Study on AC loss of single solenoid type magnet for 100 kJ HTS SMES system

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Abstract. The second generation of high temperature superconducting (HTS) strip has the outstanding characteristics of high critical temperature, large current-carrying density and high critical magnetic field, and the HTS magnets made by the strip have broad application prospects in the field of electric power, such as magnetic energy storage system, high-speed maglev train and wind power generation system. In order to promote the further development of a superconducting magnetic energy storage (SMES) system, this paper conducts modelling and simulation research on the AC losses of single solenoid type magnet for 10 kJ SMES system. Firstly, this paper optimizes the geometric parameters of the HTS magnet in the SMES system, in which the inner diameter, turns and pancake number of the superconducting magnet are the optimization variables, energy storage is the constraint condition, and the total consumption of the HTS strip is the optimization objective. Secondly, based on the T-A method, this paper established the AC loss model of single solenoid HTS magnets and calculated the AC losses of HTS magnets and thermal-conducting copper plates during the energy storage and energy release of the energy storage system.

1. Introduction

The superconducting magnet can be used in the energy storage system because its exciting current is less than its critical current and its energy loss can be ignored. By raising the inductance of the magnet or the critical current, the stored energy of the energy storage system can be increased. HTS material has the characteristics of high critical temperature, high current density and high critical magnetic field. The HTS magnet made by HTS material has high critical current at relatively high operating temperatures, so it is very suitable for a magnetic energy storage system.

The energy storage magnet can be divided into ring type and solenoid type according to the structure, and the solenoid type magnet is divided into the single solenoid and multiple solenoid structure. The single solenoid energy storage system is simple in structure and easy to make[1-3]. Ping Luo of Zhejiang University used a weighted particle swarm optimization algorithm to optimize the design of magnet for 35 kJ HTS SMES system[4]. Based on finite element software, Hao Wang of Sichuan University optimized the shape parameters of the hollow solenoid type magnet for 100 kJ SMES system based on the YBCO strip[5]. Hao Zhang from the University of Science and Technology of China designed a 500kJ HTS SMES device based on the YBCO strip and obtained Mises stress and deformation of the coil through electromagnetic calculation and stress analysis[6]. In terms of experimental testing, Yujun Dong, institute of plasma, Chinese Academy of Sciences, tested
the electrical, magnetic and force characteristics of a sample 3 M superconducting energy storage coil model, and the results showed that its performance met the design requirements [7].

At present, the HTS magnet structure optimization design of SMES system has got rich research work, but for the AC loss in the superconducting magnet relatively few research work[8], and AC loss is one of the important factors that reduce the efficiency of the energy storage system. Therefore, this paper studied the AC loss of a single solenoid type magnet for 100 kJ HTS SMES system, and deeply analyzed the AC loss of superconducting coil and conducting copper plate in the charge-discharge process of the energy storage system.

2. Geometric parameters optimization of HTS magnets

The HTS magnets adopt the double-disc structure; its optimization model is shown in Figure 1. Cold conducting copper plates with a thickness of 2mm are arranged in and between the double-disc magnets. The number of turns of each single disc coil is N, the thickness is D, and the inner radius is R. The width of the strip used is 12mm and the thickness is 0.1mm. The specific parameters of the strip used are summarized in Table 1.

![Figure 1. Optimization model of HTS magnets (DP represents double discs)](image)

| Table 1. Key parameters of second-generation HTS strip |
|---------------------------------------------|
| Material                       | YBCO                                      |
| Width                          | 12 mm                                     |
| Thickness                      | 0.1 mm                                    |
| The critical current           | 1536 A@20 K                               |
| Superconducting layer          |                                          |
| thickness                      | 1 um                                      |

The optimization variables of HTS magnets are the inner radius of the magnets, the number of turns and the number of double discs. The constraint condition is that stored energy is not less than 100 kJ of energy storage. The optimization objective is to minimize the consumption of the HTS strip. The optimization results are summarized in Table 2. It can be seen the critical current of the magnet reaches the maximum of 148 A as the number of double discs is 6, so the allowable excitation current is also higher (safety margin 0.75 is taken here). In addition, compared with other structural magnets, the magnets save more superconducting strip material. Therefore, the HTS magnet with the number of double discs of 6 is selected as the energy storage magnet in the 100kJ energy storage system in this paper. The AC loss of this magnet will be simulated.

| Table 2. Geometric parameter optimization results of HTS magnets |
|---------------------------------------------------------------|
| The number of double discs: 4 5 6 7                          |
| The number of turns: 515 377 271 274                          |
| Inner radius[mm]: 368 409 478 405                             |
| Self-induction of coil[Hz]: 20.65 18.77 16.30 17.16           |
| Critical current[A]: 131 138 148 145                           |
| Running current[A]: 98.25 103.5 111 108.8                      |
| The length of the strip[m]: 10188 10150 10054 10086           |
| The stored energy[kJ]: 100 100 100 101                          |
3. AC losses of HTS magnets

