Experimental AC loss analysis of braid type non-inductive coil for superconducting fault current limiter

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Abstract. Resistive superconducting fault current limiter (SFCL) plays a key role to realise the stability and safety of power grid and the future electric aircraft. This paper presents the design and test of a braid type non-inductive coil for SFCL. One inner coil and one outer coil were wound around a G10 tube using 4 mm-wide SuperPower wires. Two configurations of the braid type non-inductive coil were achieved by connecting the inner coil and outer coil in series and in parallel, respectively. AC loss results of these two non-inductive coils were measured and compared to investigate the AC loss dependency on coil configuration and current distribution. It has been concluded that braid type non-inductive coil has low AC loss due to magnetic field cancellation. Serial connection of the inner and outer coils leads to a good degree of field cancellation, which results in higher critical current and lower AC loss of the non-inductive coil, compared to parallel connection.

1. Introduction

High temperature superconducting (HTS) fault current limiter (FCL) becomes a promising application, with the advantages of fast response, automatic quench characteristics, and fast recovery [1-6]. Bifilar coil, also called non-inductive coil is a significant current limiting unit in resistive type HTS FCL [7, 8]. Pancake type non-inductive coil wound by two parallel-connected conductors with one joint inside is one of the most commonly used coil structure. Adjacent turns carry current in opposite direction, thus, magnetic field will cancel with each other. However, in such a coil, normally inner turns cannot have a good cooling environment due to limited contact area with liquid nitrogen except keeping some space between adjacent turns during winding. It is important to ensure inter-turn voltage withstanding in outer section of the coil. Helical type non-inductive coil wound by two conductors side by side, has less magnetic field cancellation effect compared to pancake coil, which results relatively higher AC loss in the coil. It encounters high inter-turn voltage as well, which requires high level electrical insulation [9-11].

Some researchers reported results in braid type non-inductive coil, which was composed of two coils wound in opposite direction but in parallel connection, as shown in [10]. In such a coil configuration, the inter-turn voltage is very small and there is little requirement for electrical insulation. By properly designing pitch length of inner and outer coil, magnetic field can be well cancelled and it ends up with smaller AC loss. However, the self-inductance of inner coil and outer coil are similar but still not the same, and it is practically challenging to keep the contact resistance identical, such as soldering and joint during parallel connection. Thus, it is difficult to achieve equal current sharing between inner and outer coils, which normally leads to high AC loss [9-11].

If the inner and outer coil are connected in series while keeping opposite coil direction, the current will be evenly distributed. Till now, there is no report on braid type non-inductive coil where the inner coil and outer coil have a serial connection.
In this paper, we designed and fabricated a braid type non-inductive coil. By arranging the connection of copper bars, we achieved two non-inductive configurations, one with serial connection of inner and outer coils, and the other one with a parallel connection of inner and outer coils. AC loss measurement were carried out and compared to explore loss dependence on the current sharing.

2. Measurement method

2.1. Non-inductive coil design

Table 1. Parameters of single wire

| Items                      | Values         |
|----------------------------|----------------|
| Manufacturer               | SuperPower     |
| Wire type                  | SCS4050-AP     |
| Width, (mm)                | 4              |
| Thickness of conductor, (mm)| 0.1            |
| Thickness of HTS layer, (μm)| 1              |
| Minimum $I_c$ (A)          | 127            |
| Stabilizer                 | Copper         |
| Thickness of stabilizer, (μm)| 20×2           |

Table 2. Specifications of braid type coil

| Items                      | Inner coil | Outer coil |
|----------------------------|------------|------------|
| Coil form                  | helical    | helical    |
| Winding direction          | clockwise  | anticlockwise |
| Inner diameter, (mm)       | 87         | 87.4       |
| Layer number               | 1          | 1          |
| Turn number                | 5          | 5          |
| Pitch length, (mm)         | 5          | 5          |
| Insulation                 | Kapton     | Kapton     |
| Valid distance between voltage taps, (cm)| 129.6     | 131.2     |
| Self-inductance, (μH)      | 3.30 (L1)  | 3.22 (L2)  |

