Conceptual design of an SFCL by use of BSCCO wire

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Abstract. Superconducting fault current limiters (SFCLs) are promising devices to reduce the fault current constraint when designing and operating power systems. SFCLs must meet requirements for precise operation, operating impedance, recovery time, and so on. SFCLs using YBCO thin film or bulk BSCCO meet some of these requirements. However, it is quite difficult to satisfy the requirements of precise operation and quick recovery time. A transformer type SFCL with an adjustable trigger current level can enhance the precision of operation and fulfill the requirements for SFCLs. However, not enough impedance could be generated by use of a transformer type SFCL using Ag sheathed BSCCO wire designed in the same way as an SFCL based on NbTi. Therefore, in this paper, the relationship between the geometrical dimensions and the impedance characteristics of a newly designed transformer type SFCL is deduced from simulations.

1. Introduction
Superconducting fault current limiters (SFCLs) are expected to be installed in future power systems due to their ability to reduce fault current and make power system design and operation easier. SFCLs have high impedance in fault conditions and have very low impedance in normal conditions. There are advantages to SFCLs, such as quick operation and repetitive operation. Precise and accurate operation is required if an SFCL is to be installed on a grid. Previous studies show that a transformer type SFCL with an adjustable trigger current level can enhance the precision of operation and fulfill the specific requirements for SFCLs, such as low loss in normal operation, short recovery time, ability of repetitive use, and so on[1].

A transformer type SFCL with an adjustable trigger current level, using NbTi wire, has been proposed and a trial three-phase one was designed and manufactured[1]. It has been verified by experiments that the SFCL can set the trigger current level precisely, can be designed easily, and has good limiting and recovery characteristics for sudden short circuit faults. However, an SFCL made of low temperature superconducting (LTS) materials can be mistriggered by inrush currents and switching surges propagating from a remote substation. It is considered that there are three causes of the mistriggering. Firstly, the SFCL operates at the temperature of liquid helium (about 4K) and the heat capacity of LTS materials at this temperature is so small that it causes a rapid rise in temperature of the superconducting wire. Secondly, the n-value of LTS materials is large, and therefore the heat generated is large. Finally, due to the small heat capacity of liquid helium, cooling of the heat generated in the superconducting wire is insufficient.
SFCLs made of high temperature superconducting (HTS) materials have the possibility to overcome these problems[2]. A trial SFCL using Ag sheathed BSCCO wire was designed and manufactured[3]. It has been indicated by experiments with this trial SFCL that the SFCL using Ag sheathed BSCCO wire has feasible to avoid mistriggering by inrush currents and switching surges. However, no enough impedance could be generated by use of a transformer type SFCL using Ag sheathed BSCCO wire designed in the same way as a SFCL based on NbTi. Therefore, in this paper, the relationship between the geometrical dimensions and the impedance characteristics of a newly designed transformer type SFCL is deduced from simulations.

2. SFCL with adjustable trigger current level

2.1. Principle

A transformer type SFCL with an adjustable trigger current level has been proposed[4]. It consists of two air-core superconducting coils coupled co-axially, as shown in Figure 1. The primary coil is connected to a power system and the secondary coil is short-circuited. The secondary coil can be slid axially in order to adjust the trigger current level.

When the SFCL does not operate (‘non-operating’ mode), both coils are in the superconducting state. Most of the magnetic flux generated by the current in the primary coil is canceled by the induced current in the secondary coil. As a result, the impedance of the SFCL is small. When the current exceeds the trigger current level, only the secondary coil changes to the normal state. Thus, the induced current in the secondary coil becomes small and most of the magnetic flux of the primary coil is not canceled. As a result, the impedance of the SFCL increases and the SFCL limits the current (‘operating’ mode).

![Figure 1. Basic structure of an SFCL with adjustable trigger current level.](image)

2.2. Impedance of SFCL with adjustable trigger current level

The equivalent circuit of an SFCL with an adjustable trigger current level is shown in Figure 2, where $E_1$ is the voltage across the terminals of the SFCL, $I_1$ and $I_2$ are the current of the primary and the secondary coils, respectively. $L_1$ and $L_2$ are the self inductances of the primary and the secondary coils, respectively. $M$ is the mutual inductance and $R_2$ is the resistance of the secondary coil.