3.1. AC loss modelling

In this paper, the T-A method is adopted to calculate the AC loss of HTS magnets[9-10]. In the two-dimensional axisymmetric coordinate system, the magnetic flux density components are set as \( B_r \) and \( B_z \), the current density is \( J_\theta \), the electric field intensity is \( E \), and \( \rho \) is the resistivity of the material. The superconducting material does not contain ferromagnetic materials. The established AC loss model is shown in figure 2.

![AC loss model of HTS magnets](image)

Figure 2. AC loss model of HTS magnets

The vector magnetic potential method is used to calculate the magnetic field distribution of the non-superconducting parts. The governing equation is as follows.

Where \( \mu \) is the permeability, \( \mu = \mu_0 \).

\[
\frac{1}{\mu} \nabla^2 A = -\frac{1}{\rho} \left( -\frac{\partial A}{\partial t} - \nabla V \right) \quad (1)
\]

\[
\nabla \cdot \left( \sigma \left( \frac{\partial A}{\partial t} + \nabla V \right) \right) = 0 \quad (2)
\]

The vector potential method is used to calculate the current density distribution of the superconducting part, and the governing equation is

\[
\nabla \times \rho (\nabla \times T) = \frac{\partial B}{\partial t} \quad (3)
\]

Where \( B \) is the magnetic flux density, which is calculated by the vector magnetic potential method. The resistivity of superconducting materials is defined as follows.

\[
\rho_{HTS} = \frac{E_c}{J_c(B)} \left( \frac{J}{J_c(B)} \right)^{n-1} \quad (4)
\]

Where \( E_c \) is the critical electric field strength, and \( n \) is determined by the superconducting material. Where \( E_c \) is defined as 1 V/cm, and \( n = 21 \).

The critical current density of a superconducting material dependent on a magnetic field is defined as follows.
\[ J_c(B) = \frac{J_{c0}}{1 + \sqrt{\frac{k^2|B|^2 + |B_0|^2}{B_0}}} \]  

(5)

Where \( J_{c0} \), \( B_0 \), \( k \) and \( b \) are all constants determined by superconducting materials defined, here \( J_{c0}=4.9 \times 10^{10} \text{A/m}^2 \), \( B_0=32.5 \text{mT} \), \( k=0.275 \), \( b=0.6 \).

The instantaneous AC loss \( q \) (in-unit W) of the superconducting coil and the conducting copper plate is calculated as follows.

\[ q = \iiint E_0 \cdot J_c \, dv \]  

(6)

Where \( V \) is the volume of the superconducting coil and the conducting copper plate.

The energy loss \( W \) (in-unit J) of the superconducting coil and the conducting copper plate in time \( t \) is calculated as follows.

\[ W = \int_0^t q \, dt \]  

(7)

**Table 3.** Key moments in the charging and discharging process and their current sizes

| Time | Value | Current | Value |
|------|-------|---------|-------|
| \( t_1 \) | 100 s | \( I_1 \) | 111 A |
| \( t_2 \) | 150 s | \( I_2 \) | 111 A |
| \( t_3 \) | 151 s | \( I_3 \) | 55.5 A |
| \( t_4 \) | 171 s | \( I_4 \) | 55.5 A |
| \( t_5 \) | 172 s | \( I_5 \) | 27.75 A |
| \( t_6 \) | 192 s | \( I_6 \) | 27.75 A |
| \( t_7 \) | 193 s | \( I_7 \) | 0 A |
| \( t_8 \) | 293 s | \( I_8 \) | 0 A |

3.2. Analysis of computing result

Figure 3 shows the change of instantaneous current in each turn during the charging and discharging process of the system. The eight points P1–P8 in the figure correspond to the eight excitation stages of the magnet. Among them, from the origin to P1 represents the excitation phase of the magnet, P2 to P3 represents magnet first release 75 kJ, P3 to P4 represents magnet energy storage stage after the first energy release of the magnet, P4 to P5 represents magnet second release 19 kJ, P5 to P6 represents magnet energy storage stage after the second release of the magnet, P6 to P7 represents magnet third release 6 kJ, P7 to P8 represents magnet none-energy storage stage. The time and current of each stage are summarized in Table 3.

