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AC loss measurement and simulation in a REBCO coil assembly utilising low-loss magnetic flux diverters

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Abstract

AC loss in high temperature superconducting (HTS) coils affects the performance of HTS devices. Using magnetic flux diverters (MFDs) is an effective way to reduce AC loss in HTS coils. In this paper, measurement and finite element method simulation of AC loss results in a REBCO coil assembly comprising four double pancake coils with two molypermalloy-powder MFDs are presented. Both experimental and numerical results show that MFDs can significantly reduce the AC loss in the REBCO coil assembly while generating negligible loss in themselves. Further, the influence of the distance between the coil assembly and the diverters on AC loss reduction is explored. Compared with the AC loss data in the coil assembly without MFDs, over 80% AC loss reduction is achieved when the distance between the coil assembly and the diverters is at its minimum value, 2 mm. The simulation results reveal that the AC loss reduction in the coil assembly is mainly due to the reduction of the radial (perpendicular) magnetic field component to the surface of REBCO wires in the end windings of the coil assembly.

Keywords: REBCO coils, AC loss reduction, magnetic flux diverters, FEM, H -formulation

(Some figures may appear in colour only in the online journal)

1. Introduction

AC loss (energy loss due to alternating magnetic field) is one of the critical issues in HTS (high temperature superconducting) applications such as HTS motors/generators and HTS transformers [1–3]. Therefore AC loss reduction in HTS coils is one of key aspects in designing these HTS devices. Two types of commercialised HTS wires are commonly used for these applications: multifilamentary Bi-2223 wires and REBCO coated conductors [4, 5].

One fundamental problem with Bi-2223 wires in these applications is their large filament width which causes large AC loss in perpendicular magnetic field. Sufficient AC loss reduction can only be achieved by the combination of fine filament width, tight twisting, and high resistivity barriers separating the filaments [5]. Some other issues with the use of Bi-2223 wires in coil windings

are their non-negligible AC loss in parallel magnetic field and poor in-field performance compared to REBCO coated conductors [6].

For REBCO coated conductors, achieving narrow filaments on the REBCO conductor surface through striation can reduce the hysteresis loss, which is proportional to the tape width [7, 8]. In [9], a solenoid coil wound with three-filament REBCO wires was built and the measurement result showed that the AC loss in the solenoid coil was 1/3 of that wound with non-striated wires. On the other hand, continuously transposed Roebel cables have been proven as an effective way to reduce AC loss [10, 11]. In a HTS Roebel cable, the current can be equally distributed among strands and the cable can be regarded as two parallel stacks carrying the same current in each strand [11, 12]. The magnetization loss of a Roebel cable can be reduced to half that of an equivalent stack with the same effective wire width [13]. In [14], 1 MVA transformer was

successfully demonstrated with low-loss high current-capacity Roebel cables.

However, the methods for AC loss reduction mentioned above have drawbacks. Striation which is mainly achieved by laser cutting is costly and the resulting tapes are prone to coupling loss generated in the groove between the filaments due to conductance caused by imperfect cutting. Striation can also reduce the critical current density of the wires [15]. Roebel cables on the other hand are expensive; they involve strand cutting with associated waste of REBCO material and cable assembly steps [16].

The use of ferromagnetic flux diverters is another effective method to reduce AC loss in HTS coil windings comparable to using low loss conductors. Flux diverters are used to reshape the flux distribution around coil windings to reduce AC loss or increase critical current of DC coil windings [17–28]. Previous studies have proven that magnetic flux diverters (MFDs) can reduce AC loss in Bi-2223 coils [18, 23, 24]. Studies of the effect of flux diverters in REBCO coils have only focused on single pancake coils [17, 19–22]. Finite element method (FEM) simulations in [21] and [22] have shown that Ni-alloy flux diverters attached near the upper and lower surfaces of a single pancake coil can reduce AC loss in the coil. However, the total AC loss (summation of AC loss in the HTS coil and MFDs) reduction was hampered by AC loss generated in the Ni-alloy flux diverters. In [19], AC loss reduction by amorphous iron alloy flux diverters in a 13 turns single pancake YBCO coil was studied. The measurement result showed 40% AC loss reduction in the REBCO coil compared to its original value without MFDs. Recent research [17] showed that Ni-alloy flux diverters reduce total AC loss at high operating current but increase total AC loss at low operating current in a single pancake coil wound with YBCO wires with magnetic substrate.

In practical applications such as HTS transformers and SMES (superconducting magnetic energy storage), REBCO windings are normally composed of stacks of pancake coils [14, 29]. Studies on single pancake coils are not a reliable guide to the potential of flux diverters to reduce AC loss in such applications. A stacked pancake coil winding is shown schematically in figure 1. The radial component of the magnetic field in the end part of the winding is much larger than that in the centre part of the winding [30]. Therefore, AC loss in the end windings dominates the AC loss in the whole coil winding because AC loss in REBCO wires due to perpendicular magnetic field is many orders of magnitude larger than that due to parallel magnetic field [31, 32]. MFDs attached near the ends of HTS windings can reduce the radial magnetic field component so the flux lines are parallel to the wire surface thus reducing the AC loss. FEM simulations have demonstrated significant AC loss reduction in a single-phase 6.5 MVA transformer windings using MFDs attached near the end of the windings [33]. A FEM simulation claimed 13% heat loss reduction for a 100 kJ SMES magnet wound with REBCO wires by utilising silicon steel flux diverters arranged near the end of the magnet [29]. However, there is no experimental demonstration of AC loss reduction in REBCO coil windings comprising multiple pancake coils at present.

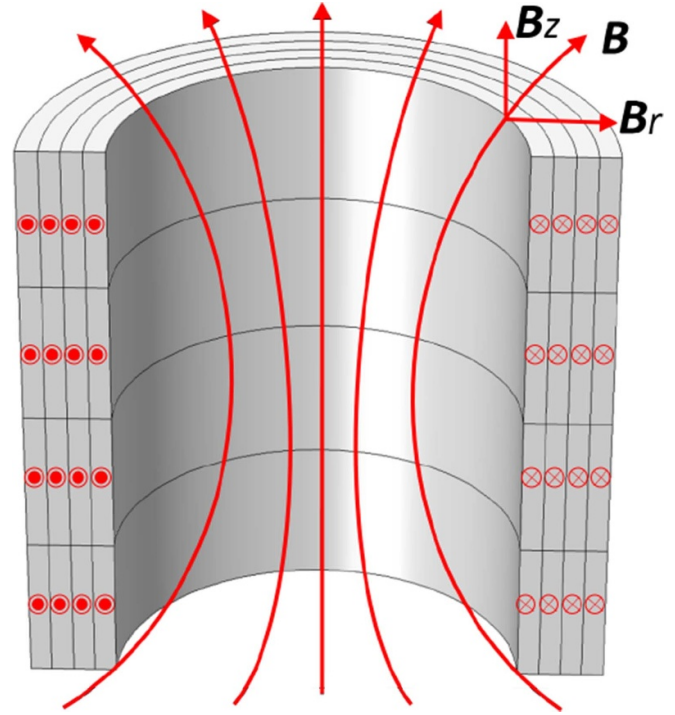


Figure 1. Schematic drawing of magnetic field distribution in an HTS coil comprising multi pancake coils. B_r is the radial component of magnetic field which is perpendicular to the HTS tape surface while B_z is parallel to the tape surface.

In this paper, transport AC loss in a REBCO coil assembly consisting of four double-pancake coils (DPCs) with and without MFDs was measured at different frequencies. Low loss Molypermalloy powder (MPP) material [34] was used as MFDs instead of high loss magnetic materials such as Ni-alloy. A schematic drawing of the REBCO coil assembly with MFDs is shown in figure 2. In order to investigate the influence of the positions of MFDs on AC loss reduction, the distance between the REBCO coil assembly and MPP MFDs, d was varied. The end windings and centre windings of REBCO DPCs are denoted EW and CW as shown in figure 2. FEM models based on H -formulation, E - J power law and modified Kim-model were built using COMSOL Multiphysics to simulate the experiment results [35–38]. The AC loss in different parts of the REBCO coil assembly was analyzed and the numerical results were compared with the experimental results.

