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Manufacture and test of the dc superconducting coil for a 220kV/300MVA SFCL

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Abstract

A 220kV/300MVA saturated iron-core superconductive fault current limiter (SI-SFCL) had been manufactured and factory test had been completed by September 2011. The superconducting coil was wounded using 17km BSCCO tapes. The height of the coil is about 0.9m, the OD is 2.08m, and the total magnetizing is about 176000 ampere-turns. The fundamental section of the coil is the 45 superconducting double-pancakes, which are divided into five groups. In each group, the pancakes are connected in series, while these five groups are connected in parallel to form the whole coil. In this way, the current could self-adjust within the groups, thus the critical current of the coil can be optimized. This configuration also allows us to arrange the pancakes with different Ics into appropriate positions as the magnetic field distribution of the coil is considered. In real operation, the magnetization and demagnetization are the most important working states of the magnetization circuit. As we know, there is massive energy stored in the iron core, while the time spent on either charging or discharging the iron core by the superconducting coil is required as short as possible in order to be compatible with the grid’s relay settings. Thus high-speed and controllable energy charging and releasing mechanism is introduced to the system.

This article introduces the manufacture, the key specifications and the magnetization and demagnetization test results of the superconducting coil for the 220kV/300MVA SFCL.

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Key word: superconducting coil; superconductive fault current limiter; energy releasing; magnetization

1. Introduction

A 220kV/300MVA SI-SFCL had been successfully manufactured and factory tested by September, 2011. The main structure of the SI-SFCL is shown in fig. 1. This six-legged giant spider-like structure, similar to that of the 35kV SFCL we accomplished in 2007, is called three-phase-in-one and loose-coupled structure [1]. There are three key components in the structure: the dc superconductor coil with its dewar, the iron core, and the ac coils with their oil tanks. Six iron frames are conjugated to form the hexagonal backbone of the structure. The superconductor dc coil encloses the central vertical column, which consists of six limbs from six iron frames. Two ac windings are arranged in one oil tank as one phase coil. Three oil tanks are used for the 3 phase device.

The superconducting bias coil is used for magnetizing all the six iron frames. During normal power transmission, the iron core are fully saturated, thus the SFCL has low impedance. While a short-circuit fault happens, the dc circuit...
will be switched open and the iron core will be de-saturated, so high impedance appears on the SFCL, limiting the fault current. After this action, the dc coil must be recharged and the device needs to be restored quickly. Therefore, the performance of charging and discharging for the dc coil is very important in the SFCL’s operation.

This paper focuses on two aspects: (a) the structure and design of the 220kV SFCL’s dc coil; (b) the factory performance tests, including discharging and recharging tests.

Fig. 1. The structure of the 220kV SI-SFCL

2. Structure and design of the superconductor coil

The dc coil consists of 45 BSCCO double-pancakes, shown in fig. 2. Every 9 pancakes are connected in series as one group. There are five groups altogether, which are connected in parallel. All the connectors between the pancakes are silver foils. Two copper leads are used as the electrodes and are connected with the dc power supply circuit.

The skeleton of the pancakes is made of FRP. Each FRP ring is composed of several parts which are glued together, so the deformation caused by temperature changing can be mostly avoided. The structural parameters of the superconducting coil are listed in table 1.

Fig. 2. The overall view of the superconducting magnet

Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID (mm)</td>
<td>1920</td>
</tr>
<tr>
<td>OD (mm)</td>
<td>2080</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>900</td>
</tr>
<tr>
<td>Total magnetizing capacity (kA-turn)</td>
<td>176</td>
</tr>
<tr>
<td>Effective turns</td>
<td>504</td>
</tr>
<tr>
<td>Rated current (A)</td>
<td>300</td>
</tr>
<tr>
<td>Number of double-pancake</td>
<td>45</td>
</tr>
<tr>
<td>The total length of tapes (km)</td>
<td>16</td>
</tr>
<tr>
<td>The total weight of the coil (kg)</td>
<td>800</td>
</tr>
</tbody>
</table>
Since the superconducting coil holds six iron limbs in its center and is set in the windows of the six iron frames, its size is mainly determined by the whole structural parameters of the 220kV SFCL. There is a simple rule for the iron frame design, the smaller the better. This means that to shorten the magnetic path of the iron frames not only can greatly enhance the function of magnetization, but also can save some manufacturing cost. For this purpose, the height of the superconductor coil should be as smaller as possible. However there are also several other boundary conditions for designing the coil.

The first boundary needed to be considered is the ampere-turns of the dc coil. According to the simulation results, in order to guarantee a deep saturated state of the iron core, in the 220kV SFCL the dc bias ampere-turns should be at least twice of ac ampere-turns during normal power transmission. For this reason, the dc ampere-turns must be no less than 150000 ampere-turns. The second condition is the \( I_c \) of the superconducting tapes used to make the coil. The \( I_c \) of a tape in the coil is about one-third of its original (self field) value due to the presence of the magnetic field generated by other pancakes in the coil. The third condition is the diameter of the coil, which is set according to the size of the central iron column.

