Study on Protection Coordination of a Flux-Lock Type SFCL With Over-Current Relay

J. S. Kim, S. H. Lim, and J. C. Kim

Abstract—**In this paper, the method for the protection coordination of a flux-lock type superconducting fault current limiter (SFCL) with an over-current relay (OCR) was proposed. Immediately after the fault happens, the fault current can be limited by the flux-lock type SFCL and, if the fault continues, can be interrupted by the circuit breaker (CB) after several cycles. However, as the fault current is decreased by the impedance occurrence of the flux-lock type SFCL, the trip signal of the OCR for the interruption of the CB can be delayed and the delayed operation of the OCR can result in the failure of the protection coordination with the backup protective device as well.**

As the method to keep the protection coordination of the flux-lock type SFCL with the OCR, the current in a coil 3 of the flux-lock type SFCL, which only flew during the fault period, was used as the input current of the OCR. Therefore, through the adjustment of the turn number's ratio between the coil 1 and the coil 3 of the flux-lock type SFCL, the operating time of the OCR could be kept to be the same as the operating one of the OCR before the flux-lock type SFCL was applied. The suggested method could be confirmed to be available through the simulation using PSCAD/EMTDC for the protection coordination between the flux-lock type SFCL and the OCR.

Index Terms—**Circuit breaker (CB), flux-lock type SFCL, over-current relay (OCR), protection coordination, protective device.**

I. Introduction

With increase in capacities of electric power transmission due to the continuous power demand and the growth of industry, the short-circuit current has increased, which leads to exceed the available interruption ratings of existing circuit breaker. To reduce the increased fault current, the various methods are being considered as solutions [1], [2]. As one of solutions, the superconducting fault current limiter (SFCL) has been proposed to limit the short-circuit current and the various type of SFCLs have been developed [3]–[6].

Among these SFCLs, the flux-lock type SFCL, which consists of two coils and high-T_C superconducting (HTSC) element, has been reported to have the advantages that decrease the power burden of the HTSC element and increase the operational current and the limiting impedance of the SFCL by adjusting the winding direction and the turn number's ratio of two coils [6]–[9].

Manuscript received October 20, 2009. First published April 08, 2010; current version published May 28, 2010. This work was supported by National Research Foundation of Korea Grant funded by the Korean Government (2009-0075355).

The authors are with the Soongsil University (e-mail: superlsh73@ssu.ac.kr).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2010.2045749

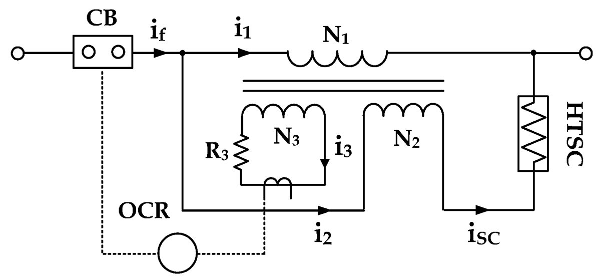

Fig. 1. Configuration of the suggested flux-lock type SFCL.

However, the decrease of the fault current due to the introduction of the flux-lock type SFCL into the power system causes the operation time of the existing over-current relay (OCR) to be delayed. The delayed operation time of the OCR can cause the interruption operation of the circuit breaker (CB) to be delayed, which can increase the burden of the devices adjacent to the CB due to the duration of the fault current and can result in the failure of the protection coordination of the OCR with the backup protection device as well.

In this paper, as the countermeasure to keep the operation time of the OCR in the power system with the flux-lock type SFCL, the method to use the current in the coil 3 of the flux-lock type SFCL as the operational source of the OCR during the fault period was suggested. Through the adjustment of the turn number's ratio between the coil 1 and the coil 3 of the flux-lock type SFCL, the operation time of the OCR could be kept to be the same as one of the OCR before the flux-lock type SFCL was applied. Through the PSCAD/EMTDC analysis for the protection coordination between the flux-lock type SFCL and the OCR, the suggested method could be confirmed to be available.

