

Current Limiting Characteristics of a Flux-Lock Type SFCL for a Single-Line-to-Ground Fault

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Abstract

We have fabricated an integrated three-phase flux-lock type SFCL, which consists of an YBCO($YBa_2Cu_3O_7$) thin film and a flux-lock reactor wound around an iron core of each phase. In order to apply the SFCL in a real power system, fault analyses for the three-phase system are essential. The short-circuit currents were effectively limited by adjusting the numbers of winding of each secondary coil and their winding directions. The flux flow generated in the iron core cancelled out under the normal operation due to the parallel connection between primary and secondary windings. However, the flux-lock type SFCL with same iron core was operated just after the fault due to the flux generating in the iron core. To analyze the current limiting characteristics, the additive polarity winding was compared with the subtractive one in the flux lock reactor. Whenever a single line-to-ground fault occurred in any phase, the peak value of the line current of the fault phase in the additive polarity winding increased up to about 12.87 times during the first-half cycle. On the other hand, the peak value in the subtractive polarity winding increased up to about 34.07 times under the same conditions. This is because the current flow between the primary and the secondary windings changed to additive or subtractive status according to the winding direction. We confirmed that the current limiting behavior in the additive polarity winding was more effective for a single-line-to-ground fault

Key Words : Flux-lock type SFCL, Subtractive and additive polarity winding, Current limiting

1. Introduction

The superconducting fault current limiters (SFCLs) have significant advantages over traditional fault current limiters. They can enhance reliability and stability for power systems. The SFCLs offer rapid and effective current limitation

without generating high impedances to the power system during normal operations.

Furthermore, they can quickly limit an over-current without power failure, and can automatically return to their superconducting state after relief from the fault. There are many different types of SFCLs such as the inductive, the resistive the hybrid and so on. The Flux-lock type SFCL belongs to the resistive type SFCLs, the structure of which is simple and compact[1].

In order to apply the SFCL in a real power system, fault analyses for the three-phase system are essential. A single line-to-ground fault, which

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Date of submit : 2006. 8. 9
First assessment : 2006. 8. 18
Completion of assessment : 2006. 9. 15

occupies approximately 70 percent among all fault types, is the most common. The integrated three-phase flux-lock type SFCL has significantly different operational characteristics and structure from the general quench type or the single-phase flux-lock type SFCL. The former of the three windings wound on the same iron core each of which has the same turn's ratio between the primary and secondary coils shows the operational characteristics that the fault phase affect the sound phase, which induces the YBCO films connected in series with secondary coil in each phase to be quenched. Meanwhile, the current limiting capacity and quench characteristics are changed by the winding directions in the three-phase. In this study, the operational characteristics in the three-phase system were investigated and their additive and subtractive winding directions based on a single line-to-ground fault were compared [2-4].

2. Structure and operational principle

2.1 Equivalent circuit of the flux-lock type SFCL

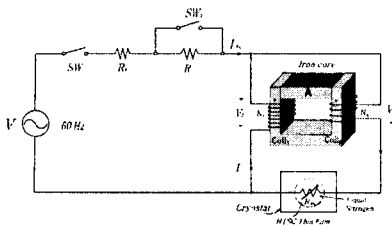


Fig. 1. Scheme diagram of the single-phase flux-lock type SFCL

As shown in Figure 1, the flux-lock type SFCL can be subdivided into three parts. The first component consists of a secondary coil, which is connected in parallel with the primary coil out of the flux-lock reactor and in series with the current

limiting component. The primary coil can be wound on the iron core to the same or opposite direction with the secondary coil. When the coils are wound as in Fig. 1, the voltages across coil 1 and coil 2 are:

$$V_1 = N_1 \frac{d\Phi}{dt}, \quad V_2 = -N_2 \frac{d\Phi}{dt} \quad (1)$$

Where $N_1:N_2$ is the turn ratio between the primary and the secondary coils, and Φ the magnetic flux linkage between the two coils. Since voltages across coil 1 and 2 are identical, equation(2) can be expressed as follows;

$$(N_1 + N_2) \cdot \frac{d\Phi}{dt} = 0 \quad (2)$$

Since the total turn numbers of the coils cannot be zero, the term 'dΦ/dt' equals zero according to Equation 2. Therefore, there is no core loss during normal operation of the SFCL: The flux generated from the primary winding is cancelled out by that from the secondary winding. This is due to the circuit wound being parallel, and the zero resistance of the YBCO (YBa₂Cu₃O₇) component. However, when the current flowing into the YBCO component exceeds its critical level after fault, resistance is generated in the component. and flux flows between the coils, and induces the current limiting behavior which effectively limit the over-current.