2. Experimental method

2.1. REBCO coil assembly and MFDs

The measurement set-up of the REBCO coil assembly and MPP MFDs are shown in figure 3. The coil assembly used in the measurement is made up of four DPCs from our earlier hybrid coil assembly [39]. The DPCs are wound with 4 mm wide SuperPower GdBCO SCS4050 M3 AP wires. The total length of wire is 33.5 m. Each DPC has 20×2 turns insulated by co-wound Nomex paper. The critical currents of the

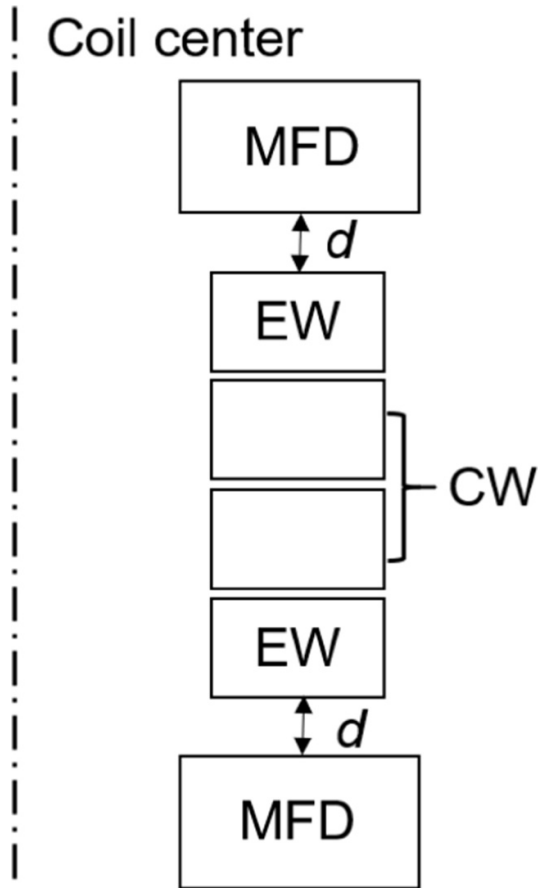


Figure 2. Schematic diagram of the REBCO coil assembly with two magnetic flux diverters. d is the adjustable distance between the end REBCO coils and magnetic flux diverters. The central winding consists of two centre REBCO double pancake coils. There are two end windings and each end winding consists of a single REBCO double pancake coil.

Table 1. Specifications of the GdBCO tapes.

Parameters	Value
Manufacturer	SuperPower
Tape width (mm)	4
Tape thickness (mm)	0.1
I_c at 77 K, s.f. (A)	89
Substrate	Hastelloy
Insulation layer	Nomex

GdBCO tape and the coil assembly at 77 K are 89 and 51.6 A, respectively. Tables 1 and 2 show the specifications of the GdBCO tape and the coil assembly. The four REBCO double pancake coils were connected by soldering four 4 mm-wide Bi-2223 strips in parallel in order to minimise the conduct resistance. The resistance in the coil assembly is approximately $0.6 \mu\Omega$ which was obtained by fitting the linear part of the $V-I$ curve for the coil assembly.

The Molypermalloy-power-125 (MPP-125) MFDs used in the measurement were fabricated from toroidal core supplied by Magnetics Inc. The MPP-125 is a compressed powder ferromagnetic material with nominal relative permeability μ_r

Table 2. Specifications of the DPCs assembly.

Parameters	Value
Height (mm)	38.3
Inner diameter (mm)	60
Outer diameter (mm)	73.5
Turns of every DPC	20×2
Numbers of DPCs	4
I_c of DPCs assembly (A)	51.6
Inductance of coil assembly at 77 K (mH)	1.53
Total length of used tapes (m)	33.5

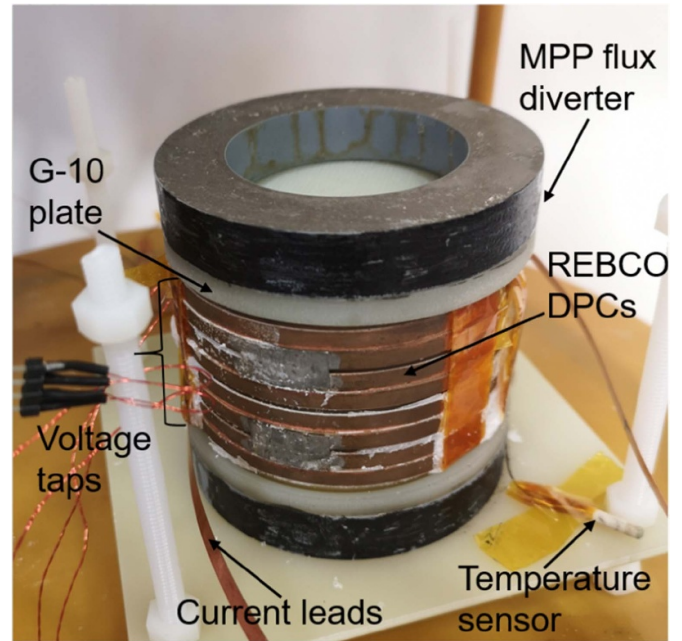


Figure 3. Set-up of REBCO coils assembly with MPP flux diverters.

Table 3. Specifications of the MPP 125 MFD.

Parameters	Value
Manufacturer	Magnetics Inc
Material	MPP 125
Inner diameter (mm)	48.8
Outer diameter (mm)	78.4
Cross section shape	Rectangular
Cross section width (mm)	14.8
Cross section height (mm)	13
Saturation field (T)	0.8

of 125. The measured electric resistivity of the flux diverter at liquid nitrogen temperature (77 K) is approximately $5 \times 10^4 \Omega \cdot \text{m}$. The eddy current loss in such a high resistivity material at $f < 100$ Hz is negligible. The inner diameter and outer diameter of them are 48.8 and 78.4 mm, respectively. The top and bottom surfaces of the MFDs were machined flat to remove the rounded corners of the original toroidal cores. They have a cross-section of $14.8 \text{ mm} \times 13 \text{ mm}$. The specifications of the MFDs are shown in table 3.

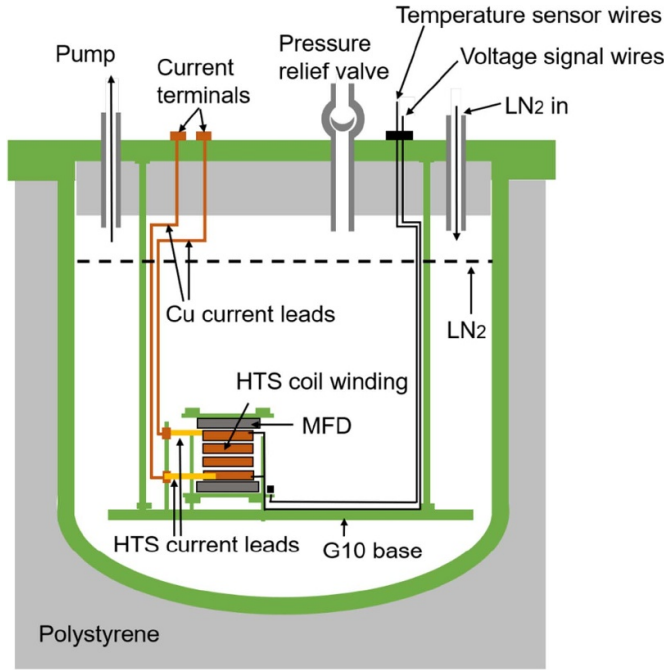


Figure 4. Schematic drawing of measurement set-up.

