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Analysis of Operating Characteristics According to the Change of Load Resistance of the SFCL Applied the Simulation Power System

Shin-Won Lee

Department of Computer Engineering, Jungwon University, 85 Munmuro Goesangun, Chungbuk, 367-805, Korea.

ORCID 0000-0002-4535-2996

Abstract

In the normal state, the flux-lock type superconducting fault current limiter (SFCL) generates the same voltage at both coils to cancel the magnetic flux, but in the fault state, the magnetic flux generates in both coils and the resistance generates to limit the fault current. This paper analyzes the current limiting characteristics of the fault and sound lines with varying load resistance using the flux-lock type SFCL. In addition, this paper analyzes the operating characteristics in the case of the subtractive polarity winding and the additive polarity winding according to the connection method of the two coils. The current limitation, quench and recovery characteristics in the case of the additive polarity winding improved more efficiently than in the case of the subtractive polarity winding through the simulation tests.

Keywords: Fault current, Flux-lock type SFCL, Load resistance, Operating characteristics, Short-circuit.

I. INTRODUCTION

Along with industrial development, soaring power demand and expansion of power generation facilities have accelerated the increase of fault current. If a fault current occurs in the system, it will affect the power system facilities such as protection equipment and the damage expect to be serious.

The superconducting fault current limiter (SFCL), one of the effective ways to limit the fault current, has actively researched at home and abroad, attracting attention as an alternative to solve the fault current problem [1-5]. The developed flux-lock type SFCL does not generate magnetic flux during normal operation, but instantaneous quenching occurs when the fault current flows over the critical current of the superconducting element, the resistance of the superconducting element increases, and magnetic flux generates inside the core of the iron to limit the fault current [6-8].

This paper analyzes the operating characteristics of the flux-lock type SFCL on fault lines and sound lines occurring fault current. After occurring fault, the load resistance of fault lines and sound lines and fault current limit characteristics according to the winding direction of two coils studied. The analysis of the simulation short-circuit experiments show that the case of additive polarity winding is superior to the case of subtractive polarity winding.

II. EXPERIMENTAL METHODES

II.I Equivalent Circuit Analysis

The flux-lock type SFCL is a structure in which two coils connected in parallel through a ferromagnetic iron core, and a superconducting element connected in series to one coil. Figure 1 shows the structure of the flux-lock type SFCL configured for the simulation. Depending on the direction of the coil connection, it classified into subtractive polarity winding and additive polarity winding, and the flux linkage in the iron core is increased or decreased depending on the connection direction.

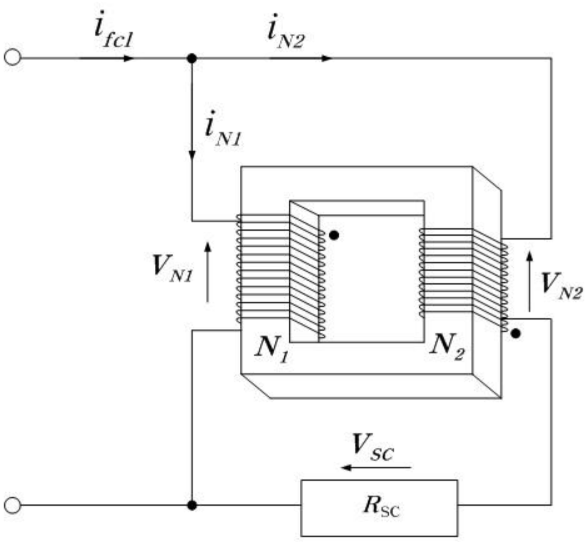

Figure 1. Structure of a flux-lock type SFCL.

In the normal state, since the superconducting element has zero resistance, the same voltage in both coils causes the magnetic flux to cancel. In the fault state, when a fault current flows higher than the critical current of the superconducting element, the superconducting element generates resistance due to the quench. At this time, the magnetic flux increased in the iron core and a resistance generated in each coil to limit the fault current.

If the voltages of coil 1 and coil 2 of the ferromagnetic iron core are V_{N1} and V_{N2}, the voltage induced in the superconducting element expressed as in Equation (1).

$$V_{SC} = (N_1 \pm N_2)\cdot\frac{d\phi}{dt} = V_{N1} \pm V_{N2} \quad (1)$$

In Equation (1), + is a case where the connection direction of the two coils is subtractive polarity winding, and - is a case where the polarity is additive polarity winding.