2.2 Operational principle

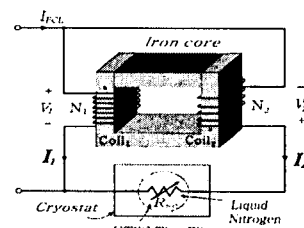


Fig. 2. Scheme in case of the subtractive polarity winding

Fig. 2 shows the subtractive polarity winding which is the reverse winding direction between the two coils. Its structure generates the opposite flux flow in the iron core after a fault. M_{12} represents the mutual-inductance between the coils through the iron core, R_{sc} represents the resistance generated in the HTSC component after its quenching. L_1 and L_2 are the self-inductances of each coil. ω is the angular frequency. I_{FCL} represents the line current. The equations for the current and voltage can be expressed as follows:

$$V_1 = j\omega L_1 \cdot I_1 - j\omega M_{12} \cdot I_2 \quad (3)$$

$$V_2 = -j\omega M_{12} \cdot I_1 + (j\omega L_2 + R_{sc}) \cdot I_2 \quad (4)$$

The additive polarity winding is in the same winding direction between the two coils. The magnetic flux with the same direction between two coils is generated by its structure. The equations for the current and voltage can be expressed as follows:

$$V_1 = j\omega L_1 \cdot I_1 + j\omega M_{12} \cdot I_2 \quad (5)$$

$$V_2 = j\omega M_{12} \cdot I_1 + (j\omega L_2 + R_{sc}) \cdot I_2 \quad (6)$$

Then, the current limiting impedance Z_{FCL} can be obtained from the circuit conditions.

$$\frac{I_{FCL}}{I_2} = \frac{j\omega L_1^2 + R_{sc}}{j\omega \cdot (L_1 + \sqrt{L_1 \cdot L_2})} \quad (7)$$

$$Z_{FCL} = \frac{j\omega L_1 \cdot R_{sc}}{j\omega \cdot (L_1 + L_2) + 2j\omega M_{12} + R_{sc}} \quad (8)$$

When the line current I_{FCL} increased up to the critical current of the component, the initial limiting current I_{INI} can be expressed as follows:

$$I_{INI} = \left(1 \pm \sqrt{\frac{L_2}{L_1}}\right) \cdot I_2 \quad (9)$$

Since the initial limiting current can be controlled by adjusting the L_1 and L_2 (between the two coils) according to equation (9), the winding directions between coils have a great influence on current limiting operation.

2.3 Equivalent circuit of the integrated three-phase flux-lock type SFCL

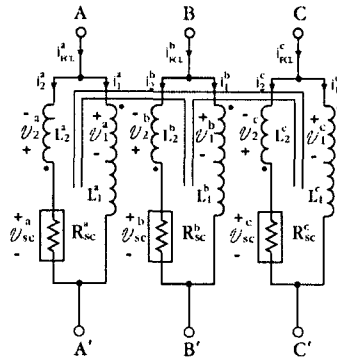


Fig. 3. Equivalent circuit of integrated three-phase flux-lock type SFCL

The equivalent circuit of the integrated three-phase flux-lock type SFCL which consists of an YBCO thin film and a flux-lock reactor wound in each single phase on the iron core is shown in Fig. 3. L_1 and L_2 represent the self-inductances between the two coils of each single phase. i_1 , i_2 and I_{FCL} are respectively the currents of the primary coil, the secondary coil and the system. N_1 and N_2 are the numbers of turns in primary and secondary coil, respectively. Where M_{11} and M_{12} are the mutual inductance between primary coils and between primary and secondary coils, respectively. Assuming that the leakage flux and the resistance of each coil can be ignored and that the normal resistances of the YBCO element R_{sc} are constant, the equations between the two coils on the phase-a in case of subtractive polarity winding can be expressed as follows:

$$x_1 = (i_1^a + i_1^b + i_1^c), x_2 = (i_2^a + i_2^b + i_2^c), x_3 = i_3^a$$

$$\begin{bmatrix} V_1^a \\ V_2^a \end{bmatrix} = \begin{bmatrix} j\omega L_1^a & -j\omega M_{12}^a & 0 \\ -j\omega M_{12}^a & j\omega L_2^a & R_{sc}^a \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad (10)$$

$$V_{sc} = (1 + \sqrt{\frac{L_2}{L_1}}) \cdot V_1 \quad (11)$$

The equations describing phase-a, phase-b, and phase-c during a three-phase subtractive and additive polarity windings can be obtained by the same method. Since the R_{sc}^a in equation (10) are nullified before the fault, the operational characteristics of the three-phase system can be similar to the single-phase system, and any phase could be affected by the others. Namely, the integrated three-phase flux-lock type SFCL before the fault come into equal effect such as the establishment of a flux-lock reactor at the individual iron core on the each phase [Please check again this sentence].