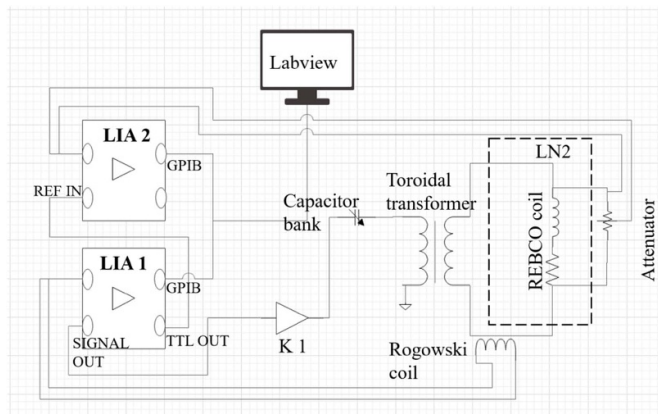


Figure 5. Schematic circuit diagram of measurement system.

2.2. AC loss measurement method

An electrical method is used for AC loss measurement of the coil assembly with and without MFDs [30]. The measurement set-up is shown in figure 4 and the schematic drawing of the measurement circuit is shown in figure 5.

Two lock-in amplifiers are used for the measurement: one for measuring the current amplitude and phase; the other for measuring the in-phase (with regard to the coil current phase) voltage of the coil assembly. A Rogowski coil (see figure 5) was used as the phase reference. The internal oscillator of one of the lock-in amplifiers supplies a sinusoidal signal to a CROWN K1 audio amplifier. The amplified sinusoidal voltage signal from CROWN K1 powers the primary winding of a toroidal transformer. The output of the secondary winding is used for energising the REBCO DPCs coil assembly immersed in liquid nitrogen at 1 atm. A capacitor bank was connected to

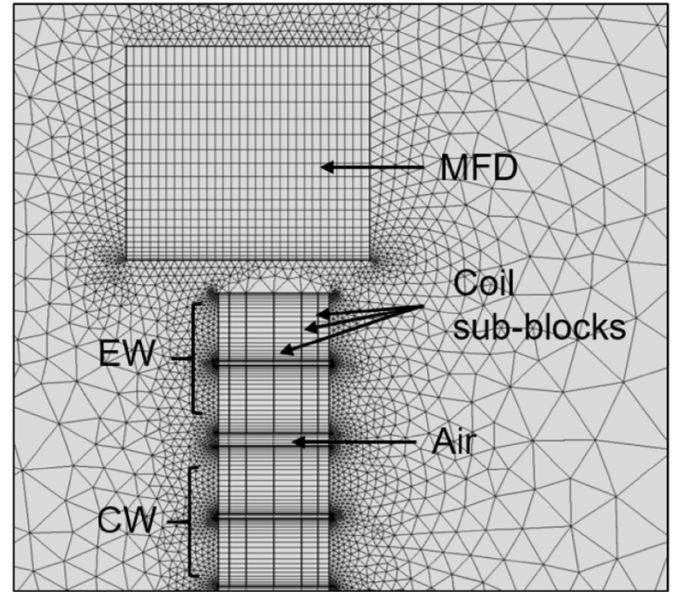


Figure 6. Structured meshes of the REBCO coil assembly and the MFDs (only upper half cross-section is shown).

the primary winding of the toroidal transformer for impedance matching.

The transport AC loss per cycle in a REBCO coil assembly with and without MFDs can be given as [30]:

$$Q_t = \frac{I_{coil, rms} \cdot V_{rms}}{f} \quad (1)$$

where $I_{coil, rms}$ is the rms current in the REBCO coil assembly, V_{rms} is the rms value of the in-phase voltage from the voltage taps attached in the ends of the coil assembly, and f is the frequency of the coil current. It is worth noting that the measured data include AC loss both in the coil assembly and the MFDs, and the measurement cannot separate the loss contributions of the HTS coil assembly and the MFDs.

3. Numerical method

3.1. Homogenized 2D axisymmetric model based on H -formulation

An axisymmetric 2D FEM model based on H -formulation was built to simulate the magnetic field distribution and transport AC loss in the REBCO coil assembly. The MFDs are positioned near the top and bottom parts of the coil assembly and the distance between the assembly and the MFDs, d , can be varied. In order to reduce the computing time, the homogenization method [40] and structured mesh [41] are used in the FEM models. The upper half cross-section in figure 6 shows the homogenized sub-blocks of the REBCO DPCs and the structured meshes. Each DPC was divided into 40 axial elements and 6 radial sub-blocks. Each MPP MFD is divided into 20 axial elements and 30 radial elements.

The E - J power law [42] in equation (2) is used in the FEM model to simulate the electromagnetic behaviours of the REBCO assembly.

$$\mathbf{E} = \frac{E_c \cdot \mathbf{J}}{J_c(B)} \left(\frac{\mathbf{J}}{J_c(B)} \right)^{(n-1)} \quad (2)$$

where $E_c = 1 \mu\text{V cm}^{-1}$, $\mathbf{E}$ and $\mathbf{J}$ are the electrical field and current density of the REBCO tapes, respectively. n is the power-law exponent of the E - J curve which is set as 25 in this model. The modified Kim model [36] in equation (3) is used to represent the $J_c(B)$ dependence of the REBCO tapes.

$$J_c(\mathbf{B}) = J_c \cdot \left(1 + \frac{(k \cdot B_{\parallel})^2 + B_{\perp}^2}{B_0^2} \right)^{-\alpha} \quad (3)$$

where k , α , and B_0 are the constants which are determined by critical current measurement under magnetic field. In this case, $k = 0.43$, $\alpha = 0.23$ and $B_0 = 37$ mT. $B_{\parallel}$ is the magnetic field component parallel to the tape surface while $B_{\perp}$ is the magnetic field component perpendicular to the tape surface. In this numerical model, $B_{\perp}$ and $B_{\parallel}$ are B_r and B_z , respectively.

In this numerical model, the relative permeability $\mu_r = 1$ is used in the REBCO assembly and air domain. The μ_r of the flux diverters used in this model is from the B - H curve of ‘Alloy Powder Core MPP 125’ in COMSOL Multiphysics which is shown in figure 7. We experimentally confirmed the μ_r of MPP 125 at 77 K has the same value as at room temperature.

3.2. Calculation of total AC loss

The AC loss Q_{sc} in the superconducting coil winding was calculated from equation (4).

$$Q_{sc} = \int \int_{V_{SC}} \mathbf{E} \cdot \mathbf{J} d\mathbf{v} dt \quad (4)$$

where, V_{SC} is the volume of the superconducting domain. The eddy current in stabiliser layers is not considered in this model.

The AC loss in MFDs consists of eddy current loss and hysteresis loss. The loss density of the MFDs was measured at 720 and 780 Hz using a conventional toroidal set-up method. A N4L PPA5530 precision power analyser was used for measurement. An MFD with the same dimension as the MFD used in the coil experiments was used. Figure 8 shows the measured Q - B relationship. The frequency-independent loss measurement results confirm hysteretic nature of the AC loss in the MPP MFDs. Eddy current loss can be ignored due to the very high resistivity in the material. AC loss in the MFDs, Q_{MFD} at different coil currents was calculated using the calculated distribution of peak flux density in the MFDs by interpolating the measured Q - B relationship shown in figure 8. It should be noted that the field configuration and eddy current geometry in the toroidal winding configuration described is not the same as that in the experimental setup with the HTS coils.

The summation of Q_{SC} and Q_{MFD} gives the total loss in the REBCO coil assembly with MFDs.

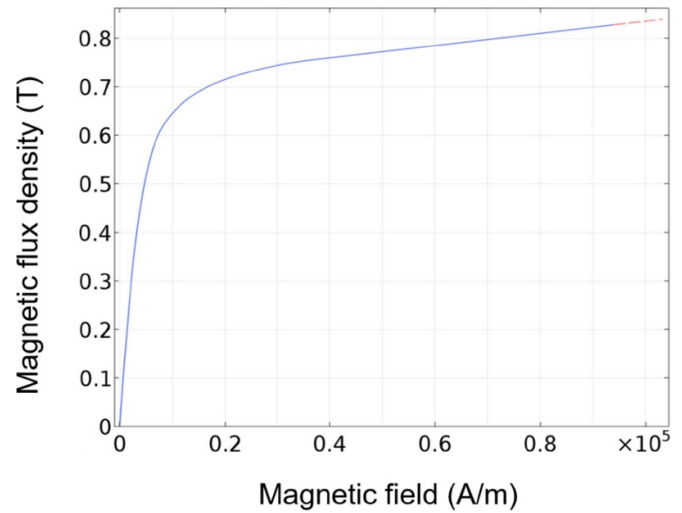


Figure 7. B - H curve of MPP 125 MFDs used in the numerical models.

