Magnet design of 10MJ multiple solenoids SMES

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Abstract. The superconducting magnetic energy storage system uses the superconducting coil to store the energy of the grid in the form of electromagnetic energy, and then release the electromagnetic energy to the power grid or other devices when needed. Compared with other energy storage technologies, superconducting magnetic energy storage systems have the advantages of fast response, adjustable active and reactive four quadrants, it can improve the stability and quality of power system, and be used for dispersion in power systems, power system and energy management. This paper mainly introduces the magnet design of four-screw SMES in 10 MJ class, including performance analysis, modular and parallel design scheme and AC loss calculation.

1. Introduction
In the traditional mode of power system, the production and consumption of electric energy must be dynamically balanced in real time. The energy storage device stores the electric energy, and the user can use the electric energy at any time and any place in the future when needed, thereby realizing the transfer of electric energy in time and space. Therefore, the application of energy storage technology to the power system will bring more fundamental changes to this traditional model. According to the type of conversion of electrical energy, energy storage technologies are mainly divided into electromagnetic energy storage, physical energy storage and chemical energy storage. Electromagnetic energy storage includes superconducting magnetic energy storage (SMES), super capacitor energy storage and super battery energy storage. The physical energy storage includes flywheel energy storage[1], compressed air energy storage, pumped storage energy and high temperature lava energy storage, etc. Chemical energy storage includes battery storage for lithium-ion batteries, flow batteries, lead-acid batteries, and sodium-sulfur batteries.

The superconducting magnetic energy storage system uses the superconducting coil to store the energy of the grid in the form of electromagnetic energy, and then release the electromagnetic energy to the power grid or other devices when needed. Compared with other energy storage technologies, superconducting magnetic energy storage systems have the advantages of fast response, adjustable active and reactive four quadrants, it can improve power system stability and power quality, and be used for dispersion in power systems, power system and energy management[2].

2. Magnet design program

2.1. Magnet design flow
The optimized design of commonly used superconducting magnets mainly includes the determination of optimization targets, the initialization of magnet parameters, the selection of optimization
algorithms, the setting of constraints, and post-processing[3,4]. In the design process of HTS SMES[5-10], the influence of different energy and power requirements on SMES is mainly reflected in the AC loss of the coil. Therefore, in addition to the requirements of energy storage and economy, the coil design of the HTS SMES should also evaluate the AC loss during power exchange of the SMES. The basic steps of the coil design of a high temperature superconducting energy storage system are as follows:

1. The optimization variables, objective functions, and constraints are set according to the energy storage requirements of the designed SMES. First, determine the independent variables to be optimized in the design of the HTS coil, such as the inner diameter of the coil, the number of turns, the number of double cakes and other parameters. Secondly, the objective function and constraints are determined, for example, the length of the superconducting tape used to achieve a certain energy storage is optimized. The constraint condition includes that the radius of the superconducting coil is larger than the minimum bending radius of the superconducting strip, and the operating current of the superconducting coil does not exceed the critical current of the coil. When the superconducting coil is operated at the maximum operating current, the stress of the superconducting strip is less than the critical value of the strip stress, etc.

2. The genetic algorithm is used to optimize the parameters of the superconducting coil several times, and the optimization results are screened. Since the genetic algorithm is a random optimization method, the optimization result may be slightly different each time. A series of optimization results will be obtained after multiple parallel optimizations. The characteristic of these optimization results is that a variety of different independent variable value combinations can obtain an approximate optimal target.

3. According to the power exchange requirements of the designed SMES, the AC loss calculation model of the coil is established, and the AC loss characteristic of the superconducting coil is calculated.

2.2. Magnet optimization

![Diagram](image-url)
The magnet design adopts YBCO strip produced by Shanghai Superconductor Co., Ltd., the strip width is 4mm, considering the insulation layer and the reinforcement layer design, the strip thickness is 0.5mm, and the critical current data of the strip 20K is shown in figure 2.

The energy storage target is set to 10MJ. The length of the wires is optimized by genetic algorithm. The working temperature of the magnet is 20 K. The critical current of the magnet is the Ic-B curve and it is tested at 20K. The load line is determined. In the calculation of the critical current of high temperature superconducting magnets, the influence of magnetic field and stress on the critical current is considered. The maximum allowable current value of the superconducting magnet under different magnetic fields is obtained by electromagnetic coupling analysis. Stress analysis is used to check mechanical stability requirements. If mechanical stability is met, this current is defined as the initial critical current of the superconducting magnet as a reference for the operating current of the magnet in subsequent analyses. Otherwise, during each iteration, the allowable operating current value will be reduced by 3% until the mechanical stability requirements are met.

The genetic algorithm is used to optimize the energy storage requirements, and the minimum amount of line is used as the optimization target, and the mechanical stress and structural parameters are checked. The optimization results for the 10MJ four-screw magnet parameters are shown in Table I. The double-cake coil adopts a double-wound method, and the working current can reach 309.8A.