The non-inductive coil was composed of 4 mm-wide SuperPower wire. The stabilizer of the wire is copper with thickness of 20 μm on both sides. Parameters of the wire were listed in Table 1. The braid type non-inductive coil was wound around one G10 tube whose outer diameter is 89 mm. The tube was grooved with two coil tracks in two opposite directions, naming one inner coil track with clockwise direction, and one outer coil track with anticlockwise direction. The grooves are 1 mm in depth. Both inner coil and outer coil have five turns with pitch length of 5 mm. Upper terminal of inner coil is aligned the same vertical height to that of outer coil but separated by 180 degrees. Lower terminal of inner coil is aligned the same vertically but separated by 180 degrees. These two coils were insulated by two layers of Kapton tapes. Voltage taps on the inner coil were soldered 20 mm away from the copper bar, so does the voltage taps on outer coil. The detailed parameters of these two coils were listed in Table 2. Figure 1 shows the view of the non-inductive coil.
As shown in Figure 1, four copper bars have been marked by number 1, 2, 3, and 4. Copper bar 1 and 2 were soldered with inner coil and copper bar 3 and 4 were soldered with outer coil. We achieved serial connection of inner and outer coils by directly connecting copper bar 2 and 3, then current flows in from copper bar 1 and then flow out from copper bar 4. We named this braid-type coil in series structure as BCS. In BCS, current amplitude flowing through these two coils are always equal, and magnetic field generated from two coils will be cancelled with each other due to opposite coil direction.

Similarly, we achieved parallel connection of inner and outer coils by directly connecting copper bar 1 and 3, then total current flows into two coils and distribute freely. We named this braid type coil in parallel as BCP. In BCP, current sharing is not equal between two coils but according to impedance of each coil branch. However, magnetic field of two coils still cancel with each other.

2.2. Experimental setup

All tests were carried out in liquid nitrogen at 77 K.

Figure 2 (a) and (b) show the schematics of AC loss measurement setup of BCS and BCP, respectively. It is worthy to point that all shunts used in AC loss test were to obtain the current in each coil branch and they have identical parameters 500 A/ 50 mV from the same brand and company. To test AC loss
in BCP, each coil was connected to one shunt. Voltage of each coil and shunt were captured by NI SCXI model. AC loss of non-inductive coil, $J/m/cycle$, was calculated by equation (1),

$$Q = \frac{1}{2} \sum_{k=1}^{2} Q_k = \frac{1}{2} \sum_{k=1}^{2} \left( \int_0^{T/f} v_k i_k dt / d_k f \right)^2$$  

Here, 1 and 2 denote inner coil and outer coil, respectively. $Q_1$ and $Q_2$ present AC loss in inner coil and outer coil. $v_k (k = 1, 2)$ is the instantaneous voltage measured from two coils. $i_k (k = 1, 2)$ is the instantaneous current measured from inner and outer coil. $d_k (k = 1, 2)$ is the valid distance of voltage taps on two coils, $d_1 = 129.6$ cm and $d_2 = 131.2$ cm. $f$ is frequency. In the test, $f$ is 27 Hz, 54 Hz and 81 Hz.

3. Results and discussion

![Figure 3 Critical current of single wire](image1)

![Figure 4 Critical current in inner and outer coil of BCS](image2)

Figure 3 shows the critical current test of single wire. The $I_c$ of the wire is 132.2 A. Figure 4 plots the critical current test of inner and outer coil of BCS. $I_c$ of inner coil and outer coil is 128.3 A and 134.2 A, respectively, which shows there is a good magnetic field cancellation in BCS. $I_c$ of inner coil is smaller than that of outer coil due to the relatively poor cooling environment of inner coil.

![Figure 5. AC loss results measured from BCS](image3)

![Figure 6. AC losses measured in BCS under 27 Hz](image4)
under three frequencies

Figure 5 plots AC loss results measured from BCS under three different frequencies, 27 Hz, 54 Hz, and 81 Hz, respectively. It is observed that AC losses under three frequencies agree well with each other, which shows hysteresis nature dominates AC loss. AC loss increases with the increase of transport current.