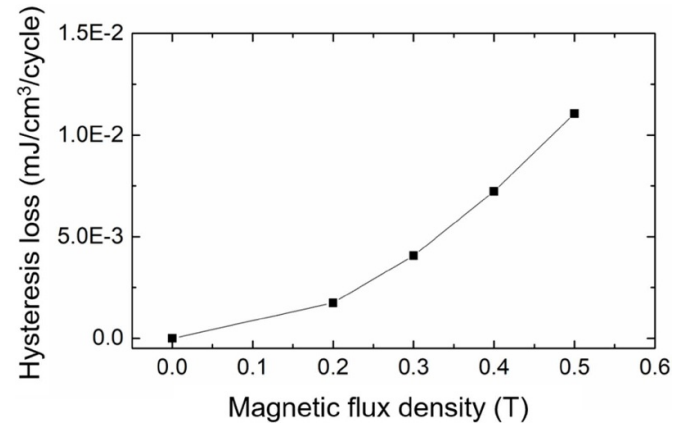


Figure 8. Measured AC loss of the MPP 125 as a function of peak magnetic flux density. Interpolation of this curve is used in the numerical model for calculating the loss in MFDs.

4. Results and discussion

4.1. Experimental results

The measured E - I curves of the REBCO coil assembly without MFDs and with MFDs at different d values are plotted together in figure 9. I_c values of the coil assembly before placing MFDs and after placing MFDs with $d = 8$ mm, 5 mm, and 2 mm at 77 K are compared. The measured coil I_c values are 51.6 A, 52.4 A, 53.4 A and 55.4 A, respectively. $1 \mu\text{V cm}^{-1}$ was taken as the voltage criterion for the coil I_c values. The I_c value is the smallest without MFDs and increases with decreasing d values. This can be explained by the numerical results shown in the numerical results section.

In figure 10, the measured AC loss values per cycle at three frequencies in the REBCO coil assembly without MFDs, and with MFDs with different d values are plotted as a function of the coil current amplitude. The measurement results in the coil assembly with and without the MFDs at different frequencies

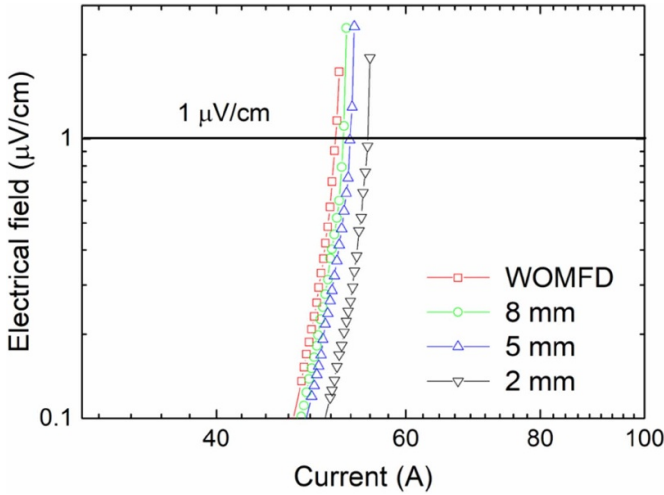


Figure 9. Measured E - I curves of the coil assembly without MFDs and with MFDs at different d values. Here WOMFD means without magnetic flux diverters.

agree well from one another. The result indicates the hysteresis nature of the loss characteristic. It should be noted that the measured values are total AC loss in the REBCO coil assembly and the MFDs. There will be difference in the measured AC loss values for different frequencies if there is any loss contribution due to eddy current in the MPP MFDs. There is some scatter in the measured loss values for $d = 2$ mm. We attribute the result to a lower S/N (signal to noise ratio) than other gaps due to the smaller loss voltage levels.

Figure 11 compares the induced voltage from a single-turn pick-up coil attached on the surface of the upper half of the top DPC in the coil assembly without MFDs and with MFDs ($d = 2$ mm) at $I_{t, rms} = 10, 15$, and 20 A. The rectangular pick-up coil has a dimension of $50 \text{ mm} \times 10 \text{ mm}$. The voltage in the pick-up coil is induced due to the time-varying radial magnetic field component and the value of the voltage is proportional to the amplitude of the radial component. The induced voltage for the coil assembly after adding MFDs is significantly reduced compared to that without MFD. At 20 A (rms), the voltage from the assembly with MFDs is approximately $1/3$ of that without MFDs. In REBCO coil assemblies, most of AC loss is caused by the radial field (which is perpendicular to the REBCO tape surface) in the end windings [31, 32]. The results in figure 11 directly show the effectiveness of MFDs for suppressing the radial field component and hence reducing the AC loss in the coil assembly.

In figure 12, the measured AC loss results per cycle in the coil assembly without MFDs, with MFDs at three d values are plotted as a function of the coil current amplitude at three frequencies. It is apparent that AC loss in the coil assembly is reduced by the MFDs and it decreases with decreasing d values at all three frequencies. At $I_{t, peak} = 30$ A (around 60% of the coil I_c) and $f = 13.96$ Hz, the AC loss value in the REBCO coil assembly without MFDs is 0.074 J/cycle . After placing MFDs with $d = 2$ mm, the total AC loss in the coil assembly and MFDs was reduced to $0.015 \text{ J cycle}^{-1}$, i.e. the total AC loss was reduced by 80%. Such a significant AC loss reduction in

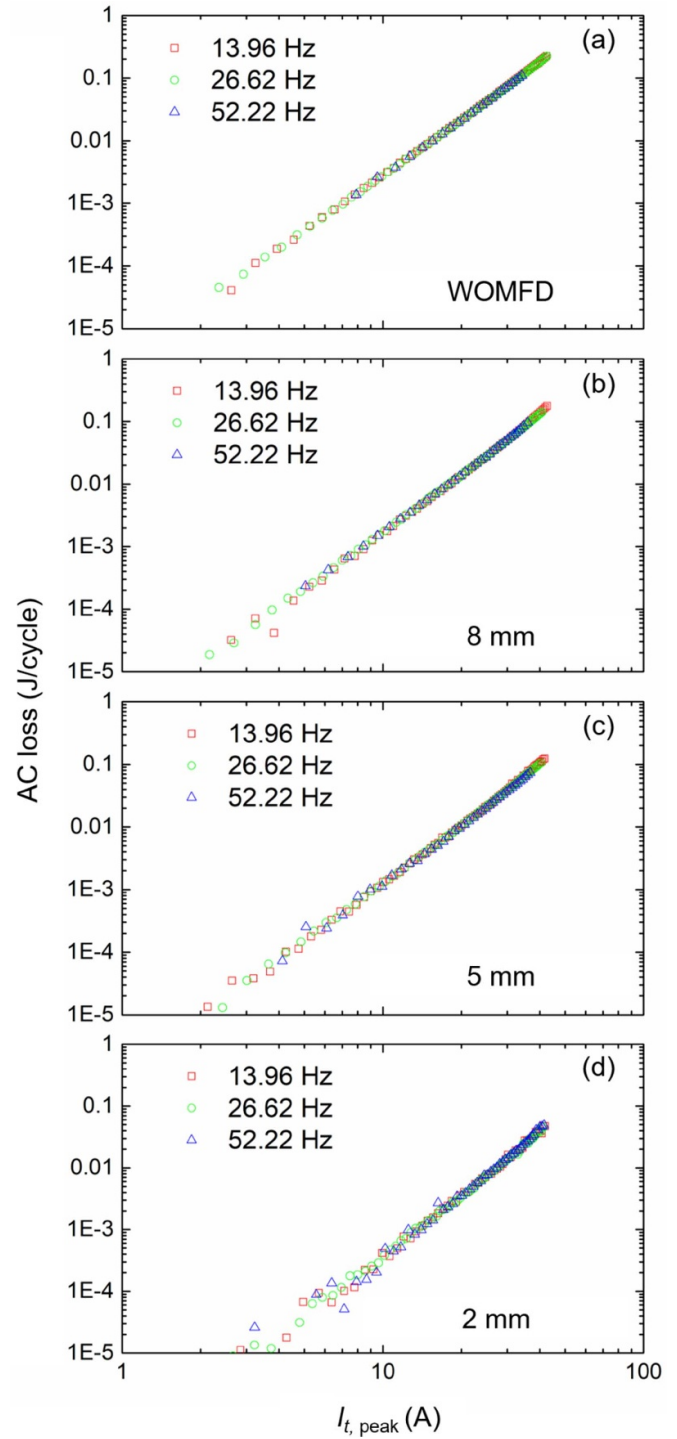


Figure 10. AC loss at different frequencies in the coil assembly with and without MFDs. Here WOMFD means without magnetic flux diverters. (a) Without MFDs, (b) with MFDs at $d = 8$ mm, (c) with MFDs at $d = 5$ mm, (d) with MFDs at $d = 2$ mm.

