Multi Solenoid Type Magnet for 1 MJ HTS SMES System

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ABSTRACT: Recently the superconducting technology was more and more mature. The development of the technology allows us to apply superconducting magnetic energy storage (SMES) system to our life. An increasing number of scientists and engineers participate in study of SMES system. The application prospect of SMES system is very extensive, however, the leakage magnetic field limits application of SMES system. In this paper, multi solenoid type magnet, an improved structural for the 1 MJ single-solenoid structure magnet, is designed by using the actively shielding theory. The multi solenoid type magnet has potential to reduce the leakage magnetic field.

1 INTRODUCTION

SMES system is a kind of power electronic device. It can use superconducting magnet to store energy and can release energy to the power system. SMES system can enhance the stability of power system when it is used in power supply system. Due to increased pressure for providing high-quality electrical energy, an increasing number of SMES systems are applied to our life. However its electromagnetic radiation problem becomes more and more serious. The leakage magnetic field of traditional SMES system has limited its application in engineering. In order to reduce the leakage magnetic field of SMES magnet, the structure of the single solenoid type superconducting magnet is analyzed by considering the 1 MJ SMES system as a reference. At the same time, we design a new structure of superconducting magnet as combination of four single-solenoids based on the principle of the actively shielding theory of SMES system.

2 SELECTION OF WIRES

High-temperature superconductors (HTS), the materials working at unusually high temperatures, include BSCCO, YBCO, MgB2 and so on. Currently, the BSCCO wires are huge applications for many SMES system. In this paper, the BSCCO wires from the ASC company are selected. The cross-sectional area of single BSCCO wire is $0.3 \times 4.1 \text{ mm}^2$. In order to maintain SMES system working properly, ten BSCCO wires are paralleled as the materials of SMES
magnet. The cross-sectional area of the multi BSCCO wires is $4.4 \times 5.4 \text{ mm}^2$. We set the current of each single wire as 100 A so that the working current of SMES magnet is 1000 A.

3 ACTIVELY SHIELDING THEORY

Generally speaking, passively shielding method and actively shielding method are two different types shielding method of SMES magnets. The passively shielding method reduces leakage flux density in SMES magnet by setting ferromagnetic materials next to SMES system. The actively shielding method reduces leakage flux density in SMES magnet by using the principle actively shielding theory. Although the passively shielding method is easier than the actively shielding method, a lot of ferromagnetic materials may be wasted by the passively shielding method. So we prefer the actively shielding method in this paper. When several single-magnets were placed by the actively shielding method, the leakage magnetic field in SMES magnet will be reduced. When the magnetic dipole moment of magnets approaches to zero, the leakage magnetic field of SMES magnet can rapidly decrease. This is the actively shielding method. The magnetic dipole moment of a single solenoid $m$ can be expressed as follow:

$$m = \omega SI$$

where $\omega$ is the turns of solenoid; $S$ is the area enclosed by magnet; and $I$ is current of the solenoid. In addition, $m$ depends on the direction of current. When several solenoid are combined, $m$ is the sum of magnetic dipole moment of each solenoid.

4 DESIGN OF MAGNET FOR SMES

Since the superconducting wires are expensive, the least materials consumption is the target we owe to. We can measure the cost of materials by calculating the volume of SMES magnets. The magnetic energy stored by the SMES magnet $E$ can be expressed as follow:

$$E = \frac{1}{2} LI^2$$

where $L$ is inductance of SMES magnet; and $I$ is current of the magnet. Since we set current of SMES magnet as 1000 A and the magnetic energy stored by the SMES magnet is 1 MJ, the inductance of SMES magnets in this paper should be set as 2 H.

4.1 Calculation method for Inductance of several magnets

4.1.1 Single solenoid type magnet

The model of single solenoid type magnet is shown as Figure 1, where $d$ is the average diameter of solenoid; $r$ is the thickness of solenoid; $a$ is the height of solenoid; $R_1$ is the inside radius of solenoid; and $R_2$ is the outer radius.
The inductance of the single solenoid type magnet $L_s$ can be expressed as follows:

$$L_s = \frac{\mu_0}{4\pi} \omega^2 d \cdot 2\pi\{1 + \frac{1}{8} \left(\frac{a}{d}\right)^2 - \frac{1}{64} \left(\frac{a}{d}\right)^4 \ln \frac{4d}{a} - \frac{1}{2} \left(\frac{d}{a}\right)^2 + \frac{1}{32} \left(\frac{a}{d}\right)^4\}$$

$$- \frac{\mu_0}{2} \omega^2 d \{\frac{\pi}{3} \left(\frac{r}{a}\right)^2 - \frac{25}{72} \left(\frac{r}{a}\right)^4 - \frac{1}{8} \left(\frac{r}{d}\right)^2 + \frac{19}{768} \left(\frac{a}{d}\right)^2 \left(\frac{r}{d}\right)^2 - \frac{1}{180} \left(\frac{r}{a}\right)^4 + \frac{67}{7200} \left(\frac{r}{a}\right)^2 \left(\frac{r}{d}\right)^2 - \frac{17}{3840} \left(\frac{r}{d}\right)^4 \} \ln \frac{4d}{a} - \left[\frac{1}{6} \left(\frac{r}{a}\right)^2 - \frac{1}{120} \left(\frac{a}{d}\right)^2 \left(\frac{r}{d}\right)^2\right] \ln \frac{a}{r}\}$$

(3)

where $\omega$ is the turns of solenoid; $\mu_0 = 4 \pi \times 10^{-7}$ H/m.

4.1.2 Axially displaced solenoid arrangement

The model of axially displaced solenoid arrangement is shown as Figure 2, where each solenoid has the same size. We call them NO. 1 and NO. 3 solenoid.

