Study on Current Limiting Characteristics of a Flux-locktype SFCL using Series Connected Two Coils with Twice Triggering Operation

Tae-Hee Han*, Seok-Cheol Ko**, Byongjun Lee*** and Sung-Hun Lim†

Abstract – The current limiting characteristics of the flux-lock type superconducting fault current limiter (SFCL) using series connected two coils with twice triggering operation, which consists of series connected two coils and two superconducting (SC) modules with the inserting resistance, was analyzed. The feature of the suggested SFCL is that it can limit the fault current by triggering either one SC module or two SC modules comprising the SFCL depending on the amplitude of the fault current. To verify the current limiting operation of the suggested SFCL, the short-circuits in the fault location with the different fault currents were tested and its useful operations were described through the analysis on the tested results.

Keywords: Current limiting characteristics, Flux-lock type superconducting fault current limiter (SFCL), Twice triggering operation, Amplitude of fault current.

1. Introduction

The continuous increment in the power demand and the power generation due to the industrial development and the economic growth has caused the increase of fault currents resulted from the short circuits in a power system. This increase of fault currents has accelerated the excess of the breaking capacity of existing circuit breakers, which could bring about the rise of economic costs resulted from the exchange of the related power equipments with larger capacity. In addition, the occurrence of a short circuit in a power system causes the bus-voltage to be dropped and the stability of the power system to be lower. With the efforts of the researchers to suppress this fault current as the most effective countermeasures, the studies for the application of the superconducting fault current limiter (SFCL) in a power system have been actively made [1-5].

The one of the advantages of the SFCL is to simultaneously perform two operations to detect and limit the fault current without the help of the additional detecting device. However, it is not easy to limit the fault current effectively according to its amplitude because of its instantaneous limiting characteristics using the quench of the superconducting (SC) modules comprising the SFCL. Among one of the developed SFCLs [4-8], the flux-lock type SFCL has been shown to have the merit to easily adjust the operational current and the limiting impedance of the SFCL by setting both the winding direction and the

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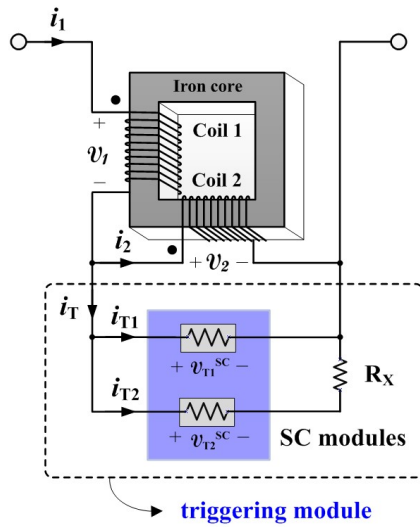Received: April 8, 2013; Accepted: February 24, 2014

inductance ratio between two coils [8-10]. Recently, the SFCL model with the peak current limiting function using two separated SC modules has been suggested and their effective current limiting characteristics have been described [10-12].

In this paper, the flux-lock type SFCL using series connected two coils with twice triggering operation was suggested and its effective fault-current limiting characteristics were analyzed. For the comparative analysis on the operation of the suggested SFCL, the short-circuit tests in two different fault locations to affect the amplitude of the fault current were conducted and its usefulness of the proposed SFCL was analyzed.

2. Structure and Operational Principle

Fig. 1 shows the circuit configuration of the suggested flux-lock type SFCL using series connected two coils with twice triggering operation. The SFCL consists of two coils wound in series on the iron core and triggering module with two SC modules connected in parallel each other through the inserting resistance (R_X), which is connected in series with one of two SC modules. Two SC modules are contributed to the triggering operation of the SFCL by quench occurrence of one SC module or two SC modules according to the amplitude of the fault current. i_1 and i_2 are the currents of coil 1 and coil 2, respectively. i_{T1} and i_{T2} represent the currents in two SC modules, respectively.

The basic operation of the suggested SFCL using series connected two coils with twice triggering operation is the same as the previous flux-lock type SFCL using magnetically coupled two coils except for its twice triggering operation according to the amplitude of the fault current. If the current of the SC₁ module (i_{T1}) exceeds its

Fig. 1. Circuit configuration of a flux-lock type SFCL using series connected two coils with twice triggering operation.

critical current (I_c) immediately after the short-circuit occurs, the resistance of the SC_1 module generates. After that, if the portion of the fault current flowing into the $SC_2(i_{T2})$ module is lower, which does not exceed its critical current, the SC_2 module keeps the zero resistance. If the larger portion of the fault current flows into the SC_2 module, on the other hand, the resistance of the SC_2 module generates by its quench occurrence due to the excess of its critical current.