REBCO coil windings using MFDs has not been reported in previous experimental works. The measurements at the other two frequencies show almost the same results. This unprecedented AC loss reduction may be attributed to the utilisation of low-loss MPP-125 MFDs. Other types of MFDs ferromagnetic materials such as Ni alloy could generate substantial loss in the

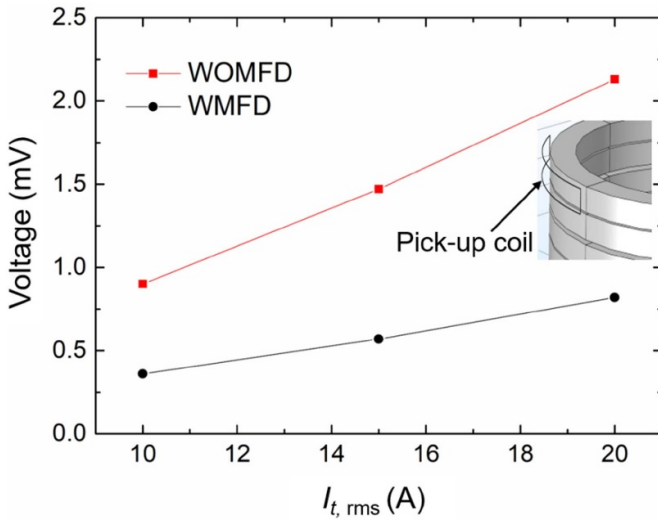


Figure 11. Induced voltages in the pick-up coil at three different currents at 52.22 Hz. The one-turn pick-up coil is attached on the upper half of the top DPC.

material themselves although they could reduce AC loss in the REBCO coil windings. However, MPP-125 MFDs have negligible AC loss (as discussed in the following section) compared with the AC loss in the REBCO coil winding. One drawback of the MPP-125 MFD is that it has relatively low saturation field (0.8 T). However, MFDs do not necessarily form part of the main magnetic circuit in actual applications and hence could avoid large magnetic fields. E.g. in HTS transformers, the main circuit is formed through the iron core which couples with HTS coil windings but the MFDs are arranged near the top and bottom of the windings and hence experience a weaker magnetic field [33]. Therefore, a saturation field of 0.8 T might be sufficient for most situations.

In figure 13, the AC loss reduction rate of the coil assembly with MFDs with three d values at different current amplitudes are compared. Compared with the AC loss in the REBCO coil assembly without MFDs, the average AC loss reduction with MFDs at $d = 8, 5$, and 2 mm are 36%, 51%, and 83%, respectively. The AC loss reduction rate increases with decreasing d value. The result suggests that MFDs should be placed as close as possible to the HTS winding in order to achieve larger loss reduction ratio in the HTS coil winding.

4.2. Numerical results

Figures 14(a) and (b) show magnetic field lines and the radial magnetic flux density distribution in the upper half cross-section of the coil winding with and without MFDs and at $f = 26.62$ Hz, $I_{t, peak} = 30$ A, and $d = 2$ mm (for the case with MFDs). The flux lines in the top DPC in the coil winding with MFDs become more parallel to the REBCO tape surface (figure 14(b)) compared with the result without MFDs (figure 14(a)). The area filled with large radial field component and the amplitude of the radial field component in the REBCO DPCs for the case without MFDs are much larger than the result with MFDs. The maximum radial field component

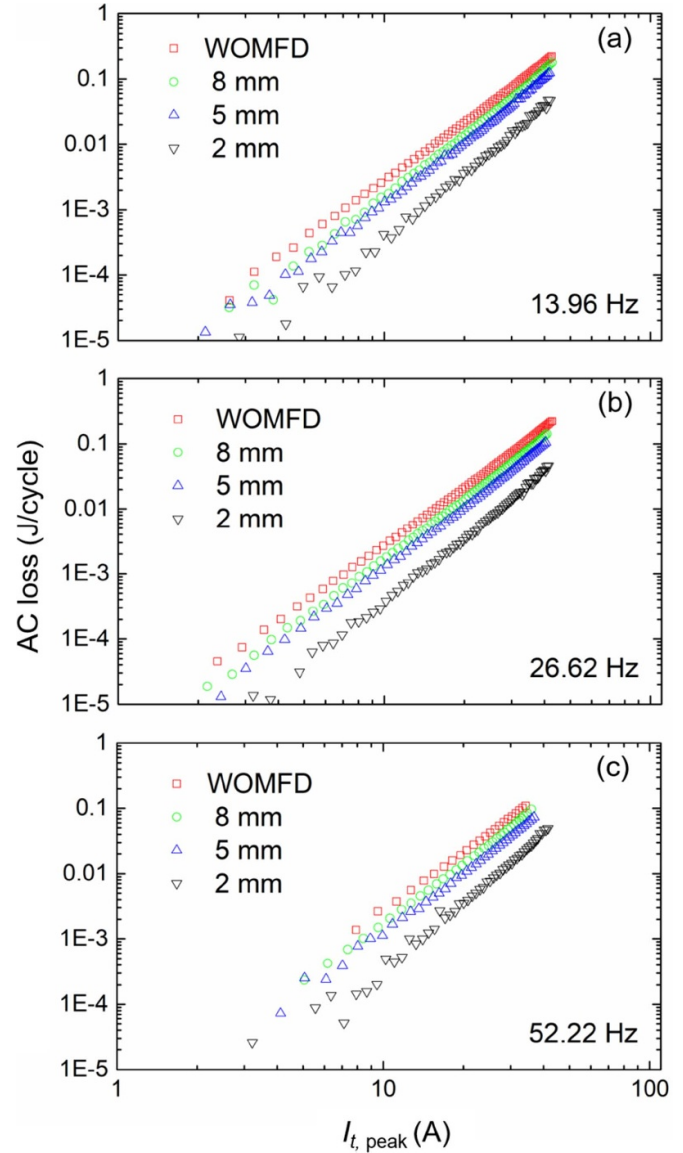


Figure 12. Measured AC loss results in the coil assembly without MFDs, with MFDs at three d values at three frequencies. (a) 13.96 Hz, (b) 26.62 Hz, and (c) 52.22 Hz.

in the top DPC without MFDs is 0.1 T while the maximum radial field in the top DPC is reduced to 0.05 T with MFDs. Apparently, the difference observed in the above comes from the presence of the flux diverters. On the other hand, the MFDs have large area with high magnetic field concentration as shown in figure 14(b). The results shown in figure 14 clearly explain why the I_c values of the coil assemblies with MFDs shown in figure 9 are larger than that without MFDs.