We assume that there is a solenoid called NO. 2 between NO. 1 and NO. 3 solenoid. NO. 2 solenoid is shown in Figure 2. The mutual inductance between NO. 1 and NO. 3 solenoid can be expressed as follow:

$$M_{13} = \frac{1}{2} (L_{123} + L_2 - L_{12} - L_{23})$$

(4)

where $L_{123}$ is self-inductance of the magnet combined by NO. 1, NO. 2, NO. 3 solenoid; $L_2$ is self-inductance of NO. 2 solenoid; $L_{12}$ is self-inductance of the magnet combined by NO. 1 and NO. 2 solenoid; $L_{23}$ is self-inductance of the magnet combined by NO. 2 and NO. 3 solenoid.
4.2 Design of the multi solenoid type magnet

Based on the actively shielding theory of SMES magnet, a new structure magnet for 1 MJ HTS SMES is designed as Figure 3, where each solenoid has the same size. The direction of current in magnet units are illustrated as this Figure.

Figure 3. Model of multi solenoid type magnet.

As shown in the figure, all of the solenoid units are numbered. The inductance of the multi solenoid type magnet $L_m$ can be expressed as follow:

$$L_m=4L-2M_{12}+2M_{13}-2M_{14}-2M_{23}+2M_{24}-2M_{34}$$

(5)

where $L$ is self-inductance of the solenoid unit; $M_{12}$ is mutual inductance between NO. 1 and NO. 2 solenoid; $M_{13}$ is mutual inductance between NO. 1 and NO. 3 solenoid; $M_{14}$ is mutual inductance between NO. 1 and NO. 4 solenoid; $M_{23}$ is mutual inductance between NO. 2 and NO. 3 solenoid; $M_{24}$ is mutual inductance between NO. 2 and NO. 4 solenoid; $M_{34}$ is mutual inductance between NO. 3 and NO. 4 solenoid. All of inductance can be calculated by equation (3) and (4).

4.3 Optimization of SMES magnet

4.3.1 Optimization of single solenoid type magnet

We choose minimum volume of single solenoid type magnet as the objective functions. The objective functions can be expressed as follow:

$$V = \pi dar = \min$$

(6)

equation (6) subjects to: $L_s=2$, $R_i \geq 0.1$, $a < d$, $a = 0.0044 \cdot \omega \frac{0.0054}{R_2-R_1}$, $R_i = \frac{d-r}{2}$,

$$R_2 = \frac{d+r}{2}.$$

4.3.2 Optimization of multi solenoid type magnet

We choose minimum volume of multi solenoid type magnet as the objective functions. The objective functions can be expressed as follow:
\[ V = 4\pi d a r = \min \] (7)
equation (7) subjects to: \( L_n = 2 \), \( R_1 \geq 0.1 \), \( a < d \), \( h \geq 0.02 \), \( a = 0.0044 \cdot \omega \cdot \frac{0.0054}{R_2 - R_1} \).

\[ R_1 = \frac{d - r}{2}, \quad R_2 = \frac{d + r}{2}. \]

4.3.3 Optimal results

By using particle swarm optimization, the structural parameters of two kinds of magnets can be optimized respectively. The optimal results are shown as Table 1.

<table>
<thead>
<tr>
<th></th>
<th>( R_1 ) (m)</th>
<th>( R_2 ) (m)</th>
<th>( a ) (m)</th>
<th>( h ) (m)</th>
<th>( V ) (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>single solenoid type magnet</td>
<td>0.3874</td>
<td>0.4623</td>
<td>0.1584</td>
<td>—</td>
<td>0.0313</td>
</tr>
<tr>
<td>multi solenoid type magnet</td>
<td>0.1904</td>
<td>0.2991</td>
<td>0.0616</td>
<td>0.0295</td>
<td>0.0412</td>
</tr>
</tbody>
</table>

5 ANALYSIS OF MAGNETIC FIELD

According to the optimal results, the ANSYS modeling simulations of the two magnets are built respectively. The magnetic flux density vector images of two magnets are shown as Figure 4.

Figure 4. Magnetic flux density vector images of magnets.

Figure 5. Section of magnetic flux density.
In order to illustrate the reduction trend of magnetic field, we print the section of magnetic flux density respectively in the middle of magnet. The images are shown as Figure 5.

As shown in Figure 4-5, magnetic flux density around the multi solenoid type magnet decreases largely compared to that around the single solenoid type magnet. The leakage magnetic field of multi solenoid type magnet decrease rapidly. By extracting magnetic flux density around two magnets, the maximum magnetic flux density with a distance of 2 m is shown as Table 2.

<table>
<thead>
<tr>
<th>Table 2. Maximum magnetic flux density with a distance of 2 m.</th>
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<tbody>
<tr>
<td>magnetic flux density (T)</td>
</tr>
<tr>
<td>single solenoid type magnet</td>
</tr>
<tr>
<td>0.962 × 10^{-2}</td>
</tr>
<tr>
<td>multi solenoid type magnet</td>
</tr>
<tr>
<td>0.135 × 10^{-2}</td>
</tr>
</tbody>
</table>

According to table 1-2, the maximum magnetic flux density with a distance of 2 m of the multi solenoid type magnet gets 85.97% reduction compared to that of the single solenoid type magnet.

6 CONCLUSIONS

Based on the actively shielding theory, we design a multi solenoid type magnet for 1 MJ SMES system in this paper. The parameters of single solenoid type magnet and multi solenoid type magnet are optimized. According to these parameters, we build the ANSYS modeling simulations of two magnets. Though the analysis of the magnetic field distribution, the results provide effectively for the improved structural. Its turns that the multi solenoid type magnet has effect on leakage magnetic shielding by consuming more HTS wires.

REFERENCES