Figure 6 shows experimental AC loss results in inner coil and outer coil of BCS, at frequency of 27 Hz. AC loss value in inner coil at each transport current is bigger than that in outer coil. Inner coil was tightly insulated by Kapton tapes and conductors of outer coil, which makes it difficult for inner coil to get cooled by liquid nitrogen. At \( I_{\text{peak}} = 40 \, \text{A} \), AC loss in inner coil is 1.81 times of that in outer coil. At \( I_{\text{peak}} = 78 \, \text{A} \), AC loss in inner coil is 2.04 times of that in outer coil.

It is worthwhile to notice that after the AC loss measurement of BCS, we did another critical current test for BCS coil, during which a small section in the copper bar joint was burnt due to a poor soldering. The \( I_c \) of BCS coil measured out of this test were shown in Figure 7. We observe that electric field in inner and outer coil suddenly increases and exceeds the voltage criteria of 1 μV/cm, when the current reaches around 90 A. Critical current for inner coil and outer coil are around 92 A and 93 A, respectively.

![Figure 7](image7.png)  
**Figure 7.** Critical current measurements of inner coil and outer coil in BCS

![Figure 8](image8.png)  
**Figure 8.** AC loss results measured in BCP under 27 Hz.

![Figure 9](image9.png)  
**Figure 9.** Current distribution in inner and outer coil at 27 Hz
Figure 8 plots AC loss results measured in BCP at 27 Hz and also compared to the losses in BCS. As the transport current increases, AC loss in BCP coil becomes higher. It is also shown in Figure 8 that AC loss in BCP is much bigger than that in BCS. At current is 30 A, loss in BCP is nearly two orders higher than that in BCS.

Figure 9 plots current distribution in inner coil and outer coil of BCP. It is quite interesting to see that in the beginning, most of the current is flowing through inner coil, which shows the impedance in inner coil branch is smaller than that in outer coil branch.

Assume the total resistance in inner coil branch of BCP is $R_1$, inductance of inner coil is $L_1$, total resistance in outer coil branch of BCP is $R_2$, inductance of outer coil is $L_2$, and mutual inductance is $M_{12}$. The voltage of two branches are $V_1$ and $V_2$, respectively. As the inner and outer coils are connected in parallel, the voltage across each coil is the same, $V_1=V_2$. We have the following equations (2)-(6):

$$V_1 = (R_1 + j\omega L_1)I_1 - j\omega M_{21}I_2$$  \hspace{1cm} (2)

$$V_2 = (R_2 + j\omega L_2)I_2 - j\omega M_{12}I_1$$  \hspace{1cm} (3)

$$M_{12} = M_{21} = M$$  \hspace{1cm} (4)

$$(R_1 + j\omega L_1 + j\omega M)I_1 = (R_2 + j\omega L_2 + j\omega M)I_2$$  \hspace{1cm} (5)

$$\frac{I_1}{I_2} = \frac{R_2 + j\omega L_2 + M}{R_1 + j\omega L_1 + M}$$  \hspace{1cm} (6)

Equation (6) shows current distribution between inner coil and outer coil depends on the resistance of the branch, and also the inductance of the branch. This is to say, in order to keep equal current distribution, it is very important to make sure these parameters the same.

As the total current increases, current in inner coil tends to be saturated. In some degree, current in outer coil starts to increase due to current saturation in inner coil, which means inner coil reach the critical state. This current redistribution indicates that there is not a balanced magnetic field cancellation due to unequal current sharing. Critical current in BCP decreases. This also explains a much higher AC loss in BCP.

4. Conclusion

In this paper, we studied two configurations of non-inductive braid type coils, namely BCS and BCP. Critical current of inner coil and outer coil in series connection is quite similar with critical current of single wire, which shows there is a good magnetic cancellation effect in this braid type coil. AC loss measured in BCS is not dependent on frequency. Due to the uneven current sharing in the inner and outer coil in BCP, the AC loss is significantly higher than that in BCS. Therefore, it is critical to ensure equally shared current in the inner and outer coil when connected in parallel. Considering the hot spot in the coil caused during the test, which brings difficulty in explaining some phenomenon, we will design and fabricate another braid type non-inductive coil for more experimental tests in the future.

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