II. Configuration and Modeling

Fig. 1 shows the configuration of the suggested flux-lock type SFCL, which consists of the current limiting part and the interrupting part. The former comprises the parallel connected two coils and the HTSC element, which is connected in series with one of two coils. The latter consists of the circuit breaker (CB) and the over-current relay (OCR), which is operated by the current of the coil 3.

In a normal time, the magnetic fluxes generated from two coils are cancelled out, which induces the zero voltage across each coil. In case that the fault occurs, the quench occurrence of the HTSC element allows the magnetic flux in each coil and the fault current can be limited by the induced voltages in three coils. Especially, the induced voltage in the coil 3 during the fault period can be contributed to the current source to operate the OCR, which orders the CB to perform the interrupting operation if the OCR's current exceeds its pick-up value determined in advance.

To investigate the operational characteristics of the suggested flux-lock type SFCL, the PSCAD/EMTDC modeling for the HTSC element (YBCO thin film) and the OCR comprising the flux-lock type SFCL was executed. The PSCAD/EMTDC modeling for the OCR and the HTSC element was carried out by composing each component with the CSMF (continuous system model function) icons included within the master library of the PSCAD/EMTDC software package [10]. Generally, the quench development and recovery of the HTSC element comprising the SFCL proceed through the complicated physical process [11]–[13]. In this paper, the mathematical expressive equation, which was previously verified through the experiments for the HTSC element comprising the SFCL, was reflected into its PSCAD/EMTDC modeling as shown in the (1) and (2) [14]–[16].

The (1) describes the resistance generation curve of the HTSC element when the quench occurs and the (2) expresses the recovery curve of the HTSC element when the HTSC element starts to recover its superconducting state. The recovery curve of the HTSC element, expressed in the (2), was considered into the modeling with two slopes as reported in [16]. In the (1), $R_{\rm n}$, $T_{\rm F}$ and t_0 represent the convergence resistance, time constant and quench starting time, respectively. a, $R_{\rm r}$ and t_1, in the (2), represent the recovery slope, the recovery starting resistance and the recovery starting time, respectively.

$$R_{SC}(t) = R_n \left[1 - \exp\left(-\frac{t - t_O}{T_F}\right)\right]^{\frac{1}{2}} \quad t > t_0 \quad (1)$$

$$R_{SC}(t) = a(t - t_1) + R_r \quad t > t_1 \quad (2)$$

The OCR transfers the trip signal for the interrupting operation of the CB when the fault current flowing into it exceeds the predetermined value. The operating time of the OCR is determined by the input current along the time-current characteristic (TCC) curve and is generally in inverse proportion to the over-current flowing through it. The numerical equation to calculate the operating time of the OCR can be described with two parameters: the tap (M) and the time dial (TD). The former represents the ratio of the input current from the current transformer to the pickup current and the latter determines the operating time (T_{trip}), which is determined by the setting rule for the protection coordination. The equation to express the operating time of the OCR can be expressed as follows:

$$T_{trip} = \left(\frac{A}{M^p - 1} + B\right) \times TD \quad (3)$$

where A, B and p are the constants determined according to the inverse, the very inverse and the extremely inverse types of the OCR. In this paper, the constants for the inverse type of the OCR [17], [18], selected in Korea Electric Power Corporation, were reflected into the modeling of the OCR. Based on the results obtained through the modeling of the HTSC element and the OCR as described above, the simulations for the protection coordination of the flux-lock type SFCL with the OCR were performed.