In figure 15, the current density distribution in the REBCO DPCs with and without MFDs are compared. Shielding currents induced by the radial magnetic field components are observed in most of the pancake coils except the innermost pancake coil. However, with MFDs, the high current density area ($|J/J_c| > 1$) in the EWs is reduced remarkably compared with the case without MFDs. In figure 15(b), with MFDs, as most AC loss is generated in the area of $|J/J_c| \geq 1$, the reduced

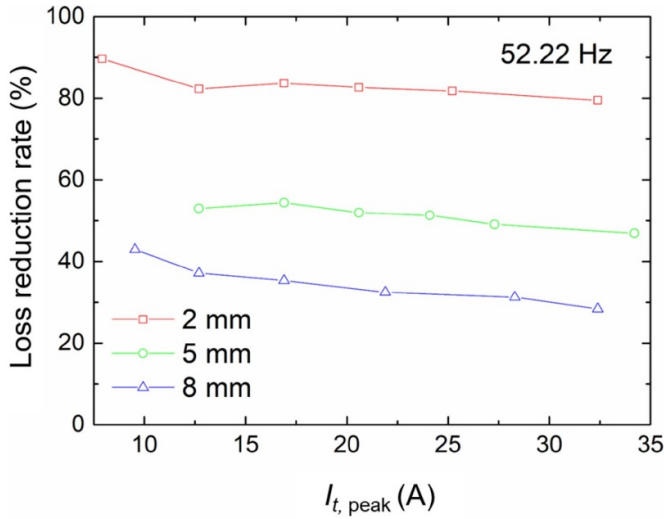


Figure 13. AC loss reduction rate versus the operating current at different d values.

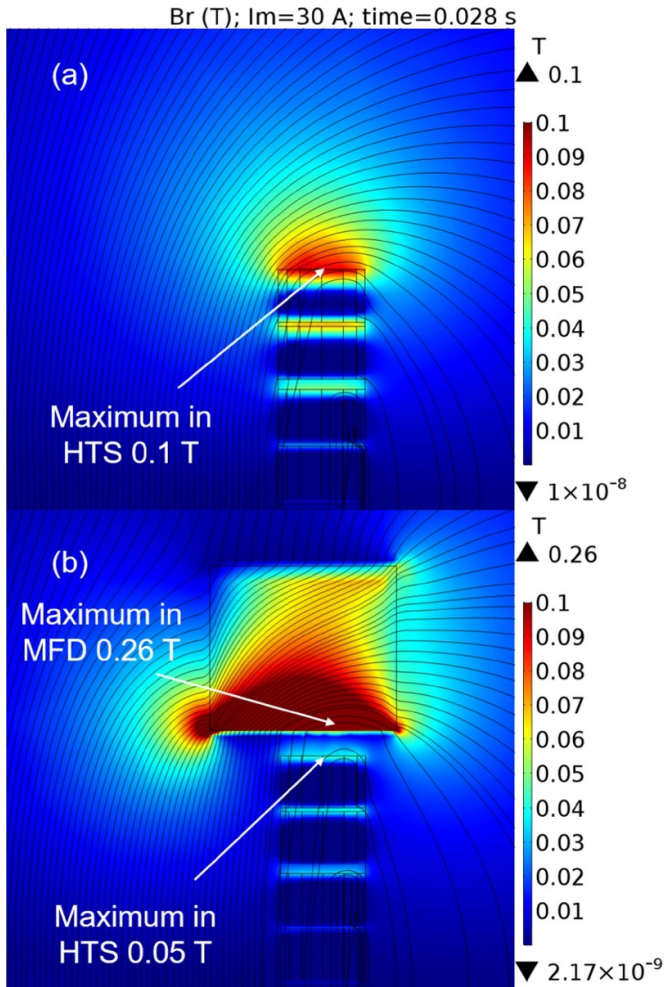


Figure 14. Magnetic flux lines and radial magnetic flux density component distribution in the upper half cross-section of the coil winding with/without MPP MFDs ($f = 26.62$ Hz, $d = 2$ mm with MFDs) at $\frac{3}{4}$ T (period); (a) without MFDs and (b) with MFDs.

area of high $|J/J_c|$ indicates that AC loss reduction is achieved in the EWs. These results mentioned above demonstrate why

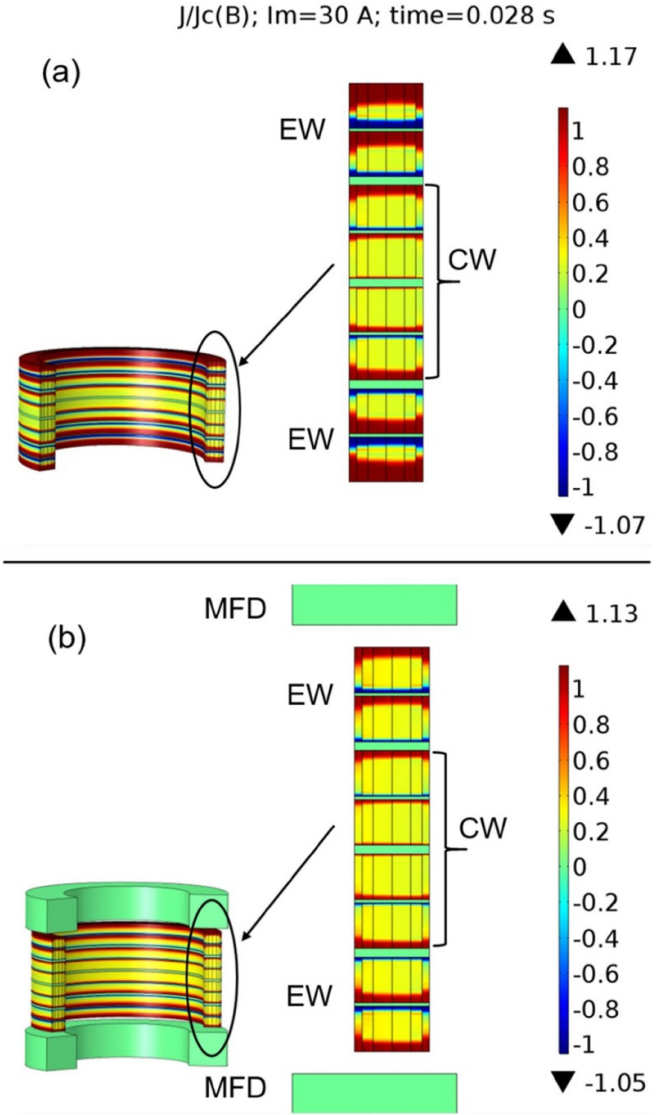


Figure 15. Distribution of current density with/without MFDs around the coil assembly ($f = 26.62$ Hz, $d = 2$ mm with MFDs) at $\frac{3}{4}$ T (period); (a) without MFDs and (b) with MFDs.

AC loss in the REBCO coil winding is reduced by the use of MFDs.

Figure 16 compares the experimentally and numerically obtained total AC loss results in the REBCO coil winding without MFDs and with MFDs with $d = 2$ mm at 26.62 Hz. A good agreement was obtained between the numerical and experimental results.

Figure 17 compares the simulated loss components in the REBCO coil winding with MFDs ($d = 2$ and 8 mm) at 26.62 Hz. It is apparent that AC loss in the MFDs is more than three orders of magnitude smaller than the AC loss in the HTS winding at $I_{t, peak} = 45$ A and the AC loss in the flux diverters can be ignored. Therefore, total AC loss in the coil assembly with the MFDs is dominated by the AC loss in the HTS windings. Nonetheless the increase of AC loss in the MFDs with decreasing d can be observed due to the increase of the magnetic field inside the MFDs. At both d values, AC loss in the EWs is much greater than that in the CW, and hence

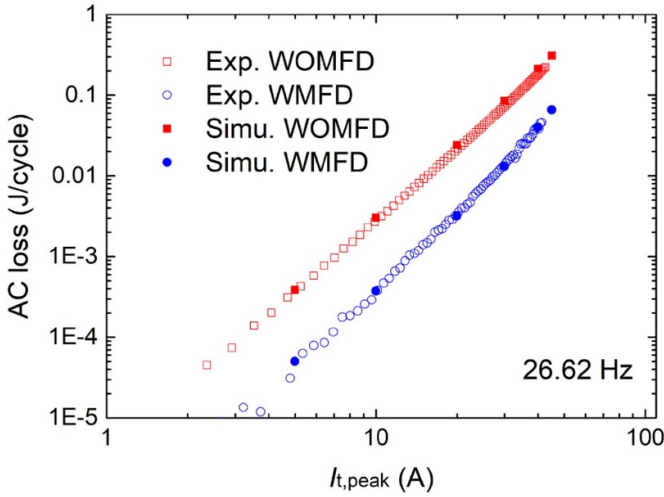


Figure 16. Comparison of the experimentally and numerically obtained total AC loss results at 26.62 Hz. WOMFD means without magnetic flux diverters while WMFD means with magnetic flux diverters. Here $d = 2$ mm.