The magnetic flux in the iron core comprising this SFCL, dependent on the resistance of SC module, occurs together with the resistance generation of one SC module or two SC modules, which contributes to the fault current limiting operation of the SFCL with twice triggering operation. In other words, the lower or the higher magnetic flux in the iron core comprising the SFCL can be generated through the resistance generation of one SC module or two SC modules. Therefore, the higher fault current can be limited through the higher magnetic flux by the resistance generation of two SC modules and the lower fault current, on the other hand, can be limited through the lower magnetic flux by the resistance generation of one SC module.

3. Construction of Experimental Circuit

The simulated power distribution system was constructed to test the available operation of the suggested SFCL in case that this SFCL was applied into a real power distribution system. Fig. 2 shows the schematic configuration of the constructed power distribution system together with SFCL. The constructed power distribution system consists of the scaled-down one distribution transformer and two feeders with series connected three
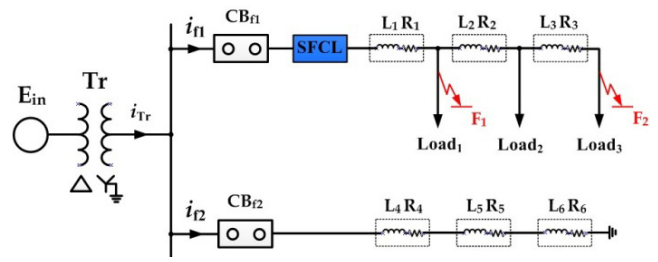

Fig. 2. Schematic configuration of a power distribution system with the SFCL where is applied into the outgoing point of the fault feeder.

Table 1. Design specifications of the experimental power distribution system with the SFCL.

Distribution transformer (Tr)	Value	Unit
Rated capacity	5	kVA
Turn ratio between primary and secondary windings (N =N_2/N_1)	2	
Impedance line	Value	Unit
Inductance of line (L_1, L_4)	1.82	mH
Resistance of line (R_1, R_4)	0.097	Ω
Inductance of line (L_2, L_5)	2.74	mH
Resistance of line (R_2, R_5)	0.14	Ω
Inductance of line (L_3, L_6)	2.5	mH
Resistance of line (R_3, R_6)	0.01	Ω
Load resistance	Value	Unit
Load$_1$	41.2	Ω
Load$_2$	20.6	Ω
Load$_3$	15.6	Ω
Two coils with series connection	Value	Unit
Turn ratio between two coils (n =n_2/n_1)	0.667	
Winding direction of TWO Coils	Additive Polarity	
Triggering Module	Value	Unit
Material of SC modules	YBCO	
Fabrication form of SC modules	Thin Film	
Critical temperature of SC modules	87	K
Critical current (I_C) of SC modules	25.7	A
Inserting resistance (R_X)	0.77	Ω

impedance lines, designed with consideration for real power distribution lines. Load resistance was designed to be branched from ending part of each impedance line. The SFCL was installed behind the circuit breaker (CB_{f1}), which was located in the outgoing point of the fault feeder.

After the source voltage of 400 [V] (E_{in}) was applied into the primary side of the distribution transformer, the short-circuits for the higher and the lower fault currents were simulated at two points of the fault feeder (F_1, F_2) as indicated in Fig. 2 with the fault arrows in front of load$_1$ and load$_3$, respectively. The design specifications of the experimental power distribution system with the suggested SFCL as shown in Fig. 2 were listed in Table 1.

4. Results and Discussions

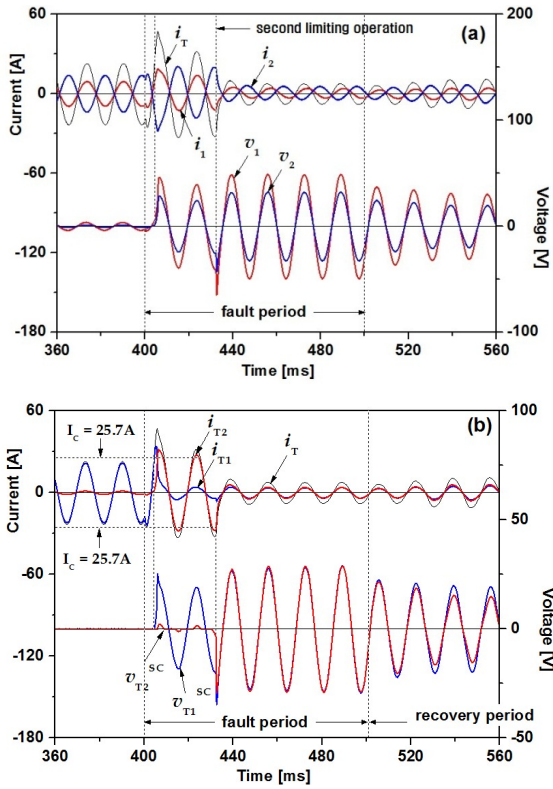Fig. 3 shows the fault current limiting characteristics of

Fig. 3. Fault current limiting characteristics of a flux-lock type SFCL using series connected two coils with twice triggering operation in case that the fault occurs at F_1 location: (a) Current and voltage waveforms of two coils comprising SFCL; (b) Current and voltage waveforms of two SC modules comprising the SFCL.

