Design and modelling of a SMES coil

Weijia Yuan, A. M. Campbell, and T. A. Coombs
EPEC Superconductivity group, Engineering Department, 9 JJ Thomson Avenue, Cambridge, CB3 0FA, United Kingdom.
E-mail: wy215@cam.ac.uk

Abstract. The design of a Superconducting Magnetic Energy Storage (SMES) coil wound by coated conductors has been presented. Based on an existing model for coated conductor pancake coils, this paper analysed the magnetic field and current density distribution of the coil at two different operation temperatures, 77K and 22K. A comparison table of the critical currents and AC losses at these two temperatures has been presented. Several steps to improve the transport current of the coil have been suggested as well.

1. Introduction
Superconducting Magnetic Energy Storage (SMES) systems have high cyclic efficiency, fast response time and deep discharge and recharge ability as an energy storage system, these advantages make it a good solution to solve problems of the connection of the distributed power generation system with the main power grid. Since long length of second-generation high temperature (2G HTS) superconductors have become commercially available, it is now possible to wind the SMES coils by 2G HTS conductors. Therefore understanding the magnetic field distribution, predicting the critical current and calculating the AC losses of the coils are necessary before the application [1–4].

Based on a recent numerical model [5], we simulated the coil with transport currents at two different temperatures. The critical currents of the coil has been predicted, the figures of the magnetic field distribution of the coil have been depicted, and the AC losses have been calculated.

2. The design and configuration of the coil
2.1. The characteristic of the tape
The properties of the superconducting tape used in this paper are based on Superpower’s SF12100 tape. Table 1 gives the details of the tape. After measurement, we find the minimum critical current of all samples is 201A at self field, 77K. From Superpower’s data we can get the expression of the critical current density with the perpendicular field (normal to the wide face of the tape and parallel to the coil radius) at two different operation temperatures as shown in equations 1 and 2:

\[ J_{c,77K} = J_{0,77K} \times \frac{B_{0,77K}}{B_{0,77K} + |B_z|} \tag{1} \]

where \( J_{0,77K} = 1.11 \times 10^8 A/m^2 \), \( B_{0,77K} = 0.12T \).
\[ J_{c,22K} = J_{0,22K} \times \frac{B_{0,22K}}{B_{0,22K} + |B_z|} \]  

(2)

where \( J_{0,22K} = 6.58 \times 10^8 \text{A/m}^2 \), \( B_{0,22K} = 1.49T \).

**Table 1.** Characteristics of Superpower’s SF12100 tapes.

| Tape configuration                  | Quantity |
|------------------------------------|----------|
| Tape width                         | 12mm     |
| Individual conductor thickness     | 0.1mm    |
| Insulation + epoxy thickness       | 0.05mm   |
| Total thickness of the tape        | 0.15mm   |
| Critical current (self-field, 77K) | 201A     |

2.2. **The design of the pancake coil**

A single layer pancake coil wound with 100 meters of this tape has been constructed. The stored energy of the coil is determined by \( \frac{1}{2}LI^2 \), while \( L \) is determined by the dimension of the coil, and \( I \) is mainly constrained by the maximum perpendicular field to the tapes as in equations 1 and 2. By producing a comparison table, we can get the design which gives the maximum stored energy in the coil wound by a certain length of conductors: the inner radius of the coil is 40mm and the outer radius is 80mm, the total turns in the coil is 266.

Figure 1 gives the cross-section view of the coil. \( z \)-axis is the coil radial direction and perpendicular to the wide face of the tape. This SMES is planned to operate at liquid nitrogen temperature level and dry cooling temperature level, thus we will analyse the coil at 77K and 22K individually.

![Figure 1. Configuration of the coil](image-url)
3. Modelling of the coil

Due to the high aspect ratio of the coated conductor, the standard finite element method (FEM) is difficult to apply to a pancake coil and the solution process will take a very long computation time. Some recent papers showed a way round this problem by using a new numerical model [5, 6]. In this paper we will retain the model assumptions in [5]. Here we go through this model briefly.

We assume the current density is distributed all over the whole cross section area of each tape rather than only the superconducting layer. In the coil there should be two regions, the critical region and sub-critical region. The flux fully penetrates in the critical region, the critical current density will be consistent with the local magnetic field as in equations 1 and 2. Since the tapes are closely packed together in the coil, the flux lines can not penetrate into the tapes and hence have to be parallel to the surface of each tape. This means there is no perpendicular magnetic field in the sub-critical region. The current density in each tape in the sub-critical region will therefore be constant and need to guarantee the transport current carried by each tape is the same. By searching for the critical boundaries which make the perpendicular magnetic field nearly zero in the sub-critical region, we can get the magnetic field and current density distribution across the coil. Figure 2 illustrates the model. The critical boundaries are two symmetric parabolae \( x(z) = \pm \frac{c_2^2 - c_1^2}{b^2} x^2 + c_1 \). The critical current density \( J_c \) flows in the critical region while a less current density \( J_m \) flows in the sub-critical region.

![Figure 2. The magnetic field and current density distribution of the coil](image_url)

We have to point out in this paper we are using fixed-division method [7] to get the solution rather than the dynamic-division method in [5]. Moreover, we are using an infinitely long stack to approximate the the coil rather than the real circular coil model. Calculation in [7] shows that for this coil dimension the infinitely long stack model will only give an error less than 10% for the AC losses, however, it can greatly save the computation time by avoiding the elliptic integrals.

