Fabrication of HTS dc Bias Coil for 35kV/90MVA SFCL

Jing-Yin Zhang, Wei-Zhi Gong, Zheng-Jian Cao, Hui Hong, Bo Tian, Yang Wang, Jian-Zhong Wang, Xiao-Ye Niu, and Ying Xin

Abstract—For a saturated iron core fault current limiter, superconductor is the only suitable material to make the dc bias coil, especially when the device is used in a high voltage power grid. Commonly, superconducting wires are used to wind the dc bias coil. Since the performance of the wires changes greatly under magnetic fields, the calculation of the field spatial distraction is essential to the optimization of the superconducting magnet. A superconducting coil with 141000 ampere-turns magnetizing capacity made of 17600 meters of BSCCO 2223 HTS tapes was fabricated. This coil was built for a 35kV/90MVA saturated iron-core fault current limiter. Computer simulations on magnetic field distribution were carried out to optimize the structural design, and experiments were done to verify the performance of the coil. The configuration and the key parameters of the coil will be reported in this paper.

Index Terms—HTS coil, superconducting fault current limiter, superconducting magnets.

1. Introduction

All the devices in electric power networks are designed and scaled in order to withstand a given maximum short-circuit current. The continuing growth of energy consumption creates a pressing demand for huge amount of power to be generated and subsequently transported, which may result in short-circuit currents exceeding the maximum values. Unfortunately, there are few options to deal with the short-circuit currents.

People have been attempting to find better solutions for fault current control through the application of superconductors since 1970’s. After the discovery of high temperature superconductors (HTS) in the late 1980’s, there was a particular push in R&D programs of superconductor fault current limiters (SFCL)\(^{[1][4]}\).

Saturated iron-core superconductor fault current limiter (SISFCL) is one type of SFCL that has been researched\(^ {4[5]}\). Fig. 1 is a schematic of a single phase SISFCL circuit. In this configuration, a superconducting dc bias coil is used to supply ampere-turns to change the iron core’s magnetizing state. The ac windings are connected to the grid in series. During normal operation in power transmission, the dc ampere-turns are sufficient to keep the iron cores in a permanent, deeply saturated state, so that the ac windings act as air-corn reactors, and therefore, grid voltage drops on them are low. When the fault comes, the ac amplitude becomes much greater than normal, and the dc ampere-turns can no longer maintain the iron core in a permanent deeply saturated state. This causes great inductive voltages to appear in the ac windings that can remarkably hinder the fault current.

Unlike some other kinds of SFCLs which resist current surges through their superconducting components directly, SISFCL resists the surge through its copper ac coils. This eliminates complications caused by the large amount of heat generated during the quench of superconductivity in the fault limiting process, making it more suitable for power grids of high voltages.

In a SISCFL, a bias coil made of ordinary conductors would require a considerable volume and sustain unacceptable energy losses. Superconductors, which have zero resistance and large current-carrying capacity, represent the best option for the material of this part.

It is a well known fact that the critical current \(I_c\) of superconducting wires changes with the magnetic field density. In the design and optimization of a superconducting magnet in a moderate field, the spatial distribution of the field must be considered when evaluating the actual current carrying capacity of the wires.

In this paper, the design, fabrication, key parameters, and performance of a bias coil for a SISFCL are introduced. The SISFCL was designed to limit the maximum fault current from 40 kA to 20 kA in a 35 kV transmission line. This device has been installed in Puji substation of China Southern Power Grid, and its first phase trail operation has been successfully completed in last December.
Table 1 gives the main parameters of the superconducting coil. The dc bias coil is a solenoid composed of 44 individual rings with a frame made from a composite of fiberglass and epoxy resin. The 44 rings are assigned into 5 sets, which consist of 10 rings, 9 rings, 5 rings, 10 rings, and 10 rings, respectively. The rings in each set are connected in series. In order to lower the induction voltage, the 5 sets are connected to each other in parallel.

