO), in which the EWs were wound with high I_c wire ($I_{c,EW} = 238$ A) whilst the CW was wound with low I_c wire ($I_{c,CW} = 86$ A). A third assembly (BSCCO/REBCO) was wound with BSCCO for its CW and with high- I_c REBCO for its EWs. The results from this work showed that the AC loss can be reduced by using REBCO wires for CW region. This is because the magnetic field in the CW is mostly parallel and the AC loss in REBCO wires due to the parallel magnetic field is small [11]. However, the lowest losses reported in that work were obtained from coil assemblies employing end windings made from expensive high I_c REBCO wire.

In this work, we have studied a new alternative hybrid coil design, which has the potential to decrease the AC losses below that of a BSCCO coil, without incurring the additional expense of high I_c REBCO end windings. In this case the coil EWs are wound with BSCCO wire, whilst its CW is wound with low I_c REBCO wire. We have measured the AC loss and I_c of the coil assembly ($I_{c,assembly}$) at 65 K and 77 K. We have then compared the AC losses with assemblies with the All-BSCCO and All-REBCO coil assemblies reported in the previous work [11].

II. EXPERIMENTAL METHOD

A. HTS coil assembly

The double pancake coils (DPCs) were manufactured by HTS-110 Ltd. The coils are dry-wound without epoxy resin encapsulation. Turn-to-turn insulation is provided by Nomex aramid paper 0.05 mm thick co-wound with the HTS wire [11].

The coil assembly studied here consisted of a REBCO CW and two BSCCO EWs. We will refer to this arrangement as the REBCO/BSCCO assembly. The CW is wound with SCS 4050 REBCO coated conductor wire manufactured by SuperPower. The wire width is 4.0 mm, thickness 0.1 mm, and the self-field $I_c = 86$ A. The CW comprised a stack of four DPCs. The DPCs were identically constructed: each had 40 turns, 9 mm height, coil inner diameter 60 mm, outer diameter 73 mm. The CW included 1.5 mm thick G-10 spacers at the ends to give a total height of 38 mm. Electrical connection between the neighboring DPCs consisted of ten BSCCO strips each 10 mm long, which were soldered in parallel to provide a low contact resistance between coils. BSCCO wire with self-field I_c of 170 A was used for these interconnects using $\text{In}_{66.7}\text{Bi}_{33.3}$ solder with a melting point of 72°C. The EWs were made with AMSC BSCCO wire which was 4.3 mm wide and 0.3 mm thick, with average 77 K self-field I_c of 156 A. The gap between the CW and EW was 1.5 mm. Fig. 2(a) shows the full coil assembly.

FIG. 2 HERE

Fig. 3 (a) shows the calculated magnetic field distribution within the REBCO/BSCCO assembly for a current of 40 A (COMSOL ver. 5.2). This represents the peak field experienced by the coil windings when $I/I_{c,assembly} = 0.72$. The flux line distribution obtained is qualitatively similar to that shown in Fig. 1. Figs. 3(b) and 3(c) show calculated variation of the radial and axial field components of the innermost, central, and

outermost layers of the assembly. In both cases, we observe small amplitude fluctuations with axial position which arise due to the air gap spacing between each DPC stack. We also see that the radial field component is broadly independent of winding layer position, reaching a maximum magnitude of 100.0 mT at either end of the assembly (axial position = ± 29.5 mm), and a minimum magnitude of zero at the center of the assembly (axial position ~ 0 mm). In contrast, the axial field component shows a strong dependence on winding layer position, with the inner and outer winding layers within each DPC experiencing axial fields of opposite direction. The axial field magnitude reaches a maximum for both the outer and inner layers at an axial position of 0 mm. These calculated field profiles support our assumption that axial field performance is of primary importance for wire employed in the CW region of the assembly.

FIG. 3 HERE

B. Measurement method

The detailed measurement method has previously been published [11]. Here we summarize the main points. Fig. 2(b) shows the measurement set-up schematic. Voltage taps connected to the end of the coil assembly were used for measurements of both $I_{c,assembly}$ and AC loss. The coil assembly was mounted in a foam-insulated non-conductive glass reinforced polymer (GFRP) LN_2 dewar [12]. The temperature of the LN_2 was controlled between 77 K and 65 K by pumping on the dewar with the pressure regulated using a manostat. Two lock-in amplifiers (Stanford 830) were used for data acquisition: one measured the current phase and amplitude using an in-house two-stage current transformer, whilst the other measured the voltage difference across the coil assembly voltage taps.

