Experimental investigation of current limiting characteristics for a novel hybrid superconducting fault current limiter (SFCL) with biased magnetic field

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Abstract. High temperature superconducting fault current limiter (SFCL) is widely considered as an effective protection for power system when the short-circuit fault currents occur. This paper proposes a novel design of a hybrid SFCL with biased magnetic field which has two-stage current limiting characteristics. This kind of SFCL limits the short current using non-inductive superconducting coil at the first stage, and then by the double-split reactor at the second stage, usually 10 ms later. The advantage of this type of SFCL is saving the amount of superconducting tapes, and it is especially attractive in large current and high voltage occasions. A prototype hybrid SFCL with biased magnetic field is designed and constructed in China Electric Power Research Institute (CEPRI) using YBCO coated conductor. A high speed Data Acquisition (DAQ) System based on LABVIEW is established to monitor and control the SFCL. The current limiting ratios for this prototype SFCL have been investigated experimentally under the operating temperature of 77 K. The experimental results show that the current limiting ratio reaches to 89.66% which validates the design and proves the potential application of this hybrid SFCL.

1. Introduction
With the growth of urban city, the fault currents of power grid in central city areas are increasing sharply. These fault currents are approaching the capacity of the general circuit breaker and it is hard to cut the fault lines in most distribution lines, especially in the urban city [1]-[4]. Thus, high temperature superconducting fault current limiter (SFCL) has been suggested to provide effective and reliable protection for power devices under fault currents [5].

There are mainly three kinds of SFCLs applied in the power system according to the current limiting mode, the resistive-type SFCLs, the inductive SFCLs and the hybrid SFCLs combining the resistive-type and the inductive type [6]. A resistive-type 10 kV SFCL produced by AmpaCity Project was tested in the Germany power system in Essen in 2014. A 24 kV/1 kA SFCL has been fabricated to meet the specific requirements of two hosting utilities, Endesa in Spain and VSE in Slovakia. In 2015, a 11 kV/30 MVA SFCL has been put into operation at Western Power Distribution’s primary substation in Birmingham, United Kingdom [7]. A 220 kV/0.8 kA saturated core inductive SFCL manufactured by InnoPower was applied in Tianjin substation, China. It could limit the fault current of...
50 kA rms to 30 kA rms. After that, a 500 kV/1800 MVA single phase saturated core inductive SFCL was tested in China Southern Power Grid Corporation in 2016 [8].

In this paper, a hybrid SFCL with biased magnetic field is proposed to investigate the fault current limiting performance. The operation principle of the hybrid SFCL is introduced in Section II. Then, the double-split reactor and a novel non-inductive high temperature superconducting (HTS) unit are designed based on finite element model in Section III. A prototype hybrid SFCL with biased magnetic field is integrated combined with the double-split reactor, the non-inductive HTS magnet and a fast circuit breaker. Finally, an experiment system including a SFCL, AC voltage power source, load and a high speed Data Acquisition (DAQ) and Monitoring System is setup to test the current limiting performance of the prototype SFCL.

2. Working principle of the novel hybrid SFCL

2.1. Construction

This novel hybrid SFCL with biased magnetic field includes three parts: (1) a double-split reactor with copper coils. It has two branches of $L_1$ and $L_2$ ($L_1 = L_2 = L$) and the two branches have a reverse connection at the same ends, which means the impedance of the reactor is zero under normal operation; (2) a non-inductive HTS magnet; and (3) a fast circuit breaker $S_1$. $Z_{load}$ is the impedance of the line load and $Z_{line}$ is the impedance of transmission line, as shown in Figure 1.

2.2. Operation principle

When the SFCL is in normal operation mode, the impedances of double-split reactor and non-inductive HTS unit are zero. Thus, the currents in two branches are equal, which means $i_1 = i_2$. However, when the fault occurs in the transmission line, the circuit current $i$ increases rapidly and the branch currents, $i_1$ and $i_2$, increase as well. When $i_2$ exceeds the critical current of non-inductive superconducting magnet, the resistance of HTS magnet rises sharply and leads to most current offsets to branch $L_1$ [9]. At this moment, the magnetic field is biased in the double-split reactor. This is the first stage of limiting fault current which is based on the non-linear resistance of superconducting magnet. When the resistance of HTS magnet reaches to a certain quench value, $S_1$ is triggered to open, usually 10 ms after the short-circuit fault takes place. Therefore, branch $L_2$ is isolated from the circuit and only branch $L_1$ is still connected. Then the impedance of branch $L_1$ limits the fault current further in the second stage until the circuit breaker $S_2$ is open.

Compared with a resistive SFCL, this hybrid SFCL has advantages of less superconducting material cost, better current limiting effect, more stability and faster recovery, since the superconducting magnet quenches and is isolated after the first half cycle. Then branch $L_1$ limits the fault current further to the rated breaking current of circuit breaker $S_2$ which cuts the circuit finally.
3. Design and construction

3.1. The double-split reactor

The 3D schematic diagram of the double-split reactor is shown in Figure 2. There are four copper coils (I, II, III, IV) in a tank with full of the electric insulating oil, branch \( L_1 \) includes coil I and IV, branch \( L_2 \) include coil II and III. An iron yoke surrounds the outside of these coils and acts as a shield layer. The 3D finite element model of the reactor is established and the magnetic flux distribution under the normal operation is shown in Figure 3. We find that the magnetic field in the center of these coils is canceled out so that the parallel inductance of the double-split reactor is very small. The maximum magnetic flux density is 20.826 mT and it is between the inner and outer coils. There is little magnetic field outside the shield layer.

