Electro-Magnetic Design of a 3MJ YBCO Magnet

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Abstract. The electro-magnetic design of two 3 MJ superconducting magnetic energy storage (SMES) magnets with YBCO conductor are presented. One magnet is with solenoidal geometry composed of double pancake coils, and the other one is with toroidal geometry. According to the magnetic field simulation results, the perpendicular component of the magnetic field of the toroidal magnet could be extremely reduced compared with the solenoidal geometry. Therefore, a lower YBCO conductor requirement could be expected due to the dependence of \( J_c \) vs \( B \) performance of the YBCO conductor. Besides, the lower leakage magnetic field is important for application. A SMES system of 3 MJ is considered, and the coil is made of multiple identical D-type pancake coils. The critical current of the used YBCO conductor at 30K is 270A under 1 T perpendicular magnetic field. The inner radius of the D-type curve is 500 mm, and the outer radius is 1000 mm. The SMES magnet is made of 96 pancake coils, where the rated operating current is 975 A and the maximum perpendicular and parallel magnetic flux density are 0.5 T and 4.0 T, respectively. Further more, the maximum hoop stress and radial stress are 283 MPa and 78 MPa.

1. Introduction

The toroidal and solenoidal geometries are two kinds of structure for the design of high-temperature superconducting (HTS) magnetic energy storage (SMES) magnets. Compared with toroidal geometry, the fabrication of solenoid seems to be simpler and the mechanical stress is more easier to handle [1], [2]. Some large scale SMES systems by using of low temperature superconductors have been developed in the last three decades [3], [4]. However, since the efficiency of the liquid helium cryogenic system is extremely low, and the thermal stability of the low temperature superconducting (LTS) magnet is unsatisfactory, fewer researches on LTS SMES with liquid helium system continuous during the last two decades.

With the development of HTS conductors, some SMES systems by using of BSCCO wires have developed for testing and demonstration with solenoidal geometry [5], [6]. For the anisotropy characteristic of BSCCO wires, the structure of HTS SMES is relatively complex than LTS SMES magnet. However, with the development of YBCO conductor, toroidal geometry is investigated since it reduces the perpendicular component of the magnetic field [7]–[10]. Therefore, a lower YBCO conductor requirement could be expected due to the dependence of \( J_c \) vs \( B \) performance of the YBCO conductor.
In this paper, the design of two 3 MJ HTS SMES magnets with solenoidal and toroidal geometry are presented, and both of the magnets are made of multiple identical pancakes using YBCO conductors.

2. Structure of the SMES magnet

A commercial 2G HTS conductor produced by Shanghai Superconductor is used for the design of the SMES. The engineering critical current of the tape at 77 K and self-field operation is 90A. According to some research results, it is better for the HTS SMES operating at 20 K~30 K. Since the rated operation current is 1 kA, several YBCO conductors are parallel connected to meet the rated operation current. The coil is made of a group of transposed YBCO strands, and the conductor is wrapped with 50 μm polyimide film for electrical insulation.

2.1. Single solenoidal magnet

The 3 MJ SMES magnet uses double pancake coils reinforced by epoxy resin. Since the perpendicular component of magnetic field at both ends of the magnet increases, the critical current of the YBCO tape decreases. Consequently, the dimension and layout of the coils are revised to meet the operation current. The pancake coils are shun wound with double YBCO tapes, and the operating current could be increased. However, for the current carrying capacity of the pancake coils is much lower than the required 1000 A operation current, a series-parallel connection method of the pancake coils is adopted.

![Figure 1. The overall distribution of magnetic flux density of the magnet at the rated operating current.](image)

Figure 1 presents the magnetic flux density distribution of the solenoidal SMES magnet with 3 MJ, and the maximum magnetic flux density is about 3.7 T. However, the calculated stray field under the a requirement of 5 Gs is about Φ 15× 21 m, which is a rather large area for magnetism safety application. Therefore, the structure of the SMES magnet needs some improvement.

| Items                                | Specifications |
|--------------------------------------|----------------|
| Operation temperature                | <30 K          |
| Inner diameter of the solenoid       | 800 mm         |
| Outer diameter of the solenoid        | 920 mm         |
| Height of the solenoid               | 1500 mm        |
| Number of pancake coils              | 96             |
| Number of turns                      | 3900           |
| Operation current                    | 1010 A         |
| Inductance                           | 5.89 H         |
| Maximum perpendicular magnetic flux density | 1.8 T       |
| Maximum parallel magnetic flux density | 3.7 T         |
| Energy                               | 3 MJ           |
| 5 Gs area                            | Φ 15×21 m      |
| Length of used YBCO tape             | 63 km          |
2.2. **Group solenoidal magnets**

In order to reduce the stray field, some prototype of different structure solenoidal magnets are presented, and one is the group connected solenoidal magnet. Considering a 4 parallel solenoidal SMES magnet structure, where the stored energy of each solenoidal magnet is 0.75 MJ, and the 4 solenoidal magnets are series connected. Since the direction of the magnetic flux of the nearby magnets are different, the stray field could be extremely restricted.