Also, the magnetic flux can be determined from Equation (11) in case of the subtractive polarity winding. N_1 and N_2 are turns of primary coil and secondary coil, respectively. In Equation(12), the “+” sign means the subtractive polarity winding and the “-” sign corresponds to the additive polarity winding.

$$V_1^a = \frac{\mu S}{\ell} N_1 [N_1 \cdot (x_1) - N_2 \cdot (x_2)] \quad (11)$$

$$V_2^a = \frac{\mu S}{\ell} N_2 [-N_1 \cdot (x_1) + N_2 \cdot (x_2)] + R_{sc}^a \cdot x_3$$

$$\phi = \frac{N_1 \cdot (x_1) - N_2 \cdot (x_2)}{R} \quad (12)$$

When the current flowing the HTSC element exceeds its critical value after a fault occurrence in any phase, the flux generated in the iron core make flux-flow not only fault-phase but also sound-phase. Therefore, the integrated three-phase flux-lock type SFCL showed the

operational characteristics that the fault phase could affect the sound phase, which induced the quenching appearance between the HTSC element in the sound phase. As a result, it can be deduced from the reliability and security viewpoint that the integrated three-phase flux-lock SFCL offers better stability for the system than the single-phase flux-lock type SFCL.

2.4 Preparation for experiments

The design parameters for the individual flux-lock reactor are shown in Table 1. The fault test in the three-phase system was used with three homogeneous flux-lock reactors, which were composed of a primary coil and a secondary coil. The coils were connected in parallel and they were wound on the same iron core in the same or opposite direction to each other. The turn ratio between the primary and the secondary coils was 63:42. In order to preserve the superconducting state, the elements were immersed into the liquid nitrogen(LN₂) bath. The values of individual critical current are shown in Table 2.

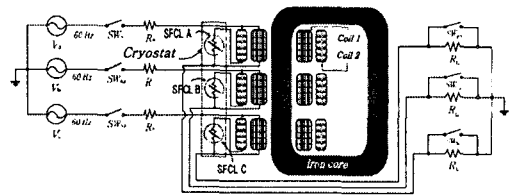


Fig. 4. Scheme of a test circuit for a single-to-ground fault in a three-phase system

Fig. 4 illustrates an experimental circuit used to test a single line-to-ground fault in a three-phase system. In order to simulate a single line-to-ground fault, the switches SW1-SWA2-SWA3 of each phase were closed during normal operation. Then the SWB1 at angle of source

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voltage was closed for the fault operation. This fault in phase-a can be called a single-line-to-ground fault.

To protect the three-phase circuit system, the switch SW_{BI} was opened after five cycle from the fault instant. The phase voltage $V_a-V_b-V_c$ was imposed by $160[V_{rms}]/60[Hz]$. A standard resistance R_0 of $1[\Omega]$ and a resistive load R_L of $50[\Omega]$ were applied in each phase. The HTSC elements of the superconducting fault current limiters connected with each phase of the experimental circuit.

Table 1. Design parameters of a flux-lock reactor

Iron core(Laminated Si)	Value	Unit
Outer horizontal length (lOX)	235	mm
Outer vertical length (lOY)	250	mm
Inner horizontal length (lIX)	137	mm
Inner vertical length (lIY)	155	mm
Thickness (d)	66	mm
Primary coil and secondary coil	Value	Unit
Turns of the primary winding(N_1)	23.2 (63)	mH (turns)
Turns of the secondary winding(N_2)	8.2 (42)	mH (turns)

Table 2. Design parameters of the SFCL units

Parameter	SFCL A	SFCL B	SFCL C
Critical current value(I_c , A)	22.63	24.13	23.41

3. Experimental results and discussions

Fig. 5 shows the operational characteristics of a single line-to-ground fault with zero ground impedance in case of the subtractive polarity winding in a three-phase system. The phase-a of a three-phase system goes to the ground through

zero impedance. The phase voltage in the fault angle of zero degree was $160[V_{rms}]/60[Hz]$.