If the line current is i_{fcl}, the current of the primary coil is i_{N1}, and the current of the secondary coil is i_{N2}, the current of each coil expressed as in Equation (2).

$$i_{fcl} = \pm i_{N1} + i_{N2} \qquad (2)$$

II.II Experimental Device

Figure 2 shows the approximate configuration of the simulation device for measuring the current limiting characteristics of the flux-lock type SFCL. The components of the experimental apparatus and each parameter are shown in Table 1, and the superconducting current limiting element used YBCO thin film having a critical temperature and a critical current of 87 [K] and 19 [A], respectively.

Table 1. Specifications of experimental circuit with a flux-lock type SFCL.

Component	Parameter		Value	Unit
Power	Power Resistor	R_S	1.2	Ω
Line 1	Line Resistor	R_1	0.108	Ω
	Line Reactance	L_1	2.655	mH
Line 2	Line Resistor	R_2	0.104	Ω
	Line Reactance	L_2	2.562	mH
Load	Load Resistor 1	R_{L1}	51.5	Ω
	Load Resistor 2	R_{L2}	10.3, 30.9, 51.5	Ω
Flux-Lock Type SFCL	Turn Number of Two Coils	N_1	60	Turns
		N_2	15	Turns
	Critical Temperature	T_C	87	K
	Critical Current of HTSC	I_C	19	A

To simulate the fault, the power supply voltage (E_s) applied 120 [V_{rms}], and after the switch SW_1 was turned on, the switch SW_2 was operated for 5 cycles of fault, causing a short circuit accident.

In Figure 2, i_s is the current flowing through the power resistance, the current flowing in the fault line and the sound line are i_1 (=i_{fcl}) and i_2, respectively.

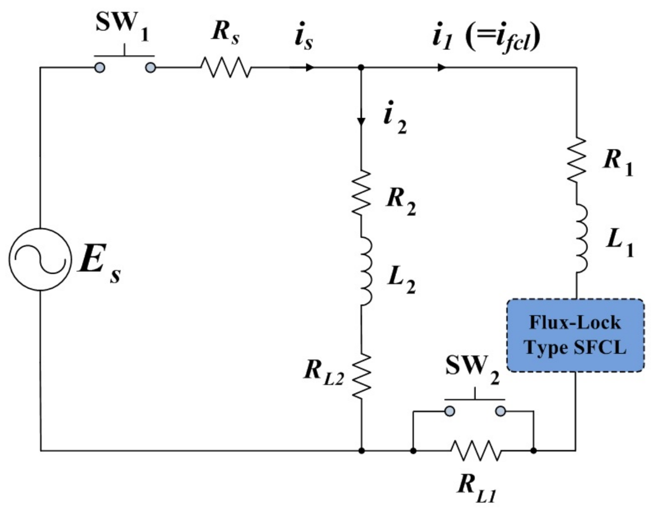

Figure 2. Experimental circuit with fault line and sound line.

III. RESULTS AND DISCUSSION

Figure 3 shows the current and voltage waveforms on the fault line and the sound line when the fault occurs no SFCL. Immediately after the fault occurred, the fault current (i_1) increased rapidly and the current limit on the fault line did not occur for 5 cycles. The small current flows in the current i_2 of the sound line. The load voltage (V_{RL1}) of the fault line shows zero voltage, and the load voltage (V_{RL2}) of the sound line shows greater than the load voltage of the fault line.

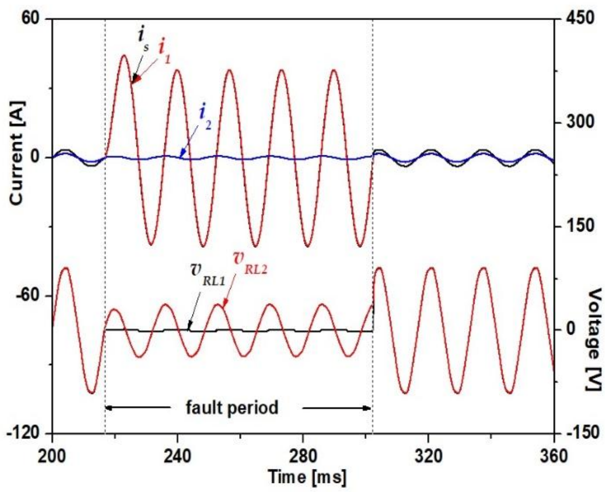

Figure 3. Current and voltage waves of fault and sound lines without a flux-lock type SFCL. (R_{L1}= 51.5Ω, R_{L2}= 51.5Ω)

Figure 4 shows the current limit and load voltage characteristics of the flux-lock type SFCL according to the wiring direction when the load resistance of the fault line and the sound line is 30.9Ω, respectively.

