AC Loss Analysis of a Single-Solenoid HTS SMES Based on H-formulation

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Abstract. There will be much AC loss generated when a superconducting magnetic energy storage (SMES) is applied in a power system to exchange power with a power network or other equipment. AC loss may cause the instability and risk of burnout to SMES. This paper presents a commonly used SMES design scheme and lists the design parameters of a 10MJ/5MW SMES. We used the finite element software COMSOL to build a simulation model to calculate the AC loss during its operation. We get the calculated results and analyse AC loss’s distribution characteristics of the 10MJ/5MW SMES which uses a single screw structure.

1. Introduction
Production and consumption of power in the power system must be dynamically balanced in real time. Energy storage devices store electric energy, and provide users electric energy whenever and wherever they need it in the future, thus realizing the transfer of electric energy in time and space. Therefore, the application of energy storage technology to the power system will bring root and branch reforms to this traditional mode [1,2]. SMES uses superconducting coils to store energy of the power network in the form of electromagnetic energy, and then release the stored energy to the network or other devices when it is needed. Compared with other energy storage technologies, SMES has the advantages such as fast response speed, active and reactive power are adjustable in four quadrants and so on [3]. It can improve the stability of power system, improve power quality, and can be used as distributed power system and energy management [1,4,5]. SMES works in a DC state without power switching, so it doesn’t have resistance and have no AC loss at this time in theory [6]. However, when SMES exchange energy with power network or other devices, it will generate much AC loss. AC loss of magnet is one of the main heat sources of magnet heating. It will cause instability to SMES’s operation, so AC loss analysis is one of the most important and complex research topics in the design of superconducting power devices. The purpose of this paper is to design a 10MJ/5MW SMES and study its’ AC loss characteristics during discharge.

In this paper, we designed the discharge mode of 10MJ/5MW single-solenoïd SMES, obtained the AC loss it generated during discharge by establishing simulation model with the finite element simulation software COMSOL and analyse the distribution characteristics of SMES’s AC loss.

2. Structure design
We choose the YBCO strip produced by Shanghai Superconducting Company to design this SMES. The width of this strip is 4mm and its’ thickness is 0.5mm while considering the insulation layer and the reinforcement layer. The curve of this strip’s critical current at 20K is shown in figure 1.
Commonly used structures of SMES are single screw, multi solenoid and ring magnet [2]. Each structure has its own electromagnetic and mechanical properties. Single-solenoid magnet is the simplest structure and also the most widely used design method. In this paper, we choose this structure to design the SMES we needed. Its’ top view of this structure is shown in following figure.

The energy-storage target designed in this paper is 10MJ. We use genetic algorithm to optimize the conductor length of magnet with single-solenoid structure. And we obtain a series of optimized magnet parameters by electromagnetic optimization calculation which can make the needed length of the superconducting strip least [6]. Optimization results are shown as following: the inner diameter of the magnet coil is 500 mm, number of double-pancakes (consisted of two single pancakes) is 32, number of a coil turns N is 512 and the working current of a coil is 257A. The outer radius of each double-pancake magnet is 740mm, and we wind two strips in parallel.

In superconducting magnetic energy storage system, energy stored in magnet can be expressed by equation 1[7], and the power of energy release can be expressed by equation 2. If inductance of the magnet is too large, voltage of the magnet will be extremely large, which will bring a great burden to the insulation design of the magnet and the selection of the converter. For this reason, we have connected superconducting coils in parallel to effectively increase the current and reduce the voltage of magnet at the same time.

\[ W = \frac{1}{2} \cdot L \cdot I^2 \]  \hspace{1cm} (1)
\[ P = U \cdot I \]  \hspace{1cm} (2)

Coils connected in parallel must be in same magnetic field to make their flowing current as same as possible. For a single-solenoid SMES, the magnetic field distribution is symmetrical up and down, so coils in the symmetrical position that have the same magnetic field configuration can be connected in parallel.

Coil of the magnet are connected with another one whose position is symmetrical with it in parallel and connect with other coils and then connected to the converter in series. The circuit topology is shown in Figure 3, where L1, L2…L32 are number of coils in the magnet from top to bottom in turn.
Fig. 3. Parallel structure diagram of superconducting coil

Table I Parameters of single solenoid magnet

| Parameters                  | Size       |
|-----------------------------|------------|
| Inner radius                | 500mm      |
| Outer radius                | 740mm      |
| Number of double-pancake    | 32         |
| Turns of single-pancake     | 512        |
| Strip width                 | 4mm        |
| Distance between double cakes| 5mm        |

Working current of the single-solenoid magnet is 514A and the inductance is 76.12H. The power of discharge we need of the SMES is 5MW, so we can control it discharge for two times. Working current of the magnet after the first discharge is 382.05A, and current after the second discharge is 326.42A. The maximum terminal voltage of the SMES is 11.78kV during the whole discharge process.