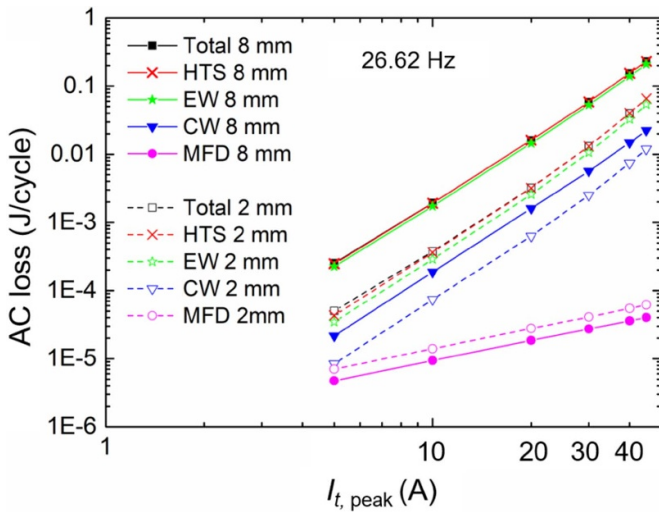


Figure 17. Comparison between simulated AC loss values at different part of the coil assembly for $d = 2$ mm and $d = 8$ mm at 26.62 Hz. Total, HTS, EW, CW, and MFD denote the loss values of the HTS coil assembly and MFDs, the whole coil assembly, the end windings, the centre winding, and the magnetic flux diverters, respectively.

AC loss in the EWs dominates AC loss in the HTS winding. Interestingly, with d value varying from 8 to 2 mm, not only AC loss in the EWs becomes smaller but so does that in the CW. However, the change in the AC loss in EWs is much greater than that in the CW. The result at 2 mm indicates that there remains capacity to reduce total AC loss by making the d value smaller, bringing the loss-level of the EWs closer to the loss-level of the CW. However, the d cannot be reduced to 0 mm considering the insulation separation between the MFDs and HTS coil windings required for practical applications.

As evident from the results in figure 15(b), there is still room for further reducing the AC loss in the double pancake

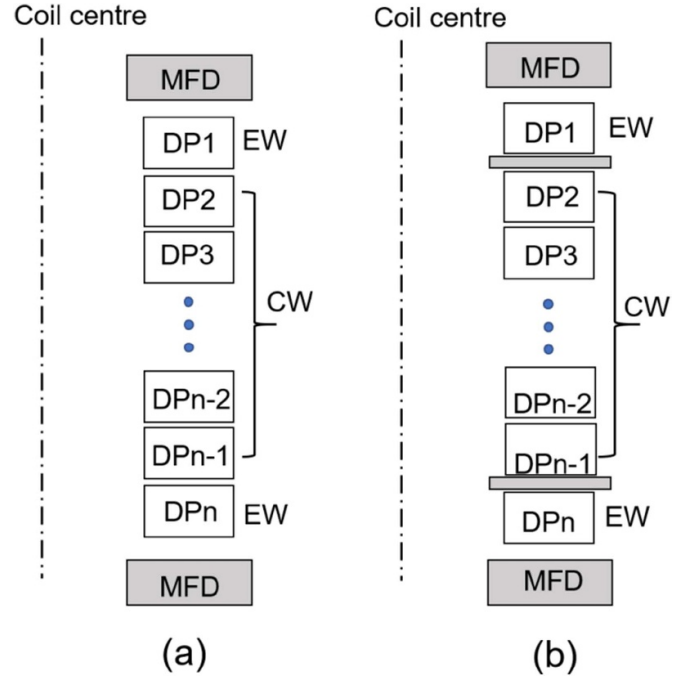


Figure 18. Coil windings stacked with large number of double pancake coils (a) Flux diverters are only attached near the end windings, (b) flux diverters are attached near the end windings and some of double pancake coils near the end windings.

coils next to the end windings. With the shape of the flux diverters described in this work, there is an obvious limit for further reducing the distance between the DPCs and the flux diverters and hence further reduce AC loss for double pancake coils next to the end windings. The limit becomes more obvious for more complicated coil windings comprising stacks of double pancake coils, because influence of the flux diverters can hardly reach DP2 and DP3 (see figure 18(a)) which can also be source of non-negligible AC loss. For coil windings stacked with large number of double pancake coils, combination of flux diverters for the end windings and some of double pancake coils nearby the end windings might be effective for minimising AC loss as shown in figure 18(b). Same strategy of AC loss reduction utilising flux diverters might be applied to hybrid coil windings comprising REBCO double pancake coils as end windings and Bi-2223 pancake coils as centre windings [6]. For 3-phase transformers, AC loss is more concentrated in the very end part of the high voltage and low voltage windings than stand-alone coil windings [32]. Therefore, flux diverters placed near the end windings might suffice for transformer applications.

5. Conclusion

In this work, we have experimentally and numerically investigated AC loss reduction in a REBCO coil assembly comprising four double pancake coils utilising low-loss MPP-125 MFDs attached near the top and bottom of the coil assembly. The frequency of the AC coil current and the distance between the coil

assembly and the MFDs, d , were varied to investigate the influence of those parameters on AC loss reduction.

The lack of frequency dependence in the experimental results confirm the hysteretic nature of AC loss characteristics in the coil assembly and the MFDs. Both experimental and numerical results demonstrate effective AC loss reduction in the coil assembly with the MFDs compared to the assembly without flux diverters. The total AC loss in the coil assembly with the diverters decreases with decreasing d . The measured data in the coil assembly with the flux diverters shows 80% AC loss reduction at $d = 2$ mm compared with the AC loss data in the coil assembly without flux diverters. Such a high AC loss reduction has not been demonstrated in any previous experimental works.

Numerical simulation reveals that the AC loss reduction in the coil assembly is mainly due to the reduction of the radial field component in the EWs and negligible self-loss in the MPP MFDs. The result suggests that using low-loss ferromagnetic materials in flux diverters and reducing d are two critical ingredients for AC loss reduction in REBCO coils.

The results obtained in this work have practical implications for the design of HTS transformers.