Table 1: Parameters of the superconducting coil

<table>
<thead>
<tr>
<th>Items</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter (mm)</td>
<td>1,240</td>
</tr>
<tr>
<td>Outer diameter (mm)</td>
<td>1,380</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>880</td>
</tr>
<tr>
<td>Rated current (A)</td>
<td>300</td>
</tr>
<tr>
<td>Total amp-turn</td>
<td>141,000</td>
</tr>
<tr>
<td>Number of rings</td>
<td>44</td>
</tr>
</tbody>
</table>

The coil supplies sufficient ampere-turns to satisfy the SISFCL’s requirement, and parallel connection greatly enhances the stability and reliability of the coil assembly as long as the joint resistance is small enough. The arrangement of the rings is mainly dependent on the simulated spatial distribution of the magnetic field.

3. Tape Arrangement

The coil is made of the superconducting wires Bi2223/Ag\(^6\)[17], and its \(I_c\) is severely influenced by the magnetic field, especially by the component of the field that is perpendicular to the tape surface. For instance, the \(I_c\) reduces to about 30% when the field perpendicular to the tape surface is 0.1 T, and reduces to about 20% when the field is up to 0.15 T.

The results of magnetic simulation on the dc coil are shown in Fig. 2. According to these results, the interior field of the coil is mainly in the axial direction, while the radial field is focused at the two ends of the coil\(^8\). The closer the position is to the frame, the stronger the radial field is. Radial field is very small at the center of the coil, and increases towards the ends with a maximum value of 0.08 T appearing at the edges of the coil ends. The required \(I_c\) of the rings at different positions in the coil would vary according to the radial field distribution.

In our design, HTS tapes with values of \(I_c\) varying from 85 A to 145 A were used to wind the rings. Each ring was wound using two tapes with lengths of 200 m, which were connected either in parallel or in series. For the parallel winding, the rings had a higher \(I_c\) and about 50 turns, while with series winding, the rings had a lower \(I_c\) and about 100 turns. The \(I_c\) value of each ring was measured in order to determine the most suitable position for the ring.

The arrangement of 44 rings is shown in Fig. 3. The 44 rings were divided into 5 sets. The 5 thick columns denote the calculated minimum \(I_c\) required for the rings at different positions of the coil. The 5 thick columns denote the measured \(I_c\) of rings in the 5 sets. The numbers of rings in the sets do not need to be the same, but the numbers of turns in these sets do need to be the same in order to have the same induction voltage and avoid uneven inductive current circling among different sets. All the rings have enough \(I_c\) margins so that the whole current capacity of the coil could be ensured.
Because of the influence of the magnetic field, it is unnecessary to make a superconducting coil with same kind of wire. By taking economic factor into account, hybrid wires may be a better option. The wires can come from different manufacturers, and can even be a mixture of first and second generation wires.

<table>
<thead>
<tr>
<th>Set ID</th>
<th>No. of rings</th>
<th>( I_c ) (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>10</td>
<td>&gt;60</td>
</tr>
<tr>
<td>b</td>
<td>9</td>
<td>55</td>
</tr>
<tr>
<td>c</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>d</td>
<td>10</td>
<td>&gt;60</td>
</tr>
<tr>
<td>e</td>
<td>10</td>
<td>&gt;60</td>
</tr>
</tbody>
</table>

### Table 2: Parameters of sets

#### 4. Parallel Connection of the Sets

In our design, the five sets of rings were connected in parallel. Parallel connection has two advantages compared with series connection.

Firstly, parallel connection can generate a tremendous effect on minimizing the total inductive voltage of the coil. Since this dc coil couples with ac coils through the iron core, the inductive voltage can not be offset completely. In our case, the inductive voltage is only one fifth of that in the series connection.