3. Simulation Model

Finite element method has been widely used to calculate current density, AC loss and magnetic field distribution of high temperature superconductor (HTS)[8]. The nonlinear E-J characteristic is introduced into the equation as the material property of superconducting material and the equation need to be solved is Maxwell equation [9,10]. According to Maxwell equations, the current density distribution and electric field distribution of superconducting strip can be calculated, and then AC loss of superconductor can be obtained by volume integral of current density and electric field which is shown as equation 3[11].

\[
Q = \int E \cdot J dS
\]

Theoretically speaking, whether it is superconducting strip, coil or magnet, AC loss can be obtained by calculating Maxwell equations after establishing the superconducting E-J relationship. The electromagnetic field characteristics of HTS magnets are extremely complex, and size of HTS tape is millimeter or hundreds of microns while the volume of coils or magnets is generally in the order of meters. So if we build model for every HTS strips in the process of establishing the simulation model for magnet, the large aspect ratio brings great challenge to subsequent numerical discretization and meshing. Moreover, HTS magnets maybe have tens of thousands of turns. It is necessary to impose separate constraints on each turn coil if we use the method mentioned above. Thousands of constraints also add great difficulty to the numerical calculation. In addition, the anisotropy of electromagnetic properties of HTS strips makes it impossible to take every strip into account when we build model for a large magnet [12,13].

To reduce degree of calculation's freedom, V.M.R.Zermo and F.Grilli of KIT Institute in Germany proposed a Homogenization Method in 2013. In this method, the adjacent several turns of a superconducting coil are equivalent to an "engineering turn" and adopt special distribution [13]. This
method greatly reduces the total degree of calculation’s freedom and guarantees a higher calculation accuracy [12,14,15]. According to the proposed homogenization method, we adopt Bulk approximation which have anisotropy and extended it to the two-dimensional axial-symmetric model.

For these reasons mentioned above, in order to reduce amount and complexity of computation, we build a two-dimension axial-symmetrical model of magnet by homogenization method. Because the magnetic field distribution of single-solenoid magnet is symmetrical, we build simulation model for one fourth of the cross-section of magnet in order to further accelerate the calculation speed. We set the boundary constraints as \( H_r = 0 \) at the boundary of air domain and \( H_r \) is the intensity of magnetic field in vertical field [13]. The geometric model of a single-solenoid magnet is shown in Figure 4. Cross-section diagrams of 16 double-pancakes are shown in it. The cross-section of each coil is re-divided into 38 engineering turns by means of logarithmic symmetry. The magnet parameters used in this simulation model are shown in table I.

![Fig.4. Homogenization model of single screw magnet](image1)

The superconducting domain of this model is partitioned by mapping, and the remaining air domain is partitioned by free triangle as shown in Figure 5. Mapping partitioning can reduce the degree of freedom and speed up the calculation. When partition the superconducting domain by mapping, we symmetrically divide HTS domain into 25 segments in the direction of coil thickness according to the sequence of equal difference.

### 4. Calculated results

#### 4.1 Operation Loss

The operation conditions of 10MJ SMES are as following: the magnet is charged to working current and then on standby, and then output energy according to the power instructions of 4.5MW and 1.5MW respectively. Each power instruction lasts for 1 second. The working current per turn of superconducting coil is 128.54A, and it will reduce to 94.58A after 4.5MW energy release, and 81.7A after 1.5MW energy release. Fig. 6 is the waveform of magnet’s working current in its’ energy release process.
Figure 7 shows the instantaneous AC loss waveform of a single-solenoid magnet in the process of energy release. Figure 8 shows the magnetic field distribution during this process. Figure 7 shows that there are two loss peaks in the process of energy release. The first peak is at 4.269s, and its’ instantaneous loss reaches 5447.4W. The corresponding point on current waveform is the inflection point from state of standby to the first energy release. The second peak is at 6.269s. Its’ instantaneous AC loss reaches 4510.6W, and the corresponding point on current waveform is the inflection point from state of the second energy release to standby. It is known that when SMES’s working current changes, the loss of magnet tends to rise greatly.

AC loss of the single-solenoid magnet in the whole process of energy release is about 7 kJ, and the loss ratio of each double-pancake is shown in Figure 9. The horizontal ordinate is the serial number of double-pancakes in different positions, and the longitudinal coordinate is the ratio of AC loss generated by a double-pancake to total loss of the magnet. It can be seen from the diagram that the AC loss of single-solenoid magnet is mainly distributed at two end of the magnet. The four double-pancakes at two end of the magnet account for 51.5% of the total loss the magnet generated, and the eight double-pancakes at two end account for 74.4% of the total loss. Therefore, the design of cooling system that provide an operation environment for SMES especially needs to focus on the refrigeration of pancakes that are at magnet’s two end.
5. Summary
This paper designs a single-solenoid 10MJ/5MW SMES. The structure of this SMES is optimized by genetic algorithm, and a set of optimized structure parameters of the magnet with minimal wire usage are obtained by electromagnetic optimization calculation. We proposed the winding mode of superconducting coils, designed the parallel connection between double-pancakes at symmetrical position, and designed the discharge mode of this magnet. At the same time, based on the above design parameters, we use the finite element simulation software COMSOL to establish a simulation model for this single-solenoid SMES. We obtain the AC loss generated in SMES during its operation by simulation, analyse the distribution characteristics of AC losses in SMES. And we can conclude two key information: 1) it is easy to produce large AC loss when the current in SMES changes. And the AC loss will be larger if the current changes more quickly. 2) most of the AC loss generated in SMES comes from the HTS pancakes at two ends of the magnet, so we need to focus on the refrigeration of pancakes that are at magnet’s two ends. The research results of this paper lay a theoretical foundation for the development of 10MJ HTS SMES, which is of great practical significance for superconducting power technology.

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