The AC loss per cycle per unit conductor length of the coil assembly is given by,

$$Q = \frac{V_{\text{rms}} I_{\text{assembly,rms}}}{f}. \quad (1)$$

where V_{rms} is the component of the coil assembly voltage in-phase with the coil current, $I_{\text{assembly,rms}}$ is the rms value of the coil assembly current, and f is the frequency of the coil assembly current.

III. EXPERIMENTAL RESULTS

A. I_c measurement of the coil assembly

$E - I$ curves for the REBCO/BSCCO assembly at 77 K and 65 K are shown in Fig. 4. In addition, $E - I$ curves for the previously measured All-REBCO and All-BSCCO assemblies are also plotted in this figure for comparison [11]. The plotted curves are obtained after subtracting resistive components due to the soldered joints between DPCs. Table 1 shows the $I_{c,assembly}$ values at 77 K and 65 K based on the usual $1 \mu\text{V/cm}$ electric field criterion, together with the values for the All-BSCCO and All-REBCO assemblies. The $I_{c,assembly}$ values at 77

K obey the relationships $I_c(\text{REBCO/BSCCO}) \approx I_c(\text{All-REBCO}) < I_c(\text{All-BSCCO})$ while at 65 K $I_c(\text{REBCO/BSCCO}) \approx I_c(\text{All-BSCCO}) < I_c(\text{All-REBCO})$. The change in relative magnitude with differing temperature is probably due to the higher I_c ‘lift factor’ of REBCO wires than that of BSCCO wires. The lift factors of $I_{c, \text{assembly}}$ values at 65 K compared to 77 K for the assemblies are listed in Table 1. The lift factor for the REBCO/BSCCO assembly is between that for the All-REBCO and All-BSCCO assemblies.

FIG. 4 HERE
TABLE I HERE

B. Coil assembly AC loss measurement

Resistive dissipation in the contact resistances, R_c , between the DPCs was confirmed to be much less than the AC loss in the HTS coil assemblies [11]. The R_c values at 77 K and 65 K are 2.29 $\mu\Omega$ and 2.10 $\mu\Omega$, respectively. The AC loss values for the coil assembly presented in the figures that follow are net AC loss values, with the ohmic loss component due to R_c subtracted.

Fig. 5 shows the measured AC loss in the assembly at 43.96 Hz and 26.62 Hz, and at 77 K and 65 K, plotted as a function of current amplitude. The AC loss results per cycle at each frequency agree very well in the high current region although there is some disagreement between the results in the low assembly-current region. This minor difference might be due to the frequency dependence of AC loss in some HTS wires [13, 14], however the frequency independence of the results at higher currents confirms that the loss is hysteretic.

Previous studies have shown that AC loss in HTS windings with AC transport current of amplitude I_t and coil critical current I_c follows a power law $\propto (I_t/I_c)^n$ where the exponent n is between 2 and 4 [2-10]. By fitting our experimental data, we find that the loss varies with current according to a power law with exponent approximately 2.3 to 2.6 which is in accordance with previously reported values [2-11].

In the figure, the AC losses (at 26.62 Hz) for the previously measured All-BSCCO assemblies also plotted for comparison. Interestingly, we observe that the AC loss of the hybrid coil REBCO/BSCCO is lower than that of the BSCCO coil across the full range of current amplitudes studied. This occurs despite the fact that the CW region of the hybrid coil employs wire with an average self-field I_c that is only approximately half of that used for the same region in the All-BSCCO assembly. The reasons behind this initially counter-intuitive observation are discussed further below.

FIG. 5 HERE

Fig. 6 shows the variation in the AC loss of the coil assembly with temperature, comparing measurements at 77 K and 65 K. The measured AC loss values at 77 K are greater than those at 65 K. This is due to the increase in $I_{c, \text{assembly}}$ with decreasing temperature.

By analogy with the standard expressions for transport loss [15] and magnetic loss [16] in an isolated wire we expect the

AC loss will decrease with reducing $I_t/I_{c, \text{assembly}}$, because the AC loss in the coil assembly is proportional to $I_{c, \text{assembly}}^{-2} (I_t/I_{c, \text{assembly}})^n$. If $n = 2.3-2.6$ then the loss at a constant current amplitude will decrease with increasing $I_{c, \text{assembly}}$ (as loss is proportional to $I_{c, \text{assembly}}^{2-n}$, where $2-n < 0$). This is consistent with our previous work [11].