Figure 4 (a) shows the fault current characteristics when the wire connected with subtractive polarity winding. Immediately after the fault accident, the total current (i_s) and the current of the fault line (i_1) limited in 1/2 cycle. The load voltage (V_{RL1}) of the fault line is almost zero during the fault cycle, and the load voltage (V_{RL2}) of the sound line compensated by the magnitude of the voltage before the fault. Figure 4 (b) shows the fault current characteristics when the wiring connected with additive polarity winding. As in the subtractive polarity winding, the fault current limited in the 1/2 cycle, and the peak of the fault current (i_{fcl}) is smaller in the additive polarity winding than in the subtractive polarity winding. This coincides with the expression (2). In addition, the load voltage (V_{RL2}) in the sound line compensated more by the voltage magnitude before the fault in the additive polarity winding than in the subtractive polarity winding during the fault occurrence.

Figure 5 shows the voltage the two coils, current waveforms, and the superconducting element along the wiring direction of the flux-lock type SFCL.

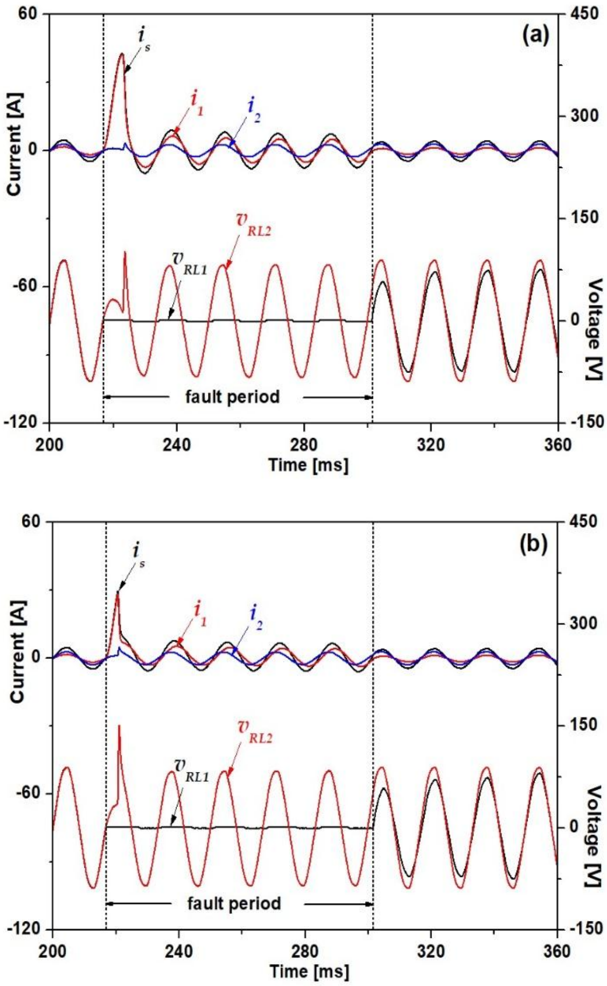

Figure 4. Fault current limiting and load voltage compensating characteristics of fault and sound lines with a flux-lock type SFCL. (R_{L1}= 51.5Ω, R_{L2}= 30.9Ω) (a) Subtractive polarity winding. (b) Additive polarity winding.

In Figure 5 (a) with subtractive polarity winding, the fault current (i_{N2}) rises rapidly on the fault line immediately after the fault occurs, and the current limit occurs after 1/2 cycle. In addition, the element voltage (V_{sc}) and the voltage of the coil 2 due to the quench of the superconducting element greatly increased. In Figure 5 (b) with additive polarity winding, the fault current rises rapidly on the fault line immediately after the fault occurs, the current (i_{N1}) of coil 1 reversed, and the superconductor voltage is equal to the difference between the two coils. The expression (2) confirmed.

Through experimental analysis, it analyzed that the coils V_{N1} and V_{N2} and the magnitude of the voltage V_{SC} induced in the superconducting element in the case of subtractive polarity winding is larger than in the case of the additive polarity winding.

