Homogeneous Current Distribution in Multi-laminated HTS Tape Conductor for Pancake Coil of SMES

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Abstract

A multi-laminated HTS tape conductor has been recently developed to fabricate large pancake coils such as SMES. If the HTS tapes are simply laminated to form the conductor, the current distribution in the laminated tape conductor of the coil is unbalanced because of different inductances of all tapes. The pancake coil has been widely used for large magnet, because the pancake coil is tightly wound and endures large electromagnetic force. The tape transpositions at both ends of the pancake coil are effective for the coil fabrication, because it cannot damage the conductor. It is very important to analyze current distribution in the multi-laminated tape conductor used for the pancake coil. In this paper, we analyze the current distribution in the tape conductor by using circuit model, and then propose a relationship between the laminated tape number of the conductor and the pancake coil number to obtain the homogeneous current distribution. We fabricated the double pancake coil based on the relation, tested it to verify the relation and demonstrated the homogeneous current distribution in the conductor.

Multi-laminated HTS tape, SMES, homogeneous current distribution, transposition

1. INTRODUCTION

Since 2nd generation HTS (2G) tape has been intensively developed in the world and has been fabricated in long length, it becomes important issue to apply the 2G tapes to the large current capacity conductors used for large coils such as SMES due to high critical current density and high mechanical strength of substrate. A pancake coil has been widely used for large SMES magnet, because the pancake coil is tightly wound and able to endure large electromagnetic force. Since the 2G tape has some 100 A current capacity at LN2 temperature and self magnetic field and less current at large magnetic field [1], conductor for the large SMES coil requires many tapes for large current.

Transposition in the conductor like conventional metallic wires seems to be effective for homogeneous current distribution during charging or discharging of the coil, but the 2G tape can be easily damaged due
to lateral bending. Although a Roebel conductor assembled with 2G tapes is good for the lateral damage and useful for reducing AC loss, it costs high because of mechanical punching process [2]-[3].

It is simple and easy to laminate the 2G tapes in one column to form the conductor, however, the current distribution in the laminated tape conductor of the coil during change is unbalanced because of different inductances of all tapes. In case that all tapes of the conductor are electrically connected and soldered along the tapes, current transfer between the tapes can occur, but coupling loss becomes very large, and hence the tapes should be insulated among them. There are some papers to suppress the current imbalance distribution in the solenoid winding coils [4]-[6]. However, there are few papers for pancake winding coils [7]-[8]. Two methods are proposed [8]; one is transpositions at both ends of pancakes with the same insulation thickness between tapes, and the other is transpositions at both ends of pancakes with the variable insulation thickness between tapes. We demonstrated that the latter method is very effective and has no restriction of pancake numbers if more than two pancakes. In this paper, we treat the former method for any pancake number coils, and find out conditions for homogeneous current distribution in the laminated conductor.

2. Analysis of current distribution

The HTS tape is composed of the YBCO thin film about 1 μm in thickness and several mm in width, high mechanical strength substrate, Cu stabilizer and insulation tape. The conductor is laminated with the several HTS tapes in one column, and then the pancake coil is wound with the conductor, where the tapes in the conductor are transposed at both ends of the pancake, that is, innermost layer and outermost layer. Since both terminals of the coil are electrically connected with solder to feed the current into the coil, all tapes have the same voltage. The all tapes in the coil have self and mutual inductances in an electrical circuit model. The electrical circuit equations of all the tapes are as follows.

\[ V = \sum_{j=1}^{n} M_{ij} \frac{dI_j}{dt} \quad (i = 1 \ldots n) \]  

where \( V \) is the voltage drop, \( M_{ij} \) is mutual inductance between \( i \)-th and \( j \)-th tape, and \( i=j \) is self inductance, \( I_j \) is \( j \)-th tape current. After calculating accurately all inductances of the tapes in the conductor, we can obtain the current distribution from the above equation.

3. Transposition

In this paper, we label the number of the tapes laminated in the conductor from the center axis of the most left side pancake coil, and introduce a simplified transposition matrix description, as shown in Fig. 2, to indicate the tape number connected at transpositions between pancake coils. The column shows the tape number laminated in the conductor, and the row shows the pancake, and hence the same number tape between the row is transposed at either end of the pancake and connected in series.

3.1. Even number tapes arrangement

First we treat the conductor laminated with even number tapes. In a simple case where the conductor is laminated with 2 tapes, the homogeneous current distribution is obtained if 2 tapes are fully transposed. Here, the term ‘fully transpose’ in the even number tapes arrangement means that the row of the matrix has different numbers.
Next we consider the four laminated tapes. In this case, we cannot obtain homogeneous current distribution for two pancakes, as shown in Fig 2. In order to obtain homogeneous current distribution, we must require 4 pancakes to fulfill the fully transposition in the matrix, and 4 symmetric transposition are shown in Figs.1 and 3. Here the term “symmetric transposition” means that the matrices of Fig. 4 are point symmetric [7]. It is concluded that the homogeneous current distribution should need full and symmetric transposition. After calculating the inductances of all connected tapes and inverting the inductance matrices, we can obtain the current distribution according to equation (1). The result of current distribution normalized by $I_1$ as a function of coil layers is shown in Fig. 4. All the 4 arrangements show the same results of Fig. 4.