![Figure 2. The 5 Gs area of magnetic flux density at the rated operating current.](image)

Figure 2 shows the magnetic flux density distribution of the SMES magnet. The 5 Gs area is restricted at 5×5×6 m space, which is extremely reduced compared with that of the single solenoid magnet structure. Unfortunately, the structure of four parallel solenoids leads to a certain deflection of magnetic flux in the magnet, and the local magnetic field intensity increases, which has a negative impact on the current carrying characteristics of superconducting tapes. Due to the bias of the magnetic field, there is greater stress between the solenoids. In addition, due to the limited energy storage of a single solenoid magnet, the energy storage density decreases, which increases the amount of superconducting tape.

**Table 2.** Specifications of the four parallel solenoidal SMES magnet.

| Items                                    | Specifications          |
|------------------------------------------|-------------------------|
| Operation temperature                    | <30 K                   |
| Inner diameter of the solenoid           | 400 mm                  |
| Outer diameter of the solenoid           | 530 mm                  |
| Height of the solenoid                   | 616 mm                  |
| Number of solenoids                      | 4                       |
| Number of pancake coils of one solenoid | 42                      |
| Number of turns of one solenoid          | 2490                    |
| Operation current                        | 973 A                   |
| Inductance                               | 6.34 H                  |
| Maximum perpendicular magnetic flux density | 2.4 T               |
| Maximum parallel magnetic flux density   | 4.7 T                   |
| Energy                                   | 3 MJ                    |
| 5 Gs area                                | 5×5×6 m                 |
| Length of used YBCO tape                 | 102 km                  |

2.3. **Toroidal magnet**

Compared with the conventional solenoid superconducting magnet, the superconducting magnet with annular structure has a relatively large size, but its stray field is relatively low. It is suitable for the occasion where there is a certain requirement for stray field, and also for the magnet with large energy storage.
Figure 3. Sketch of the D-shaped curve[13].

The D-shaped coil used for YBCO toroidal magnet is first proposed in a tokamak nuclear fusion reactor[14]. The D-shaped curve’s mathematical characteristic can be expressed as (1), and its curve sketch is as shown in figure 3

\[ y = \pm \int_{r_i}^{r_o} \left( \frac{\ln x}{\sqrt{k^2 - \ln^2 x}} \right) dx \quad C, x \in [r_i, r_o] \]

\[ k = \ln \left( \frac{r_o}{r_i} \right) \]

where \( C \) is a constant that determines the D-shaped curve along the \( y \) axis, while \( r_i \) and \( r_o \) are the inner and outer radii, respectively.

Figure 4. The overall distribution of magnetic flux density of the D-type toroidal magnet.

Figure 4 presents the overall distribution of the magnetic flux density of the D-type toroidal magnet, and we could see that the magnetic flux density at the vertical linear section near the inner diameter than other parts, which results in the concentration of stress.
According to the stress distribution analysis, the maximum stress on the D-type coil is about 107 MPa. Because only Von-Mises stress can not be used to check the material strength, it is necessary to get the stress along the YBCO tape length direction and the vertical strip surface. From the finite element analysis in figure 5, the arc transition section is the most dangerous part. Consequently, we could get the main design parameters of the toroidal SMES magnet.

Table 3. Specifications of the toroidal SMES magnet.

| Items                                      | Specifications |
|--------------------------------------------|----------------|
| Operation temperature                      | <30 K          |
| $r_i$ of the D-type curve                  | 500 mm         |
| $r_o$ of the D-type curve                  | 1000 mm        |
| Constant $C$ of the D-type curve           | 200 mm         |
| Number of pancake coils                    | 96             |
| Operation current                          | 975 A          |
| Inductance                                 | 6.32 H         |
| Maximum perpendicular magnetic flux density| 0.5 T          |
| Maximum parallel magnetic flux density     | 4.0 T          |
| Energy                                     | 3 MJ           |
| Maximum circumferential stress             | 283 MPa        |
| Maximum radial stress                      | 78 MPa         |
| 5 Gs area                                  | $\Phi$ 3×3 m   |
| Length of used YBCO tape                   | 78 km          |

2.4. Comparison of the SMES magnets

From the main parameters of the three types of SMES magnets, we could get the following conclusions:

1. The single solenoid type energy storage magnet has the simplest structure, uniform force distribution, relatively simple manufacturing process, and relatively high material utilization rate, but its stray field is large.

2. The structure of four parallel solenoids is more complex, the force is unbalanced, the manufacturing process is more complex, the need for large cryogenic vessels, the material utilization rate is the lowest, the stray field is low;

3. Toroidal magnet is more complex than single solenoid, its force is unbalanced, and its manufacturing process is relatively complex. Large cryogenic vessels are also needed, but the material utilization rate is higher and the stray field is lower than the solenoid magnets.

4. The decrease of current carrying capacity of HTS tapes under vertical magnetic field is much larger than that of parallel magnetic field, while the vertical magnetic field of ring structure magnets is
lower. Therefore, HTS materials have comparative advantages in toroidal structure magnets, especially YBCO materials have higher cost performance than Bi2223 tapes.

3. Conclusion

Electro-magnetic analysis of three kinds of SMES magnets based on solenoid and toroidal structure are presented. According to the analysis, a much higher perpendicular field occurs at the solenoid magnet, which lead to lower critical current of the used YBCO conductor. Nevertheless, based on the \( J_c \) vs \( B \) performance of YBCO conductor, the toroidal magnet could endure larger current than solenoid magnet, since the perpendicular field is lower than solenoid magnet under the same operation current. Besides, considering the required stray field limitation, toroidal magnet is much more competitive than solenoid magnet.

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