![Figure 3](image_url)

**Figure 3.** Instantaneous current in each turn during the charging and discharging process of the system.
Figure 4 shows the instantaneous AC loss of the superconducting coil during the charging and discharging process of the system. It can be seen that the loss gradually increases during the excitation process of the magnet, which is mainly hysteresis loss. During each of the three releases of energy, the coil AC loss rises suddenly and then falls rapidly due to the presence of the shielding current in the coil, which will be further analyzed later.

![Figure 4. AC losses of superconducting coils during charging and discharging of the system](image)

Figure 5 shows the instantaneous AC loss of conducting copper plate during the charging and discharging process of the system, and the vertical axis using the logarithmic coordinate system. During the excitation of the magnet, the AC loss in the copper plate first increases and then remains constant, and the value of AC loss is less than 1W. During the three releases of energy in the system, the AC loss in the copper plate rises suddenly and then falls rapidly, which is mainly caused by the eddy currents in the copper plate.

![Figure 5. AC loss of conducting copper plate during charging and discharging of the system](image)

The energy loss in the coil and copper plate can be obtained from the instantaneous loss, as shown in Figure 6. The energy loss of both increases slowly during the excitation process of the magnet, and suddenly increases during the energy release process of the system. During the whole energy storage and release process of the system, the energy loss of the superconducting coil is about 4 kJ, accounting for 4% of the total energy storage of the system. The energy loss of conducting copper plate is about 1.5 kJ, accounting for 1.5% of the total energy storage of the system. In summary, the efficiency of the energy storage system reaches 94.5% when other component losses are not considered.
Although superconducting materials have zero resistance, they still produce AC losses. In order to better understand the variation law of AC loss in the superconducting coil, the following is the in-depth analysis of the distribution law of electromagnetic field in the superconducting coil.

Figure 7 shows the distribution of magnetic flux density in the coil during the charging and discharging process of the system. The four times in the figure correspond to the time when the maximum loss of the coil occurs. From the top to the bottom in the figure are double-disc coil DP1, DP2, and DP3, respectively. Due to the symmetric boundary conditions in the model was used, the distribution of electromagnetic fields in the double-disc coil DP4, DP5 and DP6 are the same as that in the double-disc coil DP3, DP2 and DP1. The maximum magnetic field inside the coil is 1.62T, concentrated on the top of the first double-disc coil (DP1), which is the main reason that the critical current of the whole magnet is determined by the double-disc coil DP1 and DP6. As the energy of the magnet is released, the excitation current of the magnet decreases, so the maximum magnetic field of the magnet decreases.

Figure 8 shows the logarithmic distribution of the electric field intensity modulus in the magnet during the charge-discharge process of the system. It can be seen that the logarithms of the electric field intensity are all negative because the electric field is less than 1V/m. In addition, the electric field intensity of DP1 is the largest, and it is distributed on the upper and lower sides of the coil, which is similar to the distribution law of the magnetic field.
Figure 8. Logarithmic distribution of the modulus of electric field intensity in the coil ($\ln(|E_{\theta}|)$)

Figure 9. Normalized current density distribution in the coil

Figure 9 shows the normalized current density distribution in the superconducting coil during the charging and discharging process of the system, which is the same as the electric field distribution. The normalized current density of the first double-disc coil is the highest and is distributed on the upper and lower sides of the coil. During the energy release of the magnet, the normalized current density in the coil reaches its maximum value. This is mainly because the change rate of the magnetic field in the coil is large, and a large shielding current is induced in the coil. The combined effect of the shielding current and the excitation current of the coil leads to the increase of the normalized current density.

Figure 10 shows the logarithmic distribution of AC loss density in the coil during the charging and discharging of the system. It can be seen that the AC loss density of DP1 coil is the largest, and its distribution law can be explained by the distribution law of electric field intensity (figure 8) and current density (figure 9).

Figure 10. Logarithmic distribution of AC loss density in the coil ($\ln(E_{\rho}\cdot f_{\rho})$)
4. Conclusions

In this paper, the geometric parameters of the solenoid type magnet for 100 kJ HTS SMES system are optimized. The AC losses of the single solenoid type HTS magnet model have established using the T-A method. Based on this model, the AC losses of HTS coil and cold conducting copper plate in the process of energy storage and energy release has been calculated and analyzed.

The study has found that during the excitation of the magnet, the AC loss of the superconducting coil increases all the time, but the loss of the conducting copper plate first increases and then remains unchanged. During the discharge of the magnet, the losses of both the superconducting coil and the copper plate rise suddenly and then fall rapidly. In the whole energy storage and energy release process of the system, the total energy loss of the superconducting coil and conducting copper plate is about 5.5 kJ. Without considering the loss of other components, the energy storage system has an efficiency of about 94.5%. This work was supported by R&D Project of China Southern Power Grid Corporation with No.GDKJXM20172609.

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