The impedance of the SFCL $Z_{FCL}$, is described as

$$Z_{FCL}(\omega) = R_{FCL}(\omega) + jX_{FCL}(\omega) = \frac{E_1(\omega)}{I_1(\omega)} = \frac{\omega^2 R_2 M^2}{R_2^2 + \omega^2 L_2^2} + j\omega \left( L_1 - \frac{\omega^2 L_2 M^2}{R_2^2 + \omega^2 L_2^2} \right)$$

(1)
from the equivalent circuit. The relationships between \( R_2 \) and the inductive component \( X_{\text{FCL}} \), and between \( R_2 \) and the resistive component \( R_{\text{FCL}} \), are derived from (1), and are shown in Figure 3. When the value of the generated \( R_2 \) is sufficiently large in the ‘operating’ mode, the value of \( Z_{\text{FCL}} \) can be approximated as \( Z_{\text{FCL}} \approx j\omega L_1 \). Thus, \( X_{\text{FCL}} \) of \( Z_{\text{FCL}} \) is sufficiently larger than \( R_{\text{FCL}} \) of \( Z_{\text{FCL}} \). Limiting by \( X_{\text{FCL}} \) can realize low heat loss and fast recovery time.

![Figure 2. Equivalent circuit of an SFCL with adjustable trigger current level.](image)

![Figure 3. Impedance of SFCL.](image)

3. Design of SFCL by use of Ag sheathed BSCCO wire

A trial SFCL using Ag sheathed BSCCO wire was designed and manufactured[3]. It has been verified by experiments with this trial SFCL, that the SFCL using Ag sheathed BSCCO wire has feasible to avoid mistriggering by inrush currents and switching surges propagating from a remote substation[3]. In the next step, a conceptual design of an SFCL for experiments in an artificial transmission line rated at 200 V was examined.

3.1. Relationship between diameter, length of coils and characteristics of SFCL

Table 1 shows the characteristics of the Ag sheathed BSCCO wire used in the simulation. Desired characteristics of an SFCL are small waiting impedance, \( Z_{\text{waiting}} \). Furthermore, as shown in Figure 4, when the current increases above the trigger current level, the impedance should saturate immediately. Impedance characteristics of an SFCL, when the diameter or length of the coils is changed, were calculated by simulation.

![Figure 4. Ideal impedance.](image)

Table 2 shows the simulation parameters and Figure 5 shows the relationship between the impedance of the SFCL and the circuit current, \( I_{\text{FCL}} \), when the diameter or length of the coils is changed. From the simulation results 1, 2 and 3 in Figure 5, for larger diameter coils, the waiting impedance becomes notably smaller because of the smaller flux leakage. From the simulation
results 1, 4 and 5, the longer length of the coils, the slightly sharper the limiting impedance becomes because of the longer wire needed; however, the effect is small.

These results suggest that a larger diameter and longer length for the coils makes the characteristics of the SFCL superior; however, the longer length makes trigger current level adjusting more difficult because for longer length, the variation of the flux linkage is smaller. In the next section, the relationship between the height of coils and the slide distance to adjust the trigger current level, $I_s$ are considered.

Table 2. Simulation parameters (No.1)

|   | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | Coil length mm | 600 | 600 | 600 | 900 | 300 |
|   | Diameter mm | 60 | 120 | 50 | 60 | 60 |
|   | Turns | 812 | 420 | 963 | 990 | 580 |
|   | Layers | 7 | 4 | 9 | 6 | 10 |
|   | Wire length m | 153 | 158 | 151 | 186 | 109 |
| 2 | Diameter mm | 50 | 110 | 40 | 50 | 50 |
|   | Turns | 345 | 190 | 430 | 440 | 260 |
|   | Layers | 4 | 2 | 4 | 3 | 5 |
|   | Wire length m | 54 | 65 | 54 | 69 | 40 |
|   | $I_2$ (at $I_1=180A$) A | 236 | 233 | 225 | 225 | 250 |

$L_1$ mH | 3.87 | 3.88 | 3.87 | 3.87 | 3.83 |
$L_2$ mH | 0.526 | 0.669 | 0.487 | 0.527 | 0.533 |
$M$ mH | 1.2 | 1.48 | 1.1 | 1.2 | 1.19 |

Figure 5. Impedance characteristics of SFCL, when diameter or length of coils is changed.

3.2. Relationship between length of coils and slide distance

In the previous section, when the length of coils is changed, the characteristics of the SFCL do not vary significantly. Therefore, the relationship between the length of the coils and the slide distance in the secondary coil in regard to trigger current level adjusting were considered. Table 3 shows the simulation parameters. Table 4 and Figure 6 show the simulation results. Figure 6 indicates that the shorter the length of the coils, the easier it is to adjust the trigger current level. Even if the HTS material is made by the same production process, their critical currents can differ up to $\pm 10\%$ due to its complicated production process. Therefore, the SFCL’s trigger current level can differ also up to $\pm 10\%$. The results indicate that the length of the coils should be less than 300mm.