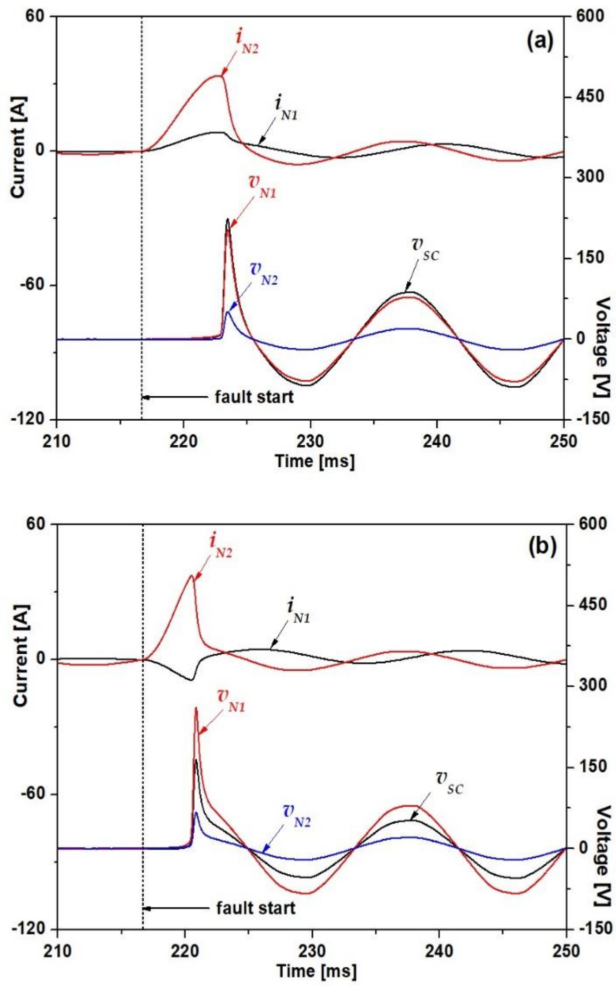

Figure 5. Fault current limiting characteristics of a flux-lock type SFCL. (R_{L1}= 51.5Ω, R_{L2}= 30.9Ω) (a) Subtractive polarity winding. (b) Additive polarity winding.

Figure 6 shows the change of recovery time according to the winding direction when the load resistance of the sound line is changed. When the load resistance was changed to 10.3 [Ω], 30.9 [Ω], and 51.5 [Ω], and in the case of the subtractive polarity winding, the recovery characteristics was shown in Figure 6 (a). The recovery time is 0.95 [s], 1.23 [s], and 1.29 [s]

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when the load resistance is 10.3 [Ω], 30.9 [Ω], and 51.5 [Ω], respectively. As the load resistance increases, the recovery time increases. Figure 6 (b) shows the recovery characteristics in the case of the additive polarity winding. The recovery time is 0.48 [s], 0.58 [s], and 0.60 [s] when the load resistance is 10.3 [Ω], 30.9 [Ω], and 51.5 [Ω], respectively. The recovery time in the additive polarity winding is shorter than in the case of the subtractive polarity winding.

