Conceptual Design for Transformer Type SC-FCL by use of Silver Sheathed BSCCO Wire

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Abstract. Superconducting fault current limiter (SCFCL) is a promising device to reduce the fault current constraint for designing and operating power systems. In this paper, conceptual design for transformer type SCFCL by use of silver sheathed BSCCO wire is described. The relation between geometrical parameters and the impedance in fault conditions is calculated by use of simulation, and the feasibility of SCFCL by use of silver sheathed BSCCO wire in laboratory level is confirmed.

1. Introduction
Superconducting fault current limiter (SCFCL) is expected to be installed in future power systems for their ability to reduce fault current. The previous works show that a transformer type SCFCL with adjustable trigger current level by use of NbTi wire, which is low temperature superconductor (LTS), can realize the precise operation and fulfill the significant requirements[1]. However, SCFCL made by LTS may be mis-triggered by switching surges.

On the other hand, SCFCL made by high temperature superconductor (HTS) have a possibility to solve this problem[2]. In this paper, conceptual design for transformer type SCFCL by use of silver sheathed BSCCO wire is described, and study on the feasibility of SCFCL by use of silver sheathed BSCCO wire in laboratory level is shown by use of simulation.

2. SCFCL with Adjustable Trigger Current Level
2.1. Principle
A transformer type SCFCL with adjustable trigger current level was proposed[3]. It consists of two air-core superconducting coils coupled coaxially, 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 slide axially in order to adjust the trigger current level.

When SCFCL does not operate (the waiting mode), both coils are superconducting state. Most of the magnetic flux generated by the current of the primary coil is canceled by the induced current of the secondary coil. As a result, the impedance of SCFCL is small.

Figure 1. Basic structure of SC-FCL with adjustable trigger current level
When the current exceeds the trigger current level, only the secondary coil turns into the normal state. Then, the induced current of the secondary coil becomes small and most of the magnetic flux of the primary coil does not canceled. As a result, the impedance of SCFCL increases and SCFCL limits the current (the limiting mode).

2.2. Impedance of SCFCL with Adjustable Trigger Current Level

From the equivalent circuit of SCFCL with adjustable trigger current level, the impedance of SCFCL ($Z_{FCL}$) is written as

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

where $L_1$ : the inductance of the primary coil, $R_2$ : the resistance of the secondary coil, $L_2$ : the inductance of the secondary coil and $M$ : the mutual inductance[3].

Eq.(1) gives the relations between the inductive component $X_{FCL}$ and $R_2$, and the one between the resistive component $R_{FCL}$ and $R_2$. These relations are shown in Figure 2. Figure 2 indicates that this kind of SCFCL with adjustable trigger current level can generate high impedance even though $R_2$ is low when the fault current flows through SCFCL. The property suggests the feasibility of the kind of SCFCL by use of the wire of the secondary coil with small normal resistance.

3. SCFCL by use of Silver Sheathed BSCCO Wire

3.1. Specification of BSCCO Wire

One of the most developed HTS wire is silver sheathed BSCCO wire. It has low resistance at normal conducting state. A transformer type SCFCL by use of small normal resistance may be feasible as mentioned in the previous section. However, the normal resistance of BSCCO wire is too small, then some considerations are necessary for designing a useful SCFCL by use of BSCCO wire.

3.2. Relations between Impedance of SCFCL and Self Inductances of Primary and Secondary Coils

Figure 3 shows how $Z_{FCL}$ varies with changes in $L_1$ and $L_2$.

When $L_2$ becomes larger, the peak of $R_{FCL}$ moves to the right, and the slope of the line of $R_{FCL}$ becomes smaller. On the other hand, $L_1$ becomes larger, both $X_{FCL}$ and $Z_{FCL}$ become larger. However, the leakage impedance also becomes larger.
3.3. Design of SCFCL by use of BSCCO Wire

When $R_2$ is efficiently larger than $L_2$, $Z_{FCL}$ is at most the inductive component. It is because the local maximum value of $R_{FCL}$ is shown at $R_2 = \omega L_2$. Then for good property, it is designed that $R_2$ is as large as possible and that $L_2$ is as small as possible. $M$ must be requested for small influence in the waiting mode.

For large $R_2$, the wire of the secondary coil should be long. For small $L_2$ with long wire, the radios of solenoid of the coil must be small. In addition, $L_1$ and $M$ must be large. The structure of filling the requests of SCFCL is as follows.

- The secondary coil is a long solenoid with small radios
- The secondary coil is in the primary coil

Figure 4 shows a structure of SCFCL by use of BSCCO wire. The inner secondary coil can be slide axially as the arrow, in order to adjust the trigger current.

![Figure 4. Structure of SCFCL by use of BSCCO wire](image)

4. Simulation

4.1. Conditions of Simulation

Before confirming the feasibility of SCFCL for laboratory experiment, the operating characteristic and parameters of detail design were considered by simulation. Figure 5 shows the simulation circuit with the equivalent circuit of SCFCL by use of BSCCO wire. For the simulation, Runge-Kutta method is used. The voltage $E(t)$ is 40 $V_{peak}$, the inductance $L_a$ and $L_b$ are 2.6 mH and 6.4 mH, respectively. A short-circuit fault is simulated by closing the switch at $t = 0.1079$ sec. Table 1 shows the size and inductances of SCFCL by use of BSCCO wire. The inductances $L_1$ and $L_2$ and $M$ are calculated by use of Biot-Savart Law.

![Figure 5. Simulation circuit with SCFCL by use of BSCCO wire](image)

| Table 1. Size and inductance of SCFCL by use of BSCCO wire |
|---------------------------------|
| **Primary Coil**    | Height | 600 mm |
|                     | Inner diameter | 60 mm  |
|                     | Turns     | 400    |
| **Secondary Coil**  | Height | 600 mm |
|                     | Inner diameter | 50 mm  |
|                     | Turns     | 120    |
|                     | Ag-ratio  | 2.2    |
| **Inductance**      | $L_1$   | 0.924 mH |
|                     | $L_2$   | 0.0570 mH |
|                     | $M$     | 0.207 mH  |

The relation between $R_2$ and the current through the secondary coil, which is calculated as a parallel circuit of BSCCO and silver sheath, is shown in Figure 6. The relation between $Z_{FCL}$ and $R_2$ is shown in Figure 7.
4.2. Results of Simulation

The circuit current ($i_1$) and the current through the secondary coil ($i_2$) were calculated in two cases, with SCFCL and without SCFCL, (Figure 8 and Figure 9).

5. Conclusion

SCFCL by use of silver sheathed BSCCO wire, with thin and long structure in order to make $L_2$ smaller and $R_2$ larger, has a good limiting characteristic. Then, the feasibility of SCFCL by use of silver sheathed BSCCO wire in the laboratory level is confirmed. Conditions of this simulation is set for laboratory experiment, so the fault current reduction becomes higher by changing the conditions. As a future work, design, manufacture and test of SCFCL are planned.

References

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Figure 6. Relations between resistance of secondary coil and current

Figure 7. Characteristic of impedance of SCFCL by use of BSCCO wire

Figure 8. Time variation of circuit current

Figure 9. Time variation of secondary current