Table 3. Simulation parameters (No.2)

|   | 2 | 6 | 7 | 8 |
|---|---|---|---|---|
| 1 | Coil length mm | 600 | 500 | 400 | 300 |
|   | Diameter mm | 120 | 120 | 120 | 120 |
|   | Turns | 420 | 384 | 350 | 308 |
|   | Layers | 4 | 4 | 3 | 3 |
|   | Wire length m | 158 | 145 | 132 | 116 |
| 2 | Diameter mm | 110 | 110 | 110 | 110 |
|   | Turns | 190 | 170 | 156 | 136 |
|   | Layers | 2 | 2 | 2 | 2 |
|   | Wire length m | 65 | 59 | 54 | 47 |
|   | $I_2$ (at $I_1=180A$) A | 233 | 240 | 243 | 250 |

$L_1$ mH | 3.88 | 3.83 | 3.88 | 3.87 |
$L_2$ mH | 0.669 | 0.636 | 0.654 | 0.639 |
$M$ mH | 1.48 | 1.43 | 1.46 | 1.43 |
Table 4. Relationship between slide distance, mutual inductance and trigger current level

| slide [mm] | M [mH] | I_s [A] | I_s/I_{s0} |
|-----------|--------|---------|------------|
| 2         | 1.48   | 81.36   | 1.01       |
|           | 1.47   | 81.91   | 1.01       |
|           | 1.46   | 82.47   | 1.02       |
|           | 1.45   | 83.04   | 1.03       |
|           | 1.44   | 83.62   | 1.04       |
| 6         | 1.43   | 80.06   | 1.01       |
|           | 1.42   | 80.62   | 1.01       |
|           | 1.41   | 81.2    | 1.02       |
|           | 1.4   | 81.78   | 1.03       |
|           | 1.38   | 82.96   | 1.04       |
| 7         | 1.46   | 80.63   | 1.01       |
|           | 1.45   | 81.19   | 1.01       |
|           | 1.43   | 82.32   | 1.02       |
|           | 1.42   | 82.9   | 1.03       |
|           | 1.39   | 84.69   | 1.04       |
| 8         | 1.43   | 80.43   | 1.01       |
|           | 1.42   | 81   | 1.02       |
|           | 1.4   | 82.15   | 1.03       |
|           | 1.37   | 83.95   | 1.04       |
|           | 1.33   | 86.48   | 1.05       |
|           | 1.3   | 88.47   | 1.06       |

4. Limiting simulation

Before confirming the feasibility of an SFCL for laboratory experiments, the operating characteristics and a detailed design were considered by simulation.

4.1. Simulation condition

Figure 7 shows the simulation circuit with the equivalent circuit of an SFCL. For the simulation, the Runge-Kutta method is used. The voltage $E(t)$ is 200 $V_{peak}$, the inductances $L_a$ and $L_b$ are 2.6 mH and 6.4 mH, respectively. A short circuit fault is simulated by closing the switch at $t = 0.103$ sec. Table 5 shows the size and inductances of the SFCL. The inductances $L_1$, $L_2$ and $M$ are calculated using Biot-Savart Law. The relationship between $Z_{FCL}$ and $R_2$ is shown in Figure 8.

4.2. Simulation results

The circuit current, $i_1$, and the secondary current, $i_2$, were calculated in two cases: with the SFCL and without the SFCL (Figures 9 and 10). With the SFCL, the fault current is limited from the first wave. Figure 9 indicates that the peak value of the circuit current is limited to about 60 %, from 304 A to 180 A, and the steady state value is limited to about 60 % from 240 A to 150 A.
Table 5. Dimensions and inductances of SFCL

| Primary coil | Secondary coil |
|--------------|----------------|
|              | Diameter mm    | 120/122.2 |
|              | Turns          | 310(62*5) |
|              | Layers         | 5         |
|              | Wire length m  | 117       |
| Diameter mm  | 110/111.32     |
| Turns        | 138(46*3)      |
| Layers       | 3              |
| Wire length m| 48             |
| Inductances  | L1 mH          | 3.91      |
|              | L2 mH          | 0.657     |
|              | M mH           | 1.46      |

Figure 8. Impedance characteristics of SFCL.

Figure 9. Time variation of circuit current.

Figure 10. Time variation of secondary current.

5. Conclusion
In the previous design of a transformer type SFCL using Ag sheathed BSCCO wire, not enough impedance could be generated. Therefore, in this paper, the relationship between the geometrical dimensions and the impedance characteristics of a newly designed transformer type SFCL is deduced from simulation. Simulation results indicate that the larger the diameter of coils, the smaller the waiting impedance, and the shorter the length of the coils, the easier it is to adjust the trigger current level. The simulation results show the feasibility of the designed SFCL to limit fault currents.

References
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