4. Calculation results

4.1. Simulation at 77K

4.1.1. The critical current \( I_{c, 77K} \)  
First we need to calculate the critical transport current of this coil at 77K based on the prediction given by this model. The critical region will penetrate
into the centre of one tape of the coil at the critical current. By increasing the transport current, we can find when the critical region just penetrates into the middle of one tape. Figure 3 and 4 give numerical solution of the coil at the critical current. In figure 4 the red lines without any numbers represent the critical boundaries of the coil, the color lines with numbers represent the flux lines. We can find that the critical region penetrates into the centre tape of the coil, which marks the critical current of the coil at 77 K as 85 A. The critical current densities almost flows everywhere in the centre tape. The perpendicular magnetic field penetrates into the centre as well.

**Figure 3.** Current density distribution at the critical current

**Figure 4.** Magnetic flux lines at the critical current

4.1.2. The solution at 80% of $I_{c,77K}$ For a normal operation of a SMES coil, 80% of the the critical current is a reasonable value. Thus we put in a 68 A transport current which is 80% of $I_{c,77K}$, which is 68 A. Then we follow the solution process in section 3 and get the figures 5 to 8. We can find in figure 5 the perpendicular magnetic field is almost zero in the sub-critical region, then increases across the tape width direction. On the edge of each tape the perpendicular field reaches the maximum. The perpendicular component is larger in the centre tapes than the top/bottom tapes. This is important for the SMES coil design: by shielding the centre tapes from the magnetic field we can put in a higher transport current. As shown in figure 6 the flux lines penetrate freely in the critical region, but the perpendicular component can not penetrate into the sub-critical region. Therefore by conducting the flux lines to penetrate less into the coil, the critical current will be gained. Figure 7 and 8 have shown the current density distribution. The current density in the sub-critical region is much less than that in the critical region. Thus we can increase the transport current by increasing the current density in the sub-critical region.

By the vortex line formula [5, 6, 8], the AC losses of the cross section area of the coil during the charging up process (i.e. from 0 to 68 A) is 2.55 J/m. The losses during an operation cycle will thus be twice the value as 5.1 J/m. Timing this value by the mean circumference of the coil, we can get the AC losses of the whole coil. And

4.2. Simulation at 22K Reducing the operation temperature will increase the current density and thus the stored energy. By the cryogen-free cooling method, we can reach the temperature around 22K. Equation 2 gives the performance of the tape at 22K. Again we need to calculate the critical current of the coil first. Our model predicts that the critical current $I_{c,22K}$ will be 640 A. The operation current at this temperature will hence be 512 A, which is 80% of $I_{c,22K}$. Figures 9 to 12 give the
solution of the coil with a 512 A transport current. The AC losses during one operation cycle is 288 J/m.

4.3. Comparison of the coil at 22K and 77K

Having got the solutions at two different temperatures, we can produce a comparison table of the performance of the coil at these two temperature. When the temperature goes down from 77K to 22K, the critical current increases from 85 A to 640 A, however, the AC losses at the operation current increases from 51.1 J/m to 288 J/m. The AC losses increasing ratio is 56.5, which is much larger than the critical current increasing ratio, 7.53. These are shown in table 2

5. Conclusions

This paper presents a design which gives the maximum stored energy of a coil wound by a certain length of conductors.

The solutions by the existing model analysing the coil at two different temperatures are consistent with the model assumptions. The centre tape of the coil will be penetrated completely
Figure 9. Magnetic field distribution at 512A

Figure 10. Magnetic flux lines at 512A

Figure 11. Current density distribution of the coil at 512A

Figure 12. Current density distribution at different tapes at 512A

Table 2. Comparison of the coil at 22K and 77K

| Coil performance   | 77K | 22K | ratio of 77K to 22K |
|--------------------|-----|-----|---------------------|
| Critical current   | 85A | 640A| 7.53                |
| Operation current  | 68A | 512A| 7.53                |
| AC losses at the operation current | 5.1J/m | 288J/m | 56.5 |

first. By shielding the centre tape and increasing the current density in the sub-critical region, we can increase the transport current of the coil.

By reducing the temperature from 77K to 22K, the critical current of the coil increases from 85A to 640A, while the AC losses at 80% of the critical current during an operation cycle increases from 5.1J/m to 288J/m.
Acknowledgments
The authors thank Mark Husband from Rolls Royce for his great help and support through this work.

References
[1] Brambilla R, Grilli F, Nguyen D N, Martini L and Sirois F 2009 Superconductor Science and Technology 22 075018 (10pp) URL http://stacks.iop.org/0953-2048/22/075018
[2] Grilli F and Ashworth S P 2007 Superconductor Science and Technology 20 794–799 URL http://stacks.iop.org/0953-2048/20/794
[3] Souc J, Pardo E, Vojencik M and Gomory F 2009 Superconductor Science and Technology 22 015006 (11pp) URL http://stacks.iop.org/0953-2048/22/015006
[4] Clem J R 2008 Physical Review B (Condensed Matter and Materials Physics) 77 134506 (pages 7) URL http://link.aps.org/abstract/PRB/v77/e134506
[5] Yuan W, Campbell A M and Coombs T A 2009 Superconductor Science and Technology 22 075028 (12pp) URL http://stacks.iop.org/0953-2048/22/075028
[6] Clem J R, Claassen J H and Mawatari Y 2007 Superconductor Science and Technology 20 1130–1139 URL http://stacks.iop.org/0953-2048/20/1130
[7] Yuan W, Campbell A M and Coombs T A Unpublished
[8] Claassen J H 2006 Applied Physics Letters 88 122512 (pages 3) URL http://link.aip.org/link/?APL/88/122512/1