Fig. 4. Fault current limiting characteristics of a flux-lock type SFCL using series connected two coils with twice triggering operation in case that the fault occurs at F_2 location: (a) Current and voltage waveforms of two coils comprising SFCL; (b) Current and voltage waveforms of two SC modules comprising the SFCL.

the SFCL in case that the fault occurs at F_1 location. As seen in Fig. 3(a), the current in coil 2 (i_2) can be observed to flow with the reverse direction to the one of coil 1, which is resulted from the winding direction between two coils with additive polarity winding. Together with the currents of the coil 2 and two SC modules, the current in coil 1 (i_1), which is equal to the current of the fault line (i_{fl}) in Fig. 2, can be also found to be limited once more about two periods after the fault occurrence. For this second limiting operation of this SFCL, it can be described from Fig. 3(b) with the initial larger current (i_T) flowing into two SC modules immediately after the fault occurrence, which makes the SC_2 module to be fully quenched in succession after the quench in the SC_1 module happens.

For about two periods after the fault occurrence as seen in Fig. 3(b), the quench and the recovery operations of the SC_2 module between the normal conducting state and the superconducting state can be observed as well. However, two periods after the fault occurrence, the SC_2 module is seen to be fully quenched, not to recover into the superconducting state.

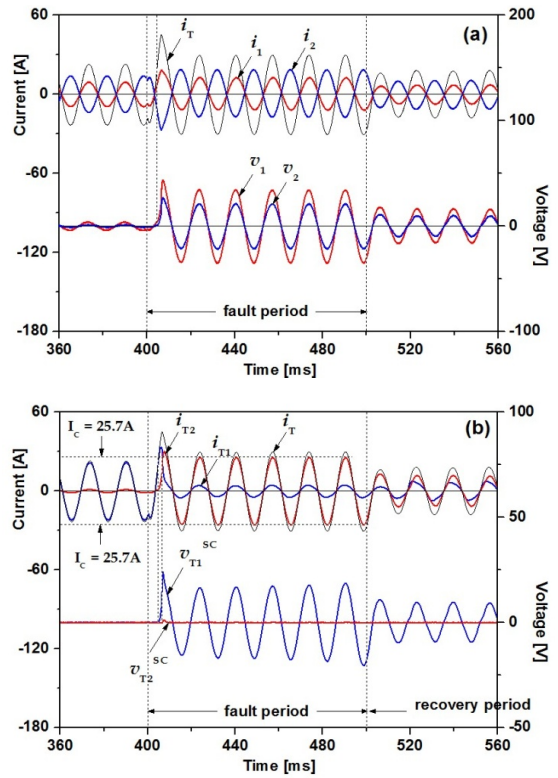The voltages of two coils, which are induced as the negligible lower amplitude before the fault occurrence and, on the other hand, are induced as the large amplitude immediately after the fault occurrence, can be seen to be increased into the larger amplitudes two periods after the fault occurrence due to the quench occurrence of SC_2 module after the quench occurrence of SC_1 module.

In case that the short-circuit occurs in another fault location of the simulated power distribution system, F_2, which is expected for the lower fault current compared to F_1 location to be generated, the fault current limiting characteristics of the SFCL were shown in Fig. 4.

Contrary to F_1 fault location, the fault current in case of the F_2 fault location can be seen to be limited only once immediately after the fault occurrence due to the lower fault current. This lower fault current is observed to have only SC_1 module to be quenched as seen from the voltage waveforms of two SC modules in Fig. 4(b).