From the figure, small imbalance is observed near the small number layers of the coil. This is explained as follows. In the above 4 transposition arrangements, inductance of tape 1 is the same as that of tape 4, and inductance of tape 2 is the same as that of tape 3, due to geometrical symmetry. But the inductance between tape 1 and 2 is different like $L_1 = L_4 \neq L_2 = L_3$, and hence we obtain the current distributions as $I_1 = I_4 \neq I_2 = I_3$. This represents the 4 tapes arrangements cannot be perfectly transposed to be geometrical symmetry simultaneously. Therefore, the difference at small number of layers are large, while those at large number become small.
We apply the above homogeneous transposition condition to 6 and 8 laminated tapes to get homogeneous current distributions. Fig. 5 shows the homogeneous current distributions for both typical transposition arrangements. It is shown that the point symmetric transposition makes homogeneous current distribution.

### 3.2. Odd number tapes arrangement

In the case of odd number tapes, since the point symmetry of the transposition matrix cannot be realized by using the same number pancakes like the case of the even number tapes arrangements. Fig. 6 shows the unbalanced current distribution result of the simple case of the 3 pancakes transposed with 3 laminated tapes, and imbalance becomes larger with increasing larger number of layers. Therefore we introduce 2 times of the odd same number pancakes to fulfill the point symmetric transposition matrix, and thereby obtain the homogeneous current distribution, as shown in Fig. 7.

It is found that it is very important to construct the point symmetry of the transposition matrix. It is
concluded from above results for homogeneous current distribution that the even number tapes requires the same pancake number of the laminated tape number, while the odd number tapes requires the 2 times pancake number of the laminated tape number.

4. Experiment

4.1. Experimental setup

We design and fabricate 4 pancake coils with point symmetrically transposition wound with 4 laminated YBCO tapes with the same insulation thickness between tapes in order to verify the above homogeneous current distribution condition. The coil parameters are listed on Table I and fabricated coil is shown in Fig. 8. The 4 laminated tapes of the conductor are expanded at the coil terminals for current measurement through Rogowski coils.

The schematic drawing of electric circuit and measurement system for the experiments is also shown in Fig. 8. The coil is immersed in liquid nitrogen. The current is forced through the power supply with variable frequency operated by a function generator, and measured through a coaxial shunt with small inductance.

The four Rogowski coils at the coil terminals are settled to measure each tape current in the conductor. Since the terminal junctions of all tapes are detachable, the current is able to pass through only one tape. Output signals from the Rogowski coils are acquired into the oscilloscope through coaxial cables. The calibration of the Rogowski coils was carried out such a way that the current from one tape with keeping the others tape current zero is measured and compared with the shunt current, and the same process are carried out for other tapes. The voltage taps are attached on the pancake coil terminals and monitored during the experiment. No extraordinary voltages are observed.

4.2. Experimental results

We measure the each tape current waveforms of the conductor as shown in Fig. 9 under the typical condition of the total peak current with 4.3 A at 200 Hz. It is found from the figure that the all tape currents are nearly equal and hence the

| Table 1 Coil parameters |
|-------------------------|
| Number of tapes         | 4          |
| Number of layers        | 20 × 4     |
| HTS tape width [mm]     | 10.2       |
| Tape thickness [mm]     | 0.31       |
| SC thickness [μm]       | 1          |
| Coil inner radius [mm]  | 113        |

Fig. 8. Fabricated double pancake coil and Experimental setup for current measurement.

Fig. 9. Current wave forms of 4 tapes.
homogeneous current distribution can be obtained as suggested from the above homogeneous condition. There is small deviation between the experimental results and the theory. This comes from the transposition fabrication error at the innermost or outermost layer due to small size of the coil. We demonstrate that the experimental results are in good agreement with the theory.

5. Conclusion

We investigate the general transposition condition of the laminated tapes with the same insulation thickness between tapes by using the electrical circuit model in order to obtain the homogeneous current distributions for even and odd number tapes. It is concluded from the numerical results that the homogeneous current distribution should require the point symmetry of the transposition matrix. In the case of the even number tapes, the same number pancakes as the tape number are needed to satisfy the homogeneous current distribution, while in the case of the odd number tapes, the number pancakes two times of the tape number are needed. In order to verify the above homogeneous current distribution condition, we design and fabricate the 2 double pancake coils wound with four laminated tapes based on the above condition. The test results show the homogeneous current distribution, and thereby we demonstrate the homogenous condition is right.

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