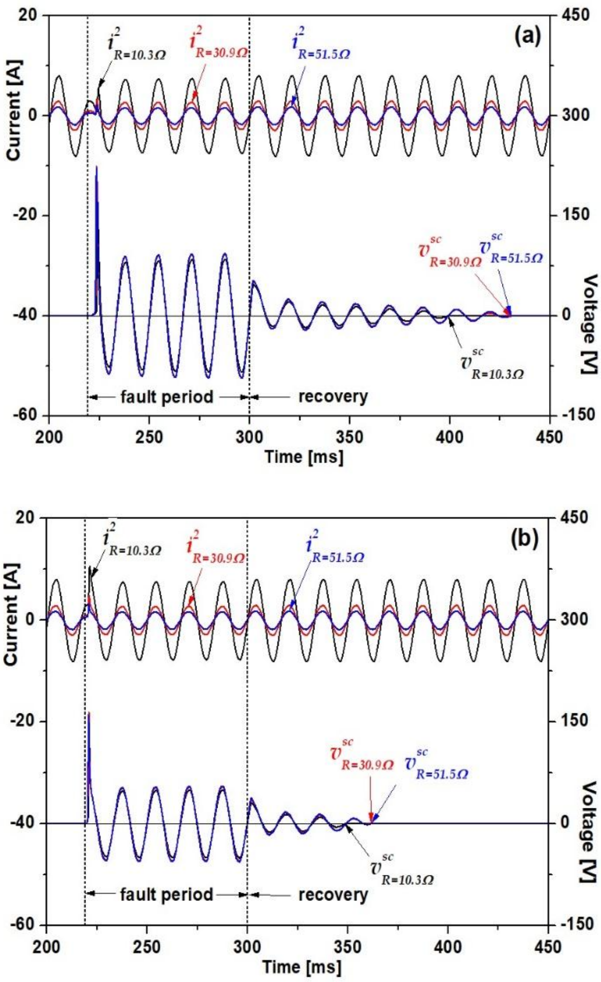

Figure 6. Recovery characteristics of a flux-lock type SFCL according to load resistances. (a) Subtractive polarity winding. (b) Additive polarity winding.

Figure 7 shows the energy consumption and resistance characteristics during the fault period of the flux-lock type SFCL according to the load resistance change. In Figure 7 (a) with subtractive polarity winding, resistance generated due to the quench of the superconducting element immediately after the fault occurs and energy consumption is increasing. As the load resistance increases, the resistance of the superconducting element increases, but the energy consumption decreases. In Figure 7 (b) with additive polarity winding, the resistance generated by the quench of the superconducting element immediately after the fault occurs, and is occurring faster than the subtractive polarity winding. As the load resistance increases, the resistance of the superconducting element increases, but the magnitude of the resistance and energy consumption is smaller than that of subtractive polarity winding. This is the same as the expression (1) and (2).

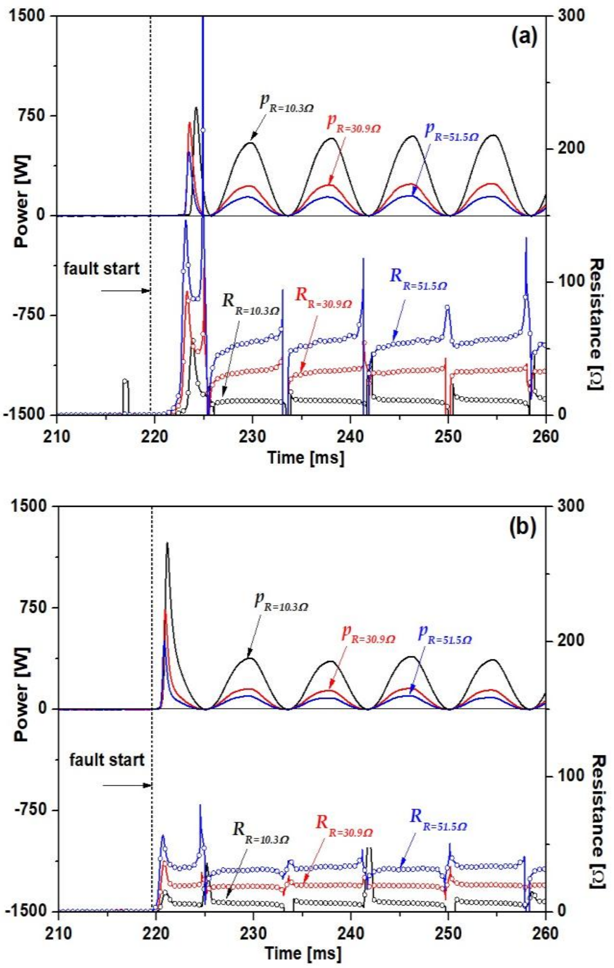

Figure 7. Power and resistance characteristics of a flux-lock type SFCL according to load resistances. (a) Subtractive polarity winding. (b) Additive polarity winding.

IV. CONCLUSION

In this paper, a short-circuit generation experiment conducted when the flux-lock type SFCL introduced into the simulation power system to analyze the characteristics of the power system. As the experimental conditions, the current limiting characteristics and voltage compensation characteristics analyzed by varying the winding direction of the two coils of the ferromagnetic iron core of the flux-lock type SFCL and the load resistance of the sound line.

In case of the flux-lock type SFCL, the current limit achieved at half cycle of fault occurrence regardless of the winding direction of the two coils. The simulation results show that the quench time and recovery characteristics improved by the case of the additive polarity winding than by the case of the subtractive polarity winding.

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