The quench characteristics and the power burdens of two SC modules during the fault period were compared for F_1 and F_2 fault locations and shown in Figs. 5 and 6, respectively. In case of F_1 fault location, until the SC_2 module is fully quenched, which corresponds to the period before the 2nd limiting operation of the SFCL starts, the larger amount of the power burden can be analyzed to be
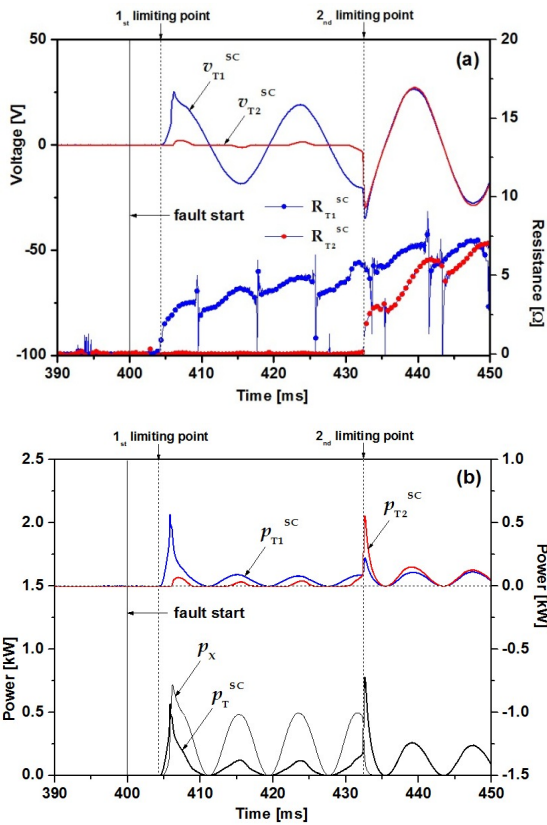
Fig. 5. Quench characteristics and power burdens of two SC modules during the fault period in case that the fault occurs at F1 location: (a) Voltage and resistance curves of two SC modules; (b) Power waveforms of two SC modules and inserting resistance.

Fig. 6. Quench characteristics and power burdens of two SC modules during the fault period in case that the fault occurs at F_2 location. (a) Voltage and resistance curves of two SC modules. (b) Power waveforms of two SC modules and inserting resistance.

generated in the inserting resistance (p_X) as seen in Fig. 5(b). On the other hand, since the SC_2 module is fully quenched, the power burden of the inserting resistance abruptly decreases and most of power burden is taken in two SC modules (p_T^{SC}). In addition, the total power burden comprising the triggering module can be observed to be decreased more than the period before the SC_2 module is fully quenched, which is thought to be favorable operation from the total power burden of the triggering module viewpoint.

In case of F_2 fault location as shown in Fig. 6, the power burden in the inserting resistance can be seen to take most of power burden of the triggering module because the SC_2 module due to the lower fault current is not fully quenched, which agrees with the analyzed result in Fig. 5.

From above analysis, the effective current limiting operation of the flux-lock type SFCL using series connected two coils through twice triggering operation using two SC modules could be obtained and confirmed to be effectively performed by triggering either one SC module for lower fault current or two SC modules for higher fault current. Especially, the total power burden in the triggering module comprising the SFCL could be
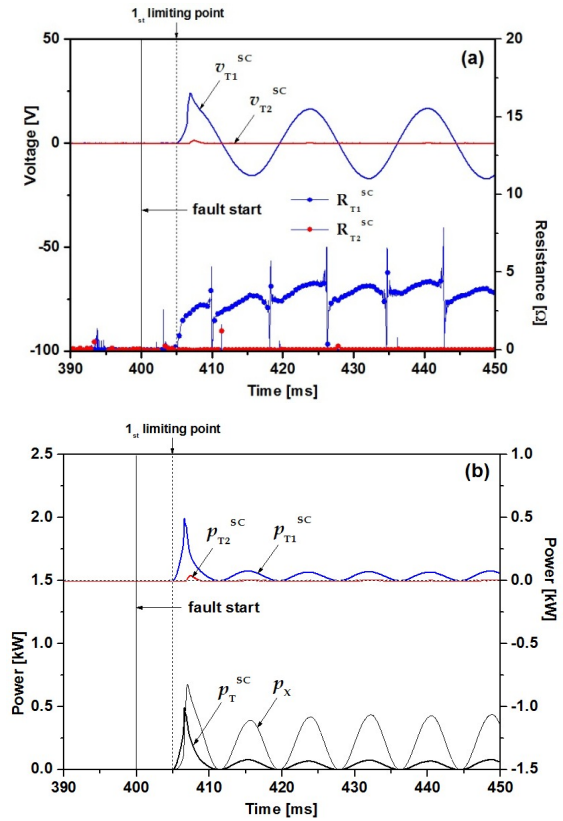
analyzed to be more decreased through the quench occurrence in two SC modules in case that the larger fault current occurred.

4. Conclusion

In this paper, the flux-lock type SFCL using series connected two coils with twice triggering operation, which consisted of two coils wound in series on the iron core and triggering module with two SC modules, was suggested. For the verification of the usefulness of the proposed SFCL, two different fault locations to affect the amplitude of the fault current in the simulated power distribution system were selected and the short-circuit tests in two selected fault locations were carried out.

Through the comparative analysis on the short-circuit tests for the fault currents with the different amplitudes, the effective fault current limiting operations of the flux-lock type SFCL using series connected two coils were confirmed to be obtained through twice triggering operation using two SC modules with the decreased power burden.

Acknowledgements

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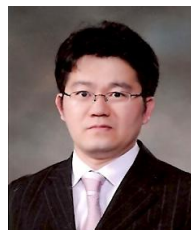
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