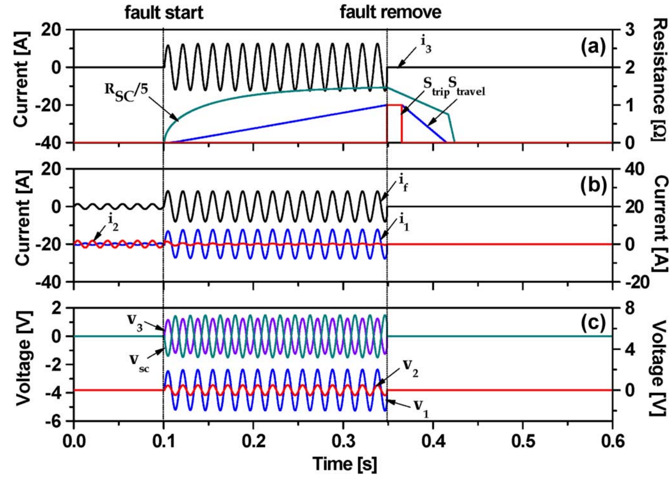

Fig. 2. Fault current limiting and interrupting characteristics of the flux-lock type SFCL using the current in the coil 3 as the input current of the OCR. (a) Current of coil 3 (i_3), resistance of HTSC element (R_{SC}) and trip and travel signals (S_{trip}, S_{travel}). (b) Line current (i_f) and currents of coil 1 and 2 (i_1, i_2). (c) Voltages of each coil and HTSC element (v_1, v_2, v_3, v_{SC}).

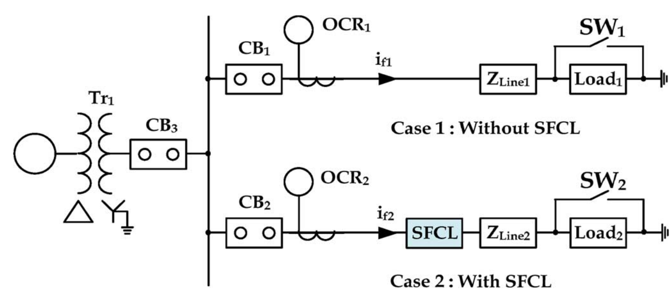

Fig. 3. Schematic configuration of a power distribution system including the flux-lock type SFCL and OCR.

Fig. 2 shows the fault current limiting and interrupting characteristics of the flux lock type SFCL using the current in its coil 3 as the input current of the OCR. After the fault happens, the voltages of all three coils can be seen to be induced together with the resistance generation of the HTSC element. The current and the voltage relationships of the flux-lock type SFCL during the fault period are described in detail in [6]–[9]. The OCR, which is operated by the current of the coil 3, starts to operate after the fault occurrence and generates the trip signal (S_{trip}) for the interrupting operation of the CB. Therefore, the fault current can be seen to be interrupted by the CB after it is first limited by the flux-lock type SFCL.

III. Results and Discussions

To analyse the protection corporation of the suggested flux-lock type SFCL with the OCR, the simulated power distribution system including the flux-lock type SFCL and the OCR was constructed as shown in Fig. 3.

The case 1 and the case 2 represent the feeder without the SFCL and the one with the SFCL, respectively. In both the cases, each OCR is set to the same pickup current to operate the CB connected to each feeder when the fault occurs. The OCR_1 corresponding to the case 1 is operated by its feeder current and,

TABLE I
SPECIFICATIONS OF POWER DISTRIBUTION SYSTEM FOR SIMULATION

Transformer (Tr_1)	Value	Unit
Capacity	5	kVA
Voltage of primary side	132	V
Voltage of secondary side	132	V
Feeder line (Z_{Line1}, Z_{Line2})	**Value**	**Unit**
$R_1 + jX$, $R_2 + jX_2$	0.01 + j0.375	Ω
Load (Load₁, Load₂)	**Value**	**Unit**
$R_{L1} + jX_{L1}$, $R_{L2} + jX_{L2}$	11.5 + j0.1	Ω