The winding numbers of the primary coil and the secondary coil were 63 turns and 42 turns, respectively. The self inductances L_1, L_2 in each coil were $23.2[mH]$ and $8.2[mH]$, respectively. After a single line-to-ground fault occurred, the initial peak line current of the phase-a increased

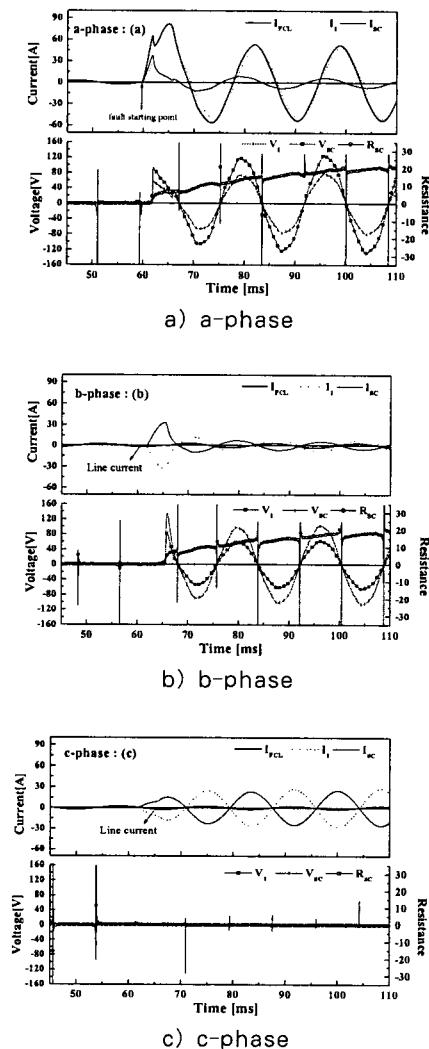


Fig. 5. Waveform in case of the subtractive polarity winding in a three-phase system ($N_1=63, N_2=42$)

for about 34.07 times during the first-half cycle. The line current of the fault phase-a was only changed due to a single-line-to-ground fault.

As shown in Fig 5(b), the current flowing into the secondary coil up to 33.35[A] at 65.30[ms] despite the line current of the phase-b being unchanged. This led to the resistance of the HTSC element. On the other hand, the integrated three-phase flux-lock type SFCL was operated just after the fault due to the flux generating in the same iron core. The initial peak voltage values of the phase-a, phase-b were 92.02[V_{rms}] at 62.09[ms] and 135.43[V_{rms}] at 65.89[ms] during the first-half cycle, respectively.

From equation (11), the calculated value of the generated voltage at the HTSC element-A was determined to be 92.51[V]. Its value from equation (11) shows the relationship between the two self-inductances. The voltage generated in phase-c was almost zero. This is certified by the voltage curve measured between the terminals of the SFCL units as shown in Fig. 5. Since the current flowing into the secondary coil and the SFCL element C didn't exceed its critical level, element C was not quenched. That is, the structure of the subtractive polarity winding didn't make enough flux which could have affected the quenching operation due to the relationship between the current flow by the magneto-motive force and the consumptive flux value ($N \cdot \Phi = L \cdot I$).

When a fault occurs, the initial limiting current in phase-a increases up to 41.06[A] at 61.07[ms]. Since its [which circuit are you referring to? Please be more precise] circuit structure reduced the flux flow after a fault, quenching operation was generated at the fault phase and the fault phase and the phase-b with current over the critical value in the secondary winding [This part of your sentence is confusing. Please check it again].

However, the secondary current in the phase-c didn't exceed the critical value. The difference between phase-b and phase-c is due to the difference in the starting point of their primary current. As a result, the quenching operation in phase-b occurred with faster flux distribution. Fig 5 illustrates that the current can be changed by each other's flux and the inductance.

