The model coil manufacture and AC losses analysis of a 100-MJ HTS SMES

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Abstract. The second generation of high temperature superconducting (HTS) strip has the outstanding characteristics of high critical temperature, high load current density and high critical magnetic field, so the HTS coils wound 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 HTS magnetic energy storage system (SMES), this paper conducts the modelling and simulation research on the ac losses of a 100-MJ toroid-type HTS SMES. Firstly, the geometric structure of the system are introduced. Then, the ac loss models of HTS coils and the non-superconducting components in the energy storage system are established by H-formulation and A-formulation, respectively. Based on both the models, we calculate the ac losses of HTS coils and related components during the process of energy storage and release. Finally, the model coils are winded and impregnated to show the structure.

1. Introduction

Magnetic energy storage system is a device that stores electric energy in the form of magnetic field energy. As known, the higher inductance and the larger current density as well as the more compact structure can obtain the higher energy storage density. In addition, the smaller the coil resistance, the higher the energy storage efficiency of the system. Since the 2G High temperature superconducting (HTS) strip, e.g., YBCO strip, has the unique characteristics of high critical temperature, large critical current density and strong critical magnetic field, the HTS coil made by the strip has high critical current at relatively high operating temperature, so it is very suitable for superconducting magnetic energy storage system (SMES).

The energy storage system can be divided into two kinds of toroid-type and solenoid-type structures. Compared with the solenoid-type structure, the toroid-type one has higher energy storage capacity and can better meet the actual demand. Therefore, a lot of researches were carried out on this toroid-type SMES [1], [2].

The design optimization of the toroid-type SMES is of significant importance, and substantial researches have been conducted [3], [4]. The genetic algorithm (GA) was applied to carry out the configuration and shape optimization of HTS coil [5]. Besides, a multi-modal optimization technique has been developed to conduct the design optimization of a 2.5-MJ class toroid-type SMES magnets [6]. Moreover, the frequency stabilization of a toroid-type SMES
was also analyzed numerically [7] and the stress distribution inside the HTS coil for a conduction cooling toroidal-type SMES magnet has been studied [8].

At present, the optimization design of the HTS coils for application of toroid-type SMES has attracted rich researches, but the research on the ac losses is relatively short [9]. However, the ac loss is one of the important factors that affect the efficiency of energy storage system; therefore, in this paper, the ac losses of HTS coil for a 100-MJ toroid-type SMES will be studied considering the process of charging and discharging of the system.

2. AC losses modelling of the designed toroid-type SMES

2.1. Geometric structure

The SMES mainly including superconducting coils, conduction cooling plate, stainless steel skeleton and current lead line. Considering the geometric symmetry and electromagnetic field symmetry of the energy storage system, the appropriate boundary conditions can simplify the modeling domain and reduce the number of mesh. In this paper, two symmetric boundary conditions and a perfect magnetic conductor boundary condition are adopted. The calculation model established here is shown in Figure 1. Figure 1(a) corresponds to the ac loss calculation model of the HTS coil, and Figure 1(b) corresponds to one of the non-superconducting components. Among them, the superconducting coil adopts the swept meshes and the non-superconducting components adopt the free tetrahedral meshes.

![Figure 1. AC loss models of the HTS coil (a) and the non-superconducting components (b).](image)

**Table 1.** Key parameters of the HTS coil

| Parameter                      | Value   |
|-------------------------------|---------|
| Superconducting layer         | YBCO    |
| Width of strip (mm)           | 12      |
| Thickness of strip (mm)       | 0.1     |
| Critical current at 20 K (A)  | 1750    |
| Length of strip (km)          | 154     |
| Number of turn per coil       | 618     |
| Number of coil                | 78      |
| Inductance (H)                | 6.9     |
| Operating current (A)         | 780     |
| Operating temperature (K)     | 20      |

2.2. Governing equation

The H-formulation with the introduction of homogenized technique was used to calculate the ac losses of the HTS coil. The governing equation of the H-formulation is,
\[ \nabla \times (\rho \nabla \times \mathbf{H}) = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}, \]  
(1)

Here, \(\mu_0\) is the vacuum permeability.

The nonlinear resistivity of superconducting coil is,

\[ \rho = \frac{E_c}{J_{c0}} \left( \frac{J}{J_{c0}} \right)^{n-1} \]  
(2)

Here, \(E_c = 10^{-4} \text{ Vm}^{-1}\), \(n = 21\), \(J_{c0} = 1.41 \times 10^9\).

The instantaneous ac loss \(q\) (unit: W) is calculated as follows.

\[ q = \iiint_V \mathbf{E} \cdot \mathbf{J} \, dv \]  
(3)

Here, \(V\) is the volume of the HTS coil or the non-superconducting components.