This reactor capacity \( S \) can be expressed by (1)

\[
S = I^2X = I^2\omega M
\]  

Where, \( I \) is the current through the reactor coil; \( \omega \) is the angular frequency (rad/s); \( M \) is the parallel inductance of branch \( L_1 \) and \( L_2 \) (H).

Based on the FEM analysis, the structure parameters of the coil I to IV in the reactor are shown in Table 1. The inductance parameters are calculated as well. The self-inductance of each branch is 5.31 mH, the mutual inductance is 4.84 mH, the coupling coefficient \( m_c \) is 0.847 and the parallel inductance is 0.437 mH.

| Structure parameter                                      | Value  |
|---------------------------------------------------------|--------|
| Single coil turns                                       | 61     |
| Single coil height/ mm                                  | 245    |
| Inner diameter of inner coil (Coil I and III) / mm       | 420    |
| Outer diameter of inner coil (Coil I and III) / mm       | 456    |
| Inner diameter of outer coil (Coil II and IV) / mm       | 502    |
| Outer diameter of outer coil (Coil II and IV) / mm       | 538    |
| Thickness of iron yoke / mm                             | 50     |
| Width of iron yoke / mm                                 | 450    |
3.2. The non-inductive HTS unit

The novel non-inductive superconducting current limiting unit applies S shape bending structure, consisting of a straight section and a bend section [10]. Two HTS tapes are connected in parallel and bent into an S shape. There is a joint at the terminals of two HTS tapes. Therefore, the current in two HTS tape are in opposite directions, shown in Figure 4. Figure 5 is magnetic field distribution at the bending position in the non-inductive HTS unit. The magnetic flux density is very small because the two superconducting tapes have the opposite currents. Therefore, the HTS unit can achieve non-inductive performance. The magnetic parameters of non-inductive HTS unit are shown in Table 2.

Then, superconducting units can be stacked in the vertical direction to construct a non-inductive HTS magnet based on the resistance requirement for current limiting.

![Figure 4. Topology of S-bending non-inductive HTS unit.](image)

![Figure 5. Magnetic flux density distribution in non-inductive HTS unit.](image)

| Items                  | Value |
|------------------------|-------|
| Inductance/ \(\mu \) H | 89.44 |
| Resistance/ mΩ        | 4.56  |

3.3. Integration of the hybrid SFCL

A prototype hybrid SFCL has been integrated by a double split reactor, a non-inductive HTS magnet and a fast circuit breaker. The double-split reactor with four coils connecting in inverse direction has been manufactured, shown in Figure 6. Ten non-inductive HTS units using YBCO coated conductor considering the prefabrication requirements have been connected in series to form a non-inductive HTS magnet, shown in Figure 7. The non-inductive HTS magnet has been immersed in a dewar and cooled by liquid nitrogen. Therefore, the heat load can be removed by the liquid nitrogen.
4. Test and analysis

4.1. The experiment principle
The experimental platform for current limiting test includes a voltage power source, a line load, a double-split reactor, a non-inductive HTS magnet and three fast circuit breakers of $S_1$, $S_2$, $S_3$, shown in Figure 8. In Figure 8, the dashed box is the fault current limiter. In the experiment, the host computer gives order to trigger a short-circuit fault by closing $S_3$. The monitoring system collects two branch voltages, $V_1$ and $V_2$, of double-split reactor, the voltage of non-inductive superconducting magnet, and two branch currents of SFCL, $i_1$ and $i_2$ in real time. The SFCL current limiting ratio test platform would also be able to test the circuit current without the SFCL, where the dashed box is removed from the testing platform [11] in Figure 8.

4.2. The experimental platform
This current limiting experimental test has two stages. Firstly, we setup the platform without SFCL and measure the circuit voltage and current under a short-circuit fault condition. Then the SFCL is connected into the circuit to limit the fault current under the same fault condition. Figure 9 is the photo of the whole experimental platform in CEPRI.
4.3. Results analysis

The experiment is carried out by triggering a short-circuit fault and cutting the power quickly. The current and voltage of the non-inductive superconducting magnet and the double-split reactor are measured. Therefore, the voltage-current curve of non-inductive HTS magnet can be obtained. During the process, all the operation would be finished within 10 ms, including the fault trigger, stepped limiting and isolation of SFCL. The circuit current limiting ratio $k$ is defined as

$$k = \left( \frac{i_{\text{fault}} - i_{\text{lim}}}{i_{\text{fault}}} \right)$$

From Figure 10, without SFCL, the effective value of short-circuit current is 1300 A. However, when using SFCL, the effective value of short-circuit current is 735.5 A at the first half wave of circuit current, therefore the current limiting ratio $k$ is $\left( 1300 - 735.5 \right) / 1300 = 43.4\%$. Then, at the second half wave of circuit current, the effective value of short-circuit current is 134.37 A, so the current limiting ratio $k$ is $\left( 1300 - 134.37 \right) / 1300 = 89.66\%$. This SFCL achieves the current limiting very well based on two-stage design.

5. Conclusion
This paper proposes a new current limiting configuration based on self-triggering and magnetic field offset principle. This configuration includes a non-inductive superconducting magnet with S-shape bending superconducting coils, a highly coupled double-split reactor using four crossover copper windings and a fast circuit breaker. We verify the topology by constructing a 10 kV SFCL prototype and test it under liquid nitrogen temperature. The result shows that it limits the fault current gradually and the maximum current limiting ratio can reach to 89.66%.

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Acknowledgments
All of the authors would like to acknowledge the financial support from National Natural Science Foundation of China under Grant of 51907180.