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References

- [1] Haran K S *et al* 2017 High power density superconducting rotating machines—development status and technology roadmap *Supercond. Sci. Technol.* **30** 123002
- [2] Iwakuma M *et al* 2001 AC loss properties of a 1 MVA single-phase HTS power transformer *IEEE Trans. Appl. Supercond.* **11** 1482–5
- [3] Jiang Q, Majoros M, Hong Z, Campbell A M and Coombs T A 2006 Design and AC loss analysis of a superconducting synchronous motor *Supercond. Sci. Technol.* **19** 1164–8
- [4] Sundaram A *et al* 2016 2G HTS wires made on 30 μ m thick Hastelloy substrate *Supercond. Sci. Technol.* **29** 104007
- [5] Jiang Z and Amemiya N 2006 Comparison of the total AC loss characteristics in YBCO conductors and BSCCO multifilamentary tapes with identical engineering critical current densities *Supercond. Sci. Technol.* **19** 742–7
- [6] Jiang Z, Staines M, Long N J, Badcock R A, Bumby C W, Buckley R G, Song W and Amemiya N 2017 AC loss measurements in a hybrid REBCO/BSCCO coil assembly *IEEE Trans. Appl. Supercond.* **27** 5900707
- [7] Sumption M D, Lee E, Cobb C B, Barnes P N, Haugan T J, Tolliver J, Oberly C E and Collings E W 2003 Hysteretic loss vs. filament width in thin YBCO films near the penetration field *IEEE Trans. Appl. Supercond.* **13** 3553–6
- [8] Amemiya N, Yoda K, Kasai S, Jiang Z, Levin G A, Barnes P N and Oberly C E 2005 AC loss characteristics of multifilamentary YBCO coated conductors *IEEE Trans. Appl. Supercond.* **15** 1637–42
- [9] Iwakuma M *et al* 2009 Development of REBCO superconducting power transformers in Japan *Phys. C* **469** 1726–32
- [10] Long N J, Badcock R A, Hamilton K, Wright A, Jiang Z and Lakshmi L S 2010 Development of YBCO Roebel cables for high current transport and low AC loss applications *J. Phys. Conf. Ser.* **234** 022021
- [11] Jiang Z *et al* 2010 Transport AC loss characteristics of a nine strand YBCO Roebel cable *Supercond. Sci. Technol.* **23** 025028
- [12] Terzieva S, Vojenčiak M, Pardo E, Grilli F, Drechsler A, Kling A, Kudymow A, Gömöry F and Goldacker W 2009 Transport and magnetization ac losses of ROEBEL assembled coated conductor cables: measurements and calculations *Supercond. Sci. Technol.* **23** 014023
- [13] Zhou W, Jiang Z, Staines M, Song W, Bumby C W, Badcock R A, Long N J and Fang J 2018 Magnetization loss in REBCO Roebel cables with varying strand numbers *IEEE Trans. Appl. Supercond.* **28** 8200108
- [14] Glasson N D, Staines M P, Jiang Z and Allpress N S 2013 Verification testing for a 1 MVA 3-phase demonstration transformer using 2G-HTS Roebel cable *IEEE Trans. Appl. Supercond.* **23** 5500206
- [15] Amemiya N, Kasai S, Yoda K, Jiang Z, Levin G A, Barnes P N and Oberly C E 2004 AC loss reduction of YBCO coated conductors by multifilamentary structure *Supercond. Sci. Technol.* **17** 1464–71
- [16] Song W, Jiang Z, Staines M, Badcock R A and Fang J 2018 Experimental and numerical transport AC losses in a four-strand Roebel cable bifilar stack *Supercond. Sci. Technol.* **31** 115001
- [17] Liu G, Zhang G and Jing L 2019 Experimental and numerical study of the frequency-dependent transport ac losses of the YBa₂Cu₃O_{7- δ} coil with and without flux diverters *Supercond. Sci. Technol.* **32** 055002
- [18] Furuse M, Kondoh J, Tanaka H and Umeda M 2003 AC loss measurement of HTS coils with ferromagnetic disks *IEEE Trans. Appl. Supercond.* **13** 2356–9
- [19] Pardo E, Šouc J and Vojenčiak M 2009 AC loss measurement and simulation of a coated conductor pancake coil with ferromagnetic parts *Supercond. Sci. Technol.* **22** 075007
- [20] Liu G, Zhang G, Jing L and Yu H 2017 Numerical study on AC loss reduction of stacked HTS tapes by optimal design of flux diverter *Supercond. Sci. Technol.* **30** 125014
- [21] Ainslie M D, Yuan W and Flack T J 2013 Numerical analysis of AC loss reduction in HTS superconducting coils using magnetic materials to divert flux *IEEE Trans. Appl. Supercond.* **23** 4700104
- [22] Ainslie M D, Hu D, Zou J and Cardwell D A 2015 Simulating the in-field AC and DC performance of high-temperature superconducting coils *IEEE Trans. Appl. Supercond.* **25** 4602305
- [23] Al-Mosawi M K, Beduz C, Yang Y, Webb M and Power A 2001 The effect of flux diverters on AC losses of a 10 kVA high temperature superconducting demonstrator transformer *IEEE Trans. Appl. Supercond.* **11** 2800–3
- [24] Furuse M, Tanaka H, Kondoh J and Umeda M 2004 Experimental study on AC loss reduction of HTS coils by use of ferromagnetic disks *IEEE Trans. Appl. Supercond.* **14** 1090–3
- [25] Majoros M, Glowacki B A and Campbell A M 2000 Transport ac losses and screening properties of Bi-2223

- multifilamentary tapes covered with magnetic materials *Phys. C* **338** 251–62
- [26] Majoros M, Glowacki B A and Campbell A M 2000 Magnetic screening as a possible way to decrease transport AC losses in multifilamentary superconductors — basic theoretical considerations *Phys. C* **334** 129–40
- [27] Wen H, Bailey W, Goddard K, Al-Mosawi M, Beduz C and Yang Y 2009 Performance test of a 100 kW HTS generator operating at 67 K–77 K *IEEE Trans. Appl. Supercond.* **19** 1652–5
- [28] Kim S H *et al* 2004 Analysis of perpendicular magnetic fields on a 1 MVA HTS transformer windings with flux diverters *IEEE Trans. Appl. Supercond.* **14** 932–5
- [29] Deng X, Tang Y, Ren L, Shen S, Xu Y, Shi J and Li J 2014 The effect of flux diverters on energy storage capacity and heat losses in a HTS SMES *IEEE Trans. Appl. Supercond.* **24** 5700105
- [30] Jiang Z, Long N J, Staines M, Badcock R A, Bumby C W, Buckley R G and Amemiya N 2016 AC loss measurements in HTS coil assemblies with hybrid coil structures *Supercond. Sci. Technol.* **29** 095011
- [31] Pardo E, Šouc J and Kováč J 2012 AC loss in ReBCO pancake coils and stacks of them: modelling and measurement *Supercond. Sci. Technol.* **25** 035003
- [32] Song W, Jiang Z, Zhang X, Staines M, Badcock R A, Fang J, Sogabe Y and Amemiya N 2018 AC loss simulation in a HTS 3-Phase 1 MVA transformer using H formulation *Cryogenics (Guildf)* **94** 14–21
- [33] Song W, Jiang Z, Staines M, Badcock R A, Wimbush S C, Fang J and Zhang J 2020 Design of a single-phase 6.5 MVA/25 kV superconducting traction transformer for the Chinese Fuxing high-speed train *Int. J. Electr. Power Energy Syst.* **119** 105956
- [34] Swihart M A 2004 Inductor cores—material and shape choices *Magnetics*® available at: www.mag-inc.com
- [35] Hong Z, Campbell A M and Coombs T A 2006 Numerical solution of critical state in superconductivity by finite element software *Supercond. Sci. Technol.* **19** 1246–52
- [36] Kim Y B, Hempstead C F and Strnad A R 1962 Critical Persistent Currents in Hard Superconductors *Phys. Rev. Lett.* **9** 306–9
- [37] Shen B, Grilli F and Coombs T 2020 Overview of H-formulation: a versatile tool for modeling electromagnetics in high-temperature superconductor applications *IEEE Access* **8** 100403–14
- [38] Hong Z, Ye L, Majoros M, Campbell A M and Coombs T A 2008 Numerical estimation of AC Loss in MgB₂ wires in self-field condition *J. Supercond. Novel Magn.* **21** 205–11
- [39] Jiang Z, Endo N, Wimbush S C, Brooks J, Song W, Badcock R A, Miyagi D and Tsuda M 2019 Exploiting asymmetric wire critical current for the reduction of AC loss in HTS coil windings *J. Phys. Commun.* **3** 095017
- [40] Zermeno V M R, Abrahamsen A B, Mijatovic N, Jensen B B and Sørensen M P 2013 Calculation of alternating current losses in stacks and coils made of second generation high temperature superconducting tapes for large scale applications *J. Phys. D: Appl. Phys.* **114** 173901
- [41] Rodriguez-Zermeno V M, Mijatovic N, Traeholt C, Zirngibl T, Seiler E, Abrahamsen A B, Pedersen N F and Sørensen M P 2011 Towards faster FEM simulation of thin film superconductors: a multiscale approach *IEEE Trans. Appl. Supercond.* **21** 3273–6
- [42] Rhyner J 1993 Magnetic properties and AC-losses of superconductors with power law current—voltage characteristics *Phys. C* **212** 292–300