FIG. 6 HERE

In Fig. 7, we compare the AC loss values in the coil assembly, at 77 K and 65 K, normalized by $I_{c, \text{assembly}}$ squared, $(I_{c, \text{assembly}})^{-2}$ as a function of assembly-current amplitude normalized by $I_{c, \text{assembly}}$. The $I_{c, \text{assembly}}$ values are those in Table 1. The scaled AC loss results at 77 K and 65 K are in good agreement. This indicates that AC loss can be scaled by the overall threshold transport I_c measured at the 1 μV criterion across the entire series connected coil assembly. This is again consistent with previous work [11], whilst similar scaling of AC loss by the overall cable I_c have also been observed in HTS Roebel cables [12, 17]. Theoretical justification of this scaling is provided by Wolfbrandt and Magnuson [18], who derived from Brandt and Indenbom [16] an expression for total AC loss in a superconductor per cycle per length, which is valid in the case of field-independent J_c , with $Q = kI_c^2 \Gamma(i, \beta)$ where $i = I/I_c$, $\beta = H/H_c$, $H_c = J_c t / \pi$, and t is thickness of superconductor. In reality, local conductor I_c in different part of the coil assembly is different. The AC loss in the coil assembly per cycle, by integrating whole length, can then be given as

$$\begin{aligned} Q_1 l_1 + Q_2 l_2 + \dots + Q_n l_n &= k I_{c1}^2 \Gamma(i_1, \beta_1) l_1 \\ &+ k I_{c2}^2 \Gamma(i_2, \beta_2) l_2 + \dots + k I_{cn}^2 \Gamma(i_n, \beta_n) l_n \\ &= k I_{c, \text{assembly}}^2 (c_1 \Gamma(i_1, \beta_1) l_1 + \\ &c_2 \Gamma(i_2, \beta_2) l_2 + \dots + c_n \Gamma(i_n, \beta_n) l_n) \end{aligned} \quad (2)$$

where $I_{c1}, I_{c2}, \dots, I_{cn}$ are local conductor I_c values, $i_1, i_2, \dots, i_n$ are $I_t/I_{c1}, I_t/I_{c2}, \dots, I_t/I_{cn}$, $\beta_1, \beta_2, \dots, \beta_n$ are $H/H_{c1}, H/H_{c2}, \dots, H/H_{cn}$, and $l_1, l_2, \dots, l_n$ are individual conductor lengths which have conductor critical currents of $I_{c1}, I_{c2}, \dots, I_{cn}$, respectively. The total conductor length of the coil assembly is given by $l = l_1 + l_2 + \dots + l_n$ and $c_1, c_2, \dots, c_n$ are constant expansion coefficients defined by $(I_{c1}/I_{c, \text{assembly}})^2, (I_{c2}/I_{c, \text{assembly}})^2, \dots, (I_{cn}/I_{c, \text{assembly}})^2$.

The loss in the coil will be dominated by regions where the field dependence has reduced $I_{c,i}$, to the point that the local $I_{c,i} \approx I_{c, \text{assembly}}$. In these regions the $c_i \approx 1$. In higher I_c regions the $c_i > 1$, but the associated Γ_i values will be much lower due to the higher I_c and these terms will contribute much less to the sum. Hence Eq. (2) explains why the overall coil assembly AC loss can be scaled by the overall coil assembly I_c , $I_{c, \text{assembly}}$ even considering variations in local conductor I_c .

FIG. 7 HERE

In Fig. 8, we compare the AC loss at 77 K in the three coil assemblies normalized by the $I_{c, \text{assembly}}$ squared, $(I_{c, \text{assembly}})^{-2}$ as a

function of normalized coil current. The AC losses follow the order $Q(\text{All-BSCCO}) > Q(\text{REBCO/BSCCO}) > Q(\text{All-REBCO})$. The AC loss in the All-BSCCO assembly is greater than that in the REBCO/BSCCO assembly, due to the larger AC loss in the BSCCO CW than in the REBCO CW. This arises due to the high near parallel (axial) field in the central section as can be seen in Fig. 3(b) [19]. The superconducting filamentary region of the BSCCO wire is two orders of magnitude thicker than the superconducting film thickness of the REBCO tape, around 150 μm for the BSCCO wire versus 1 μm for the coated conductor. The larger dimensions in the direction of flux motion mean that the parallel field magnetic losses will be larger for BSCCO than for REBCO. Using a slab model at 100 mT field amplitude, we estimate the loss to be reduced to 7.9 $\mu\text{J m}^{-1}$ per cycle for the REBCO wire compared to 2.0 mJ m^{-1} per cycle for the BSCCO tape - a factor of around 250 less. The comparison between the REBCO/BSCCO and All-REBCO assemblies is also interesting, as they both share the same REBCO CW. The difference between these two assemblies lies solely in the wire used to form the EWs. The YBCO EW has dimensions almost identical to the BSCCO EW, so the difference is simply due to the disparity between the two wires. The self-field I_c for the YBCO EWs is 238 A, whilst for the BSCCO EWs $I_c = 156$ A. The $I_{c, \text{assembly}}$ for the All-REBCO assembly at 77 K is almost the same as the REBCO/BSCCO assembly as listed in Table 1 [11]. However local $I/I_{c, \text{EW}}$ values in the EWs of the All-REBCO assembly are smaller than the local I/I_c values in the EWs of the REBCO/BSCCO assembly because of higher wire I_c values of the REBCO. Hence according to Eq. (2), AC loss in the EWs of the All-REBCO assembly should be smaller than that of the REBCO/BSCCO assembly, and this effect more than compensates for any relative reduction in REBCO wire performance in perpendicular field.

