Current limiting characteristics of a magnetic shielding type Superconducting Fault Current Limiter of REBCO pancake coils

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Abstract. Superconducting Fault Current Limiters (SFCLs) are installed in the electric power system, and expected to limit fault current and improve system stability. In this paper, we focus on the transformer magnetic shielding type SFCL made of REBCO wires. This SFCL limits fault current mainly with reactance for small fault current. When fault current gets larger, resistance component is added and a larger impedance is generated. In this time, we fabricated the transformer type SFCL composed of pancake coils and investigated the basic characteristics. The pancake coil type has the advantage that the amount of superconducting wire is less and the size of SFCL becomes smaller than solenoid coil type. As the results of experiment, it was confirmed that SFCL limits fault current with reactance and resistance properly. Regarding the current limiting impedance, it almost agreed with the designed value, and confirmed the current limiting operation as expected.

1. Introduction

In recent years, many distributed generations using sustainable energy such as solar power generation have been interconnected with the power system. As a result, power systems have become larger scale and more complicated. Along with this, the large fault current and the decrease of the power system stability becomes serious problems.

Superconducting Fault Current Limiter (SFCL) is expected as one of the useful devices to solve these problems, due to its reliable and effective fault current limiting ability [1]-[4]. The SFCL is the electricity equipment, which has low impedance in the normal state and generate large impedance in fault condition. Therefore, SFCL do not influence on power systems in steady state condition and only limits fault currents only in fault condition.

While various types of SFCLs are invented and used proper situation, our studies propose a transformer magnetic shield type SFCL. It has the REBCO primary coil and REBCO secondary coil, which are arranged coaxially. Because this SFCL mainly limits fault current with reactance component, the temperature rise occurred by joule heat is small and it quickly returns to the superconducting state in preparation for the next accident. In the previous studies, we fabricated the transformer magnetic shield type SFCL composed of REBCO solenoid coils and reported its current limiting characteristics [5]-[8]. In this paper, we newly designed transformer type SFCL composed of REBCO pancake coils and investigated the basic characteristics of SFCL.
2. Transformer Magnetic Shielding Type SFCL

2.1. Current limiting principle

The transformer magnetic shield type SFCL composed of pancake coils consists of four REBCO pancake coils which are arranged on the same axis. The two inside pancake coils are primary coils and connected to the power systems. The outer two pancake coils are secondary coils, which are short-circuited.

In the steady-state condition, both coils are in the superconducting state and the current through the secondary coil is induced to cancel the magnetic flux generated by the current of the primary coil. Therefore, the transformer type SFCL has slightly small leakage reactance in stand-by mode. When the fault current flows through the primary coil, the secondary coil turns to normal state first, which means that the induced secondary coil current exceeds its critical current. The trigger current level is defined as the primary coil current at this time and it can be designed by adjusting the turn ratio of the coils. Because of the resistance of the secondary coil wire, induced current gets saturated and the magnetic flux of the primary coil is no longer cancelled enough. Therefore, a limiting reactance appears and limits the fault current. When the fault current is much larger, the primary coil also turns to normal state and limiting resistance additionally appears. Therefore, transformer magnetic shielding type SFCL can limits the fault current effectively by both the reactance and resistance.

2.2. Equivalent circuit of the transformer type SFCL and Limiting impedance $Z_{fcl}$

Fig. 1 shows the simplified equivalent circuit of the transformer type SFCL. This circuit is equivalent to the equivalent circuit of the transformer with the short-circuited secondary coils. The impedance $Z_{fcl}$ of the transformer type SFCL is calculated by using Kirchhoff’s law and obtained as

$$Z_{fcl} = \left( R_1 + \frac{\omega^2 M^2 R_2}{R_2^2 + \omega^2 L_2^2} \right) + j\omega \left( L_1 - \frac{\omega^2 M^2 L_2}{R_2^2 + \omega^2 L_2^2} \right)$$

(1)

where $R_1$ and $R_2$ are the resistances, $L_1$ and $L_2$ are the self-inductances of the primary and secondary coil, respectively. $M$ is the mutual inductance and $\omega$ is the operating angular frequency. The real part and the imaginary part of (1) are the resistive and inductive component of $Z_{fcl}$ respectively.