Fig 6 shows the operational characteristics of a

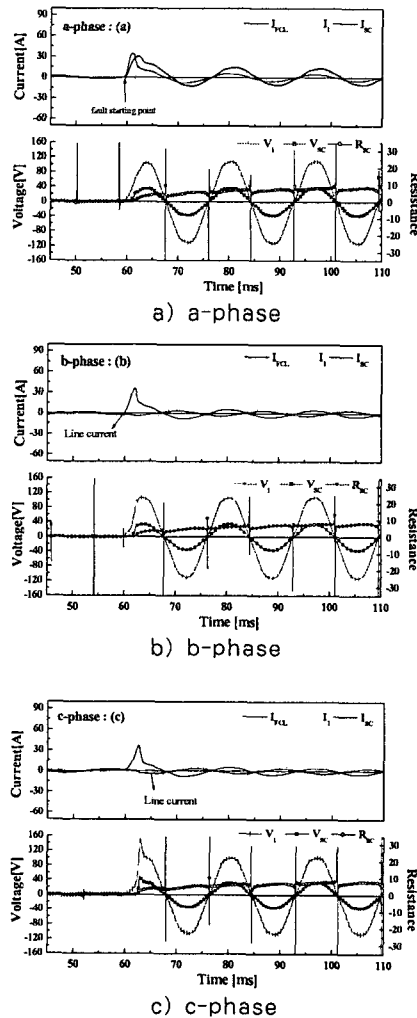


Fig. 6. Waveform in case of the additive polarity winding in a three-phase system ($N_1=63$, $N_2=42$)

single line-to-ground fault with the additive polarity winding in a three-phase system under the same conditions. When a single line-to-ground fault occurred in phase-a, the initial peak line current increased up to 31.32[A] at 62.17[ms] during the first-half cycle. The behavior of the line current in the fault phase-a was similar to the subtractive polarity winding in a single-to-ground fault.

However, as shown in Fig 6-(b), (c), the currents flowing into the secondary coil increased up to 35.83[A] at 61.91[ms] and 36.82[A] at 62.57[ms], respectively. Therefore, the voltage curves measured between the terminals of SFCL B and C were generated owing to the structure integrated with the same iron core.

Thus, when a fault in the three-phase system occurred in any one of three phases, the HTSC elements of all phases experienced current limiting operations.

The initial peak voltage of the HTSC element in the phase-a was 34.85[V] at 63.92[ms]. From Equation (11), the calculated value was determined as 42.25[V]. From the three-phase system can be controlled by adjusting the self-inductance of the primary and secondary windings [what can be controlled? Please check again]. To compare the power burden of the HTSC element and the fault current, Fig. 7 shows the resistance curves of the HTSC elements in the integrated three-phase flux-lock type SFCL using flux linkage which resulted from the winding method between the two coils. The resistance value of the HTSC element in the case of the additive polarity winding direction was lower than the subtractive polarity winding direction. In case of the subtractive polarity winding, it was determined that resistance values among HTSC elements appeared irregularly by unbalanced quenching operation according to their flux flow values

between the two coils.

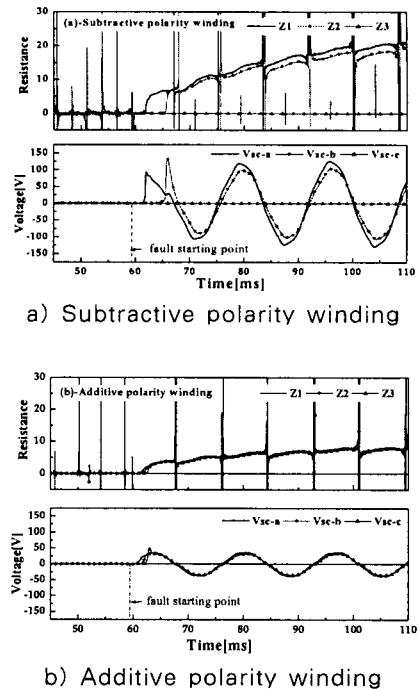


Fig. 7. Voltage and resistance characteristics

Since the HTSC element in phase-c, in case of the subtractive polarity winding was not quenched, no resistance was generated. That is, the power burden after a single line-to-ground fault instant could be affected by the winding methods. The study confirmed that the integrated flux lock type SFCL in the same iron core had the advantage to increase the power capacity because the power burden among HTSC elements was dispersed into not only fault-phase but also sound-phase owing to the flux from the same iron core.

4. Conclusion

In order to apply the SFCL in a real power system, fault analyses for the three-phase system

are essential. Thus, we investigated the current limiting characteristics of the integrated three-phase flux-lock type SFCL with a single-line-to-ground fault according to the winding method between the two coils.

The operational principle due to the flux generation in the same iron core has significant advantages before and after a fault. When a fault occurred in any phase, the flux by the same core made the flux flow in all phases which induced quenching in the HTSC elements without a fault.

Therefore, the distribution of the power burden among HTSC elements could possibly increase the power capacity by increasing the number of the quenched elements. However, the peak values of line currents in the fault phase between the subtractive and additive polarity windings were different because of the variation of the flux and inductance, respectively. The study confirmed that the additive polarity winding method was more effective than the subtractive one the current limiting characteristics for three-phase system [something is missing to connect this part to the beginning of the sentence. Please check again].

Acknowledgement

This study was supported by research funds from chosun university 2005.

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