TABLE II
SETTING PARAMETERS FOR MODELING OF OCR, FLUX-LOCK TYPE SFCL AND HTSC ELEMENT

OCR	Value	Unit
Pickup current for instantaneous operation	40	A_{rms}
Pickup current for a definite time delay operation	12	A_{rms}
TD	1	
A	39.85	
B	1.084	
p	1.95	
Flux-Lock Type SFCL	**Value**	**Unit**
Turns' Number of Coil 1 (N_1)	40	Turns
Turns' Number of Coil 2 (N_2)	10	Turns
Turns' Number of Coil 3 (N_3)	20, 30, 40	Turns
Inserting Resistance of Coil 3 (R_3)	0.1	Ω
HTSC element	**Value**	**Unit**
Convergence resistance (R_n)	5	Ω
Time constant (T_F)	0.05	s
Critical current (I_C)	20	A
1st and 2nd recovery slopes (a_1, a_2)	-10, -100	1/s
2nd recovery starting resistance (Rr_2)	2.5	Ω

on the other hand, the OCR_2 corresponding to the case 2 where the flux-lock type SFCL is installed is operated by the coil 3's current of the flux-lock type SFCL. To compare the protection coordination of the flux-lock type SFCL with the OCR_2, which uses the current of the coil 3 as its input current (case 2), the fault current limiting and interrupting characteristics of the flux-lock type SFCL with the OCR, which is operated by its feeder current, were investigated as well. The specifications of the power distribution system, organized for the simulation, are shown in Table I. The setting parameters of the OCR and the flux-lock type SFCL including the HTSC element are listed in Table II.

Fig. 4 shows the feeder current waveform (i_{f1}) and the trip and the travel signals of the OCR (S_{trip}, S_{travel}) due to whether the flux-lock type SFCL is introduced or not in case that the fault occurs. In the simulation, the fault was started at 0.1 s and removed at 0.6 s after the fault lasted for 0.5 s. The OCR was set to operate properly within the fault period, 0.5 s by the setting rule of OCR. In case that the flux-lock type SFCL is not installed (Fig. 4(a)), the travel signal of the OCR gradually increases after the fault happens and when it reaches '1', the OCR produces a trip signal and the CB performs the interrupting operation. On the other hand, in case that the flux-lock type SFCL is installed in the feeder of the power distribution system (Fig. 4(b)), the OCR, which is scheduled to be operated by the feeder current, does not produce the trip signal to operate the CB as well as the travel signal, which results from the decreased fault current by

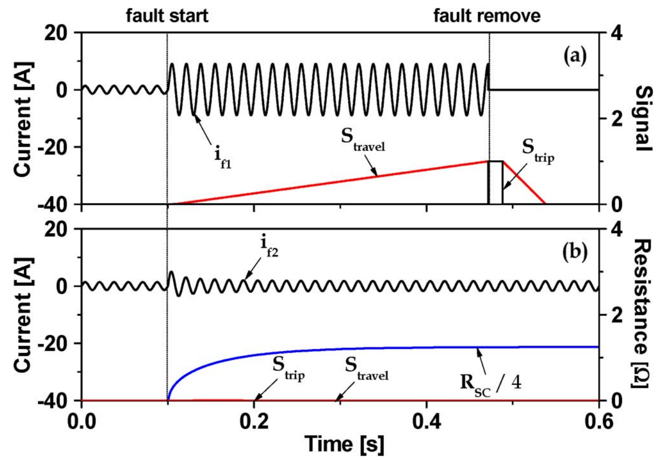

Fig. 4. Feeder current (i_{f1}), trip and travel signals of OCR (S_{trip}, S_{travel}) and resistance curve of HTSC element (R_{SC}). (a) In case that the flux-lock type SFCL is not installed (case 1). (b) In case that the flux-lock type SFCL without coil 3 is installed in the feeder (case 2).

the flux-lock type SFCL. To keep the protection coordination of the flux-lock type SFCL with the OCR, the method to operate the OCR by the coil 3's current of the flux-lock type SFCL was suggested.

Fig. 5 shows the current limiting and interrupting characteristics of the flux-lock type SFCL with OCR using the current of its coil 3 as input current. Unlike the flux-lock type SFCL with OCR operated by its feeder current as seen in Fig. 4(b), the decreased fault current can be seen to be interrupted after the fault current is limited by the flux-lock type SFCL. Although the feeder current is decreased by the limiting operation of the flux-lock type SFCL, the higher induced current in the coil 3 during the fault period can be contributed to the operation of the OCR. In other words, the operation time of the OCR, which uses the coil 3's