Fig. 2 shows $Z_{fcl}$ as a function of $R_2$ at $R_1 = 0$. When only the secondary coil gets in the normal state, a larger reactance appears when $R_2$ is much larger than $\omega L_2$ as known from Fig. 2. Therefore, transformer type SFCL limits the fault current mainly by the reactance component. When the fault current is much larger, the primary coil also turns to normal state and $R_1$ is added to the resistance component.

Fig. 1 Equivalent circuit of the transformer type SFCL.
3. Concept of the SCFL composed of pancake coils

In previous studies, we fabricated the transformer magnetic shield type SFCL composed of REBCO solenoid coils and the basic characteristics experiments were carried out in order to obtain its limiting ability in a lab-scale system [7],[8]. In this paper, we designed and fabricated the transformer type SFCL composed of REBCO double pancake coils. By using double pancake coils, the size of the SFCL becomes smaller compared to the solenoid coil type SFCL. Therefore, the amount of superconducting wires can be reduced. Table. 1 shows the comparison of the specifications of the solenoid coil type and pancake coil type. This solenoid coil type SFCL is designed to be installed in a lab-scale power system [9]. Compared with almost the same parameters, it is confirmed that pancake coil type is smaller than solenoid coil type and the amount of wires is also less.

| Table. 1 Specifications of solenoid coil type and pancake coil type SFCL. |
|---------------------------------|-----------------|-----------------|
| Parameter                       | Solenoid coil   | Pancake coil    |
| Primary coil wire               | REBCO           | REBCO           |
| Secondary coil wire             | REBCO           | REBCO           |
| Coil diameter                   | 100 mm          | 180 mm          |
| Coil height                     | 250 mm          | 40 mm           |
| Primary coil length             | 62.8 m          | 39.8 m          |
| Secondary coil length           | 10.7 m          | 7.9 m           |
| Primary wire turns              | 50 × 4          | 5 × 9 × 2       |
| Secondary wire turns            | 17 × 2          | 1 × 9 × 2       |
| Primary inductance              | 1.38 mH         | 1.78 mH         |
| Secondary inductance            | 42.1 μH         | 40.1 μH         |
| Mutual inductance               | 229 μH          | 213 μH          |
4. Design of SFCL

The prototype model of SFCL composed of REBCO pancake coils was designed and fabricated in order to experiment in a lab-scale power system. Table. 2 shows the specifications of the REBCO wire. The critical current (0.1 μV/cm criterion, 77 K) of the REBCO wires used the primary and secondary coils is 85 A and 167 A respectively.

The Table. 3 shows the specifications of the prototype model of SFCL. Fig. 3 shows the cross section of the SFCL and Fig. 4 shows the photograph of the SFCL. The both coils are wound on the Fiber Reinforced Plastics (FRP) pipe as pancake shape of seven layers. The FRP pipe has a diagonal slit to pass the wire next to the outer layer. The primary coils are connected to the power system and secondary coils are short-circuited. The turn ratio is 5 to set the trigger current level 37.6 A. The inner and outer diameter of the SFCL is 100 mm, 160 mm, respectively and the height is 40 mm to set it cryostat whose inner-diameter is 346 mm and height is about 1000 mm. The FRP plate inserted between each coils is a radial shape, which is a gap to have enough cooling area.

### Table. 2 Specifications of the REBCO wire for the transformer magnetic shielding type SFCL.

| Parameter                  | Super Power® SCS4050-AP 2G HTS |
|---------------------------|---------------------------------|
| Width                     | 4.0 mm                          |
| Total thickness           | 0.1 mm                          |
| REBCO                     | 1 μm                            |
| Copper layer              | 40 μm                           |
| Silver layer              | 3.8 μm                          |
| Hastelloy C276 layer      | 50 μm                           |
| Average n-value           | 30                              |
| Width                     | 4.0 mm                          |

### Table. 3 Specifications of SFCL.

| Parameter             | SFCL          |
|-----------------------|---------------|
| Primary coil wire     | REBCO        |
| Secondary coil wire   | REBCO        |
| Coil diameter         | 160 mm       |
| Coil height           | 40 mm        |
| Primary coil turns    | 5 × 7 × 2 turn|
| Secondary coil turns  | 1 × 7 × 2 turn|
| Primary wire length   | 28.3 m       |
| Secondary wire length | 5.72 m       |
| Primary inductance    | 684 μH       |
| Secondary inductance  | 22.5 μH      |
| Mutual inductance     | 99.9 μH      |
| Trigger current       | 37.6 A       |