Within time \(t\), the energy loss \(W\) (unit: J) is calculated as follows.

\[ W = \int_0^t q \, dt \]  
(4)

The operating processes of HTS coil are: (1) the coil is charged to the operating current and then remain constant; (2) the power output is conducted according to the power commands of 50 MW and 20 MW respectively; (3) each power command is maintained for 1 s. The operating current of each turn of the superconducting wire is 780 A (the external current lead current is 5460 A). After 50-MJ release energy, the current per turn of the coil drops to 552 A. After 20-MJ release energy, the current per turn of the coil drops to 428 A. Figure 2 shows the operating current in each turn of the coil during the energy release process, and Table 2 gives these values for each moment.

![Figure 2. Operating current of the HTS coil during the whole operating process of the system.](image)

**Table 2. Moments during the whole operating process**

| Moment | \(t_1\) | \(t_2\) | \(t_3\) | \(t_4\) | \(t_5\) | \(t_6\) |
|--------|--------|--------|--------|--------|--------|--------|
| Values | 45 s   | 105 s  | 106 s  | 120 s  | 121 s  | 130 s  |
3. Results and discussion

3.1. Electromagnetic distributions

Figure 3 shows the magnetic field distributions of the different components at $t_1$. It can be seen that the maximum magnetic fields inside the HTS coil, copper plate are about 11.38 T, 11.64 T respectively. During the system energy release process, these magnetic fields gradually decrease due to decrease of the exciting current of HTS coil.

![Figure 3. Magnetic flux density distributions of the different components.](image)

Figure 4 shows the current density distributions inside the different components at $t_1$. One can find that the normalized current density of the HTS coil is about 1, indicating that the operating current of the coil is below the critical current, ensuring its safe operation. The current densities inside these normal conductors are in $10^7$ order, which is induced by the varying magnetic field generated by the HTS coil. In particular, the current density inside copper plate is larger than those of the stainless steel skeleton and current lead line, since the copper plate is closer to the HTS coil.

![Figure 4. Current density distributions of the different components.](image)
3.2. AC losses

Figure 5 shows the instantaneous ac losses inside the different components. During the excitation process, the loss of HTS coil increases rapidly to 28 W, and then decreases to 0.8 W after the excitation. At instant $t_2$, the energy storage system releases 50 MJ, and the coil loss rises rapidly, reaching a maximum value at 6.4 W (corresponding time $t = 106$ s). At instant $t_4$, the system releases 20 MJ, and the loss rises rapidly again, reaching a maximum value at 10 W (corresponding time $t = 121$ s). The reason why the ac loss in the second release is larger than one in the first release may be owing to the larger hysteresis loss in the HTS coil.

The ac losses of the copper plate and stainless steel skeleton are presented in Figure 5(b) and (c), respectively. During the excitation process, the losses of the copper plate and stainless steel skeleton increase rapidly to 63 W and 32 W, respectively, and then remain unchanged. At the end of the excitation, both the losses reduce to 0 W. During the energy release, both the loss rises rapidly, firstly reaching the maximum losses of 10 kW in copper plate and 5.1 kW in stainless steel skeleton; secondly reaching the maximum losses of 2.7 kW in copper plate and 1.45 kW in stainless steel skeleton. Both the losses at the second release energy are smaller than the first one because the coil current become smaller.

The loss of the current lead line is presented in Figure 5(d), where the loss includes the ac loss and dc loss. During the excitation process, the losses of the current lead gradually increases to 1.84 kW and then remains unchanged. During the energy release, the losses rapidly drops to 925 W and then to 555 W. Since the dc loss of the current lead is proportional to the square of transport current, the greater the current, the greater the dc loss. Compared with the dc loss, the ac loss of current lead line will be negligible.

Based on the instantaneous ac losses of each component, the total energy losses of each component can be calculated. It should be noted that since the symmetric boundary conditions were used in the model, the number of each component in the SMES need to be considered. It can be concluded that the storage energy efficiency of the developed toroid-type SMES reaches 94%, which can satisfy the actual requirement.
3.3. Model coil manufacture

Based on the structure above, the model coils are manufactured. Each coil is impregnated with wax to avoid the delamination according to the impregnation experiment with different impregnation material. The coils are showed in Figure 6. After the test, there is no degradation with the performance of YBCO tape.

Figure 5. AC losses inside the different components.

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Figure 6. The model coils manufacture

4. Conclusions

The ac loss models of a toroid-type SMES were established based on the H-formulation for the HTS coil component and A-formulation for normal conductor components. The conclusions are summarized as follows.

During the excitation process, there is large ac losses generated in the non-superconducting components, which is comparable with one generated by the HTS coil. Among them, the loss in the
copper plate is the highest one since the copper plate is closer to the HTS coil or subjected to a stronger magnetic field. The calculated results show that the storage energy efficiency of the developed toroid-type SMES reaches 94%, which can satisfy the actual requirement. The model coils are also made to show the details structure.

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