When fault current comes, there is an inductive voltage surge in the dc bias coil, which can be described by

\[
u = R I_0 \exp(-ct) \exp\left(-\frac{R}{L}t\right)
\]

where \( u \) stands for the transient voltage impacting on the dc coil, \( R \) is the resistance of controlling circuit, \( I_0 \) is the total current in the coil in the normal state; \( c \) stands for the ratio of resistance to inductance in the coil, which is unrelated with the connection mode, \( L \) is the inductance of the coil, and \( t \) represents time. Only \( L \) can be changed by the connection mode. Obviously, the smaller \( L \) is, the lower the surge voltage would be.

<table>
<thead>
<tr>
<th>Set ID</th>
<th>( R ) (Ω at normal temperature)</th>
<th>( R ) (mΩ at 77K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>33.3</td>
<td>0.14</td>
</tr>
<tr>
<td>b</td>
<td>39.7</td>
<td>0.16</td>
</tr>
<tr>
<td>c</td>
<td>65.8</td>
<td>0.24</td>
</tr>
<tr>
<td>d</td>
<td>34.3</td>
<td>0.15</td>
</tr>
<tr>
<td>e</td>
<td>32.8</td>
<td>0.21</td>
</tr>
</tbody>
</table>

#### Table 3: Resistance of the sets

Secondly, parallel connection can enhance the current-carrying capacity and stability of the coil through not only the set resistances but also a so-called current self-adjusting phenomenon.

The set resistances are shown in Table 3. At 77 K, the joint resistances of sets range from 0.14 mΩ to 0.24 mΩ, because of differing joint types and numbers. This results in uneven current in the parallel branches. Set c has the highest resistance, so the smallest current would pass through it. This inhomogeneous current distribution is acceptable for a dc bias coil and is even beneficial to the magnetization ability of the coil. According to the \( I_c \) values, Set c is the weakest set, so its resistance would go up quickly when current is beyond 50 A. If parallel connection was adopted, the current through Set c would be self confined to 50 A, and the overflow current could be shared by other sets with higher \( I_c \), making the coil robust.

In our previous experiments we have revealed that when two superconductor rings with different values of \( I_c \) are connected in parallel, if the joint resistance is small enough, the total \( I_c \) is close to the sum of the \( I_c \) of each rings. Since the increasing resistance of a branch in the critical state strongly depresses the current rise, the additional current is pushed to other branch. We call this phenomenon current self-adjusting. Because of current self-adjusting, when the total current needs to be increased to enhance the magnetization ability of the coil, the surplus current would pass through sets other than Set c, which improves the coil stability.

Fig. 4 is a photograph of the completed superconducting coil. Experiments were carried out to test the performance of the coil. When the sets were connected in series, the coil quenched at 62 A. When the sets were connected in parallel, a test current of 300 A was kept running for 2 h, then the current was increased to 350 A for 30 min. No trace of quench was observed in the entire testing process. This result demonstrates that the current-carrying capacity and magnetization power of the coil can be significantly improved by parallel connection.

![Fig. 4. Superconducting coil.](image)

The parallel connection needs a larger dc supply than series connection; fortunately, a suitable dc source is available in practice.

Fig. 5 is a photograph of the assembled SISFCL which was installed for the first phase trial operation in a practical grid, as shown in Fig. 6. The trial operation was executed successfully last December.
5. Conclusions

A superconductive coil with 141,000 ampere-turns magnetizing power, made of 17,600 meters of BSCCO 2223 HTS tapes, was designed and fabricated as a component for building our 35kV/90MVA SFCL. The 17,600 meters of HTS tapes were wound into 44 individual rings comprised of five different sets. For the most efficient use of HTS tapes, the positions of the rings were configured according to the $I_c$ values of the rings and the calculated field distribution. To minimize the hazard of induced voltage, the five sets were connected in parallel. The parallel connection is advantaged to enhance the performance of the coil. It is believed that the current going through each of the five sets can be self-adjusting, allowing higher $I_c$ sets to have larger current flows.

References


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