![Fig. 3 The cross section diagram of the SFCL composed of pancake coils](image)
5. Experiment

5.1. Experimental Method

Fig. 5 shows the experimental circuit diagram. The circuit consists of a variable autotransformer which generates the various level of voltage, a load reactor (1.33 mH), a shunt resistor (0.25 mΩ), a magnetic switch and the SFCL. The SFCL is set in the cryostat and immersed in Liquid Nitrogen. The power source frequency is 60 Hz. When the magnetic switch closed at \( t = 0 \) s, various fault current flows through the circuit by changing the voltage level across the variable autotransformer, and the switch is opened at \( t = 0.1 \) s.

The primary coil current and the terminal voltage across the SFCL were measured. Furthermore, the fundamental waves of the terminal voltage across the SFCL and the primary coil current are obtained by the Fourier Transform and the SFCL limiting impedance is calculated for the various fault current. The current through the secondary coil cannot be measured by a shunt resistor because of short-circuited. Therefore, it is measured by a Rogowsky coil.

![Fig. 5 Experimental circuit diagram](image-url)
5.2. Experimental Results

Fig. 6 shows the terminal voltage across the SFCL, the primary coil current and the secondary coil current when the voltage across the variable autotransformer is 10 Vrms, 30 Vrms and 100 Vrms respectively.

When the voltage across the variable autotransformer is 10 Vrms, the current through the primary and secondary coil are smaller than critical current. Therefore, both coils are in the superconducting state. Due to the leakage inductance (240 μH), the SFCL generates about 2.0 V and the phase of the current through the primary coil and the terminal voltage across the SFCL is shifted by nearly 90°.

When the voltage across the variable autotransformer is 30 Vrms, the fault current gets larger than trigger current level. Thus, the secondary coil turns to the normal state while the primary coil is in the superconducting state. The peak value of fault current is reduced to 60 A from 70 A by the SFCL.

When the voltage across the variable autotransformer is 100 Vrms, both primary and secondary coil current is larger than critical current and both coils turn to the normal state. The peak value of fault current is reduced to 140 A from 240 A and limited to about 60 percent by the SFCL.

![Fig. 6 Results of in fault condition. The voltage across the variable autotransformer is (a) 10 V. (b) 30 V. (c) 100 V.](image)

Fig. 7 shows the limiting impedance for the peak primary coil current. Though both coils are in the superconducting state, 0.09 Ω reactance is appeared due to the leakage inductance. When the fault current exceeds trigger current (37.6 A), the reactance and resistance components start to appear. In this region, the reactance component is dominant. When the fault current is larger than critical current of the primary coil (85 A), resistance component increases and the SFCL limits the fault current with reactance and resistance. When the fault current exceeds 140 A, the resistance component rapidly increase due to the heat generation of wire and the fault current is limited by mainly resistance component. Finally, the reactance component saturated at about 0.25 Ω, which agrees the expected value, ωL = 0.258 Ω.

Additionally, current limiting operation can be estimated from the phase difference. Fig. 8 shows the phase difference the peak fault current. In the region 1, the phase difference is about 90° because of the leakage inductance. The phase difference is about 60° in the region 2. In this region, the reactance component is dominant. In the region 3, the phase difference decreases gradually. Therefore, the fault
current is limited by the resistance and reactance. As a result, it is confirmed that the current limiting operation was performed as designed.

![Fig. 7 Impedance for the primary coil current (peak)](image1)

![Fig. 8 Phase difference for the primary coil current (peak)](image2)

6. Conclusion
The transformer magnetic shield type SFCL composed of REBCO pancake coils was designed and fabricated. This SFCL limits the fault current mainly by reactance and much larger fault current is limited by reactance and resistance. The basic characteristics experiment was carried out and the SFCL limiting performance was investigated in terms of impedance and phase difference. As a result, it is confirmed that the SFCL limits the fault current effectively by the reactance and resistance component and the limiting impedance is matched the designed value. In terms of phase difference, the SFCL is proved to shift to the resistance and reactance limiting as the fault current increases.

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