The manufacturing costs of the coil assemblies are in reverse order to the AC losses incurred, i.e. the cost of (All-BSCCO) < (REBCO/BSCCO) < (All-REBCO) and hence provide a reverse incentive to minimizing AC loss.

The results above indicate that the hybrid REBCO/BSCCO assembly structure enables AC losses to be reduced below that of an All-BSCCO coil. This reduction occurs despite employing low- I_c REBCO wire for the CW windings – for the case studied here the self-field I_c of the REBCO wire used in the CW region is only half that of BSCCO wire to which it is compared [11].

FIG. 8 HERE

IV. CONCLUSION

We have measured AC loss and coil assembly I_c at 77 K and 65 K in a HTS coil assembly which has a hybrid winding made up of a central winding wound with low self-field I_c REBCO wires, and end windings wound with BSCCO wires possessing a substantially higher self-field I_c value.

The AC losses in the coil assembly at 77 K and 65 K can be normalized by $(I_{c, \text{assembly}})^2$, and plotted versus the coil current normalized by the $I_{c, \text{assembly}}$. This shows that the losses follow a

simple frequency-independent power-law dependence on the ratio $I/I_{c, \text{assembly}}$. This relationship can be explained using an equation by Wolfbrandt and Magnuson which takes into consideration variable local conductor I_c .

The AC loss in the hybrid coil assembly studied here were found to be smaller than losses incurred in a similar All-BSCCO assembly measured in previous work. However it is larger than the losses previously measured in an All-REBCO assembly which employed EWs made from very high I_c wire.

Our results imply that the design strategy of employing low I_c REBCO wire in regions of parallel field within a coil, is a valid approach when seeking to minimize both AC losses and manufacturing input costs. It can deliver magnet designs which exhibit lower AC loss than an All-BSCCO assembly, yet at substantially lower cost than an All-REBCO assembly employing high- I_c wire.

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Table 1. I_c assembly values at 77 K and 65 K

Name of coil assembly	I_c , assembly at 77 K (A)	I_c , assembly at 65 K (A)	I_c , assembly at 65 K / I_c , assembly at 77 K
REBCO/BSCCO	55.0	110.4	2.0
All-REBCO [11]	55.5	117.2	2.11
All-BSCCO [11]	63.6	110.1	1.73

Fig. 1. (a) Schematics of magnetic field distribution in an HTS magnet and (b) the schematic of HTS assemblies [11]

Fig. 2. (a) Assembled HTS coil assembly with REBCO CW and BSCCO EWs, (b) the schematic of measurement set-up.

Fig. 3. (a) Calculated magnetic field distribution around REBCO/BSCCO assembly using COMSOL Multiphysics for a current of 40 A ($I_t/I_{c, \text{assembly}} = 0.72$), (b) calculated variation of the radial field components of the innermost, central, and outermost layers of the assembly, and (c) calculated variation of the axial field components of the innermost, central, and outermost layers of the assembly.

Fig. 4. Measured $I_{c, \text{assembly}}$ values in the REBCO/BSCCO assembly at 77 K and 65 K. The curves for All-REBCO and All-BSCCO assemblies are for references [11].

Fig. 5. Measured coil AC loss results in the REBCO/BSCCO assembly (a) 77 K, (b) 65 K.

Fig. 6. Comparison of AC losses in the REBCO/BSCCO at 77 K and 65 K (a) 43.96 Hz, (b) 26.62 Hz.

Fig. 7. Comparison of normalized AC losses in the REBCO/BSCCO at 77 K and 65 K (a) 43.96 Hz, (b) 26.62 Hz.

Fig. 8. Comparison of normalized AC losses in REBCO/BSCCO, All-REBCO, and All-BSCCO assemblies at 77 K.