The arrangement of the 45 pancakes in the superconductor coil was optimized according to their \( I_c \)'s and the magnetic field distribution. As the simulation results, along the axis of the coil, the vertical magnetic field to the surface of the HTS tape becomes larger when approaching both ends of the coil, and the maximum value is about 0.12T. So pancakes with lower \( I_c \)'s were placed at the middle part of the coil, while those with the highest \( I_c \)'s were put at the ends of the coil.

3. Performance tests

3.1. \( I_c \) measurements

In the process of making the coil, we measured the \( I_c \) of each unit at different manufacture stages: (a) \( I_c \) of tapes, (b) \( I_c \) of the pancakes, (c) \( I_c \) of pancake groups, and (d) \( I_c \) of the whole coil. These measurements were necessary for the quality control and also helped us to arrange the assembly order of the pancakes. All the \( I_c \) data of single tapes, pancakes and pancake groups can be found in fig. 3, and the x-axis shows the order codes of these units.

![Fig. 3. \( I_c \) of each unit at different manufacturing stages](image)

Fig. 3 clearly shows that after the tapes were wound into pancakes, their \( I_c \)'s decreased about 40-50% from about 180A to about 100A. Besides the 3-5% processing attenuation, the main reason was the magnetic field created by other pancakes in the group. When the pancakes were assembled into the coil, the \( I_c \)'s of the groups decreased further, and only about 30\% \( I_c \) of the tape at self field could be remained. The minimum \( I_c \) of the groups was 68A, while the maximum was 74A. However, taking the advantages of parallel connection, the coil’s \( I_c \) could be as large as the sum of all the five groups’. The \( I_c \) of the coil without iron core was 350A. If the coil was holding the iron core, the \( I_c \) would be higher because most of magnetic field would be concentrated in the iron core and the field vertical to the tapes would reduce[2-3]. The magnetization capacity of this coil is greater than 176000 ampere-turns, which meets the design requirement.

3.2. Magnetization and demagnetization
The dc coil is an inductive load to the dc power supply. Its magnetization and demagnetization must go through a large energy charging or discharging process. According to the operational rules of the SFCL, these processes should be as short as possible, so there must be a high-power magnetization and short-time energy releasing mechanisms in the magnetization circuit [4-6]. The magnetization circuit has three main operation modes:

- **Low power constant current magnetization.** This operation mode is for normal power transmission. Under this mode, a constant current, generally ranged 100-300A, flowing in the dc coil and the superconducting dc coil magnetizing the iron core. The setting of the value of the constant current depends on the load current of the ac coils and is controlled by the control unit. At this state, the voltage between the two current leads of the superconductor coil is very low, just a fraction of a volt.

- **The demagnetizing mode.** This mode is for current limiting. According to design of the SFCL, as soon as a short-circuit fault takes place and fault current is greater than a set threshold, demagnetization of the iron core will start. The demagnetization mode begins with switching off the magnetization circuit by the high speed switch – IGBT. After the magnetization circuit open, the magnetic energy stored in the iron core in operation mode 1 described above will released in the form of current flowing through the piezoresistors in the energy release circuit. The excitation voltage of the piezoresistors is 5.4kV. The piezoresistors also suppress the voltage surge caused by the quick opening of the magnetizing circuit, protecting the elements of the dc magnetization circuit. The current in the energy release circuit reduces to zero in about 25 milliseconds. It should be pointed out that the demagnetization of the iron core is virtually realized in the first 5 milliseconds during which the majority of the stored magnetic energy is released.

- **High power forced magnetization.** This mode is for fast re-magnetization of the iron core after demagnetization due to a short circuit event. In most cases, the line breakers of a power grid are required to try to re-close after being opened in a short circuit fault. To accommodate this utility requirement, the SFCL must return to low impedance state before the breaker’s re-close attempt. Usually, the required restoration time is hundreds of milliseconds. Therefore, high power forced magnetization is needed for fully magnetizing the iron core in such short period of time. In our set-up, the voltage for the forced magnetization is 1200V and the time of the re-magnetization is less than 600 milliseconds.

4. Summary

As a key component of the 220kV SFCL, the superconducting coil with optimized design was fabricated and assembled with other parts of the device. The performance of the magnetization circuit can guarantee the restore time of the SFCL to satisfy the utility requirement for reclosing the line breakers after a short-circuit fault. Now, the 220kV/300MVA SFCL is installed at the substation. Field tests and in-grid live trial operation will be carried out soon. More test results and operation information about the device will be reported in the future.

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