The magnetic field and stress distribution of the magnet can be seen in figure 3, where (a)(b)(c)(d) is the perpendicular magnetic field of the magnet, parallel magnetic field, radial stress and hoop stress distribution.

![Figure 2 The critical current data of the strip 20K](image)

![Figure 3 Magnetic field and stress distribution](image)

| Category                        | Value       |
|---------------------------------|-------------|
| Inner radius of coil            | 470mm       |
| Turns of the coil               | 650         |
| Number of the double coils      | 14×4        |
| Distance between adjacent coils | 180mm       |
| Maximum vertical magnetic field | 2.84T       |
| Maximum parallel magnetic field | 4.2T        |
| Operational current             | 309.8A      |
| Line quantity                   | 177.2km     |
| Circumferential stress          | 3.1MPa      |
2.3. Modular design program

In a HTS SMES, the stored energy of the magnet can be expressed by Equation 1, and the discharge energy of the magnet can be expressed by Equation 2. If the inductance of the magnet is very small, the voltage at both ends of the magnet will increase, which will increase burden on the insulation design of the magnet and the converter. One way to reduce the voltage of the magnet is to increase the current by paralleling, but the current sharing problem in the parallel connection is not easy to solve; the other method is to modularize the magnet to reduce the inductance of each module unit magnet, thereby reducing Voltage.

\[ W = \frac{1}{2} LI^2 \]  
\[ P = UI \]  

When grouping magnets, you need to distribute them as evenly as possible. This is not just the same number of groups, but also the same magnetic field environment. Since the upper and lower sides of the solenoid type magnet are symmetrical, the four-solenoid magnet has two modular solutions. One is divided into four modules, that is, each single solenoid magnet is used as one module; the other is divided into eight modules, and the upper and lower portions of each single solenoid magnet are divided into two groups.

The operating condition of the designed 10MJ magnet is to output 6MJ of energy at a constant power of 4.5MW and 1.5MW per second after the magnet is charged to the operating current. The power and current waveforms of this process are shown in figure 5.

| Category | Value |
|----------|-------|
|          |       |

Table II  
Four modular operating parameters of 4-solenoid magnets (Single module)
The working current of the magnet is 309.8A, and the maximum voltage of the magnet and the converter during the discharge process is 4.87kV. The operating parameters of the eight-modular magnet are shown in Table III. During the discharge, the maximum voltage of the magnet and the converter is halved to become 2.44kV.

2.4. AC loss calculation

The current commercial superconducting tape is not a single material, but a complex composite material. In addition to the superconducting material itself, it also includes a large number of auxiliary materials, such as substrate materials, materials that enhance mechanical stability. Therefore, it is difficult to calculate the AC loss of this composite material from the perspective of superconducting tape. On the other hand, it is quite complicated in terms of the AC loss factor that affects the superconductor itself[11,12]. For example, the transmission current passing through the superconductor, the magnitude of the magnetic field received by the superconductor, the direction of the magnetic field, and the critical parameters of the superconductor itself (critical current, n value, and their relationship under the magnetic field) all affect the value of the AC loss[13-15].
For superconducting magnets, the calculation of AC loss is more complicated. In the through-flow state of the superconducting magnet, the magnetic field is extremely complicated. When the energy storage magnet is subjected to power exchange, the current waveform is changed, and it is difficult to evaluate the AC loss of the magnet by a general mathematical analysis method. The emergence of the finite element method (FEM) provides us with a new way to solve the AC loss of superconducting magnets [16,17].

In this paper, the H-equation method [18,19] with high usage rate is used to calculate the AC loss of the magnet. In order to speed up the calculation, the model adopts a homogenization modeling method.

Figure 6 shows the instantaneous loss waveform of a single solenoid magnet during the release process. It can be seen from the figure that there are two loss peaks in the phase-release energy of the magnet. The first peak is at 2 s and the instantaneous loss reaches 4826.8 W. The current waveform enters the inflection point of the 4.5MW release phase from the working current phase; the second peak is at 3s, and the instantaneous loss reaches 3828W, corresponding to the inflection point of the current waveform reaching the stable phase after 1.5MW release.

![Figure 5: Current waveform of discharge process](image1)

![Figure 6: AC loss of four solenoid magnets](image2)

![Figure 7: Loss distribution of four solenoid magnets](image3)
The AC loss generated by the magnet during the entire energy release process is about 6.2 kJ, and the loss of the double coil in the process is as shown in figure 7. As can be seen from the figure, the AC loss of the single solenoid magnet is mainly concentrated at the end of the magnet, wherein the four double cakes at the end account for 74.3% of the total loss of the magnet, and the six double cakes at the end account for 88.2% of the total loss of the magnet.

3. Conclusion
This article mainly introduces the electromagnetic design process and design results of the 10MJ-class multi-spiral SMES magnet. Calculate the main parameters of the magnet and the value of the AC loss during operation. Research shows that when designing large-capacity superconducting SMES magnets, the multi-module design method can effectively reduce the terminal voltage of the magnet, thus reducing the difficulty of magnet insulation design. This provides an idea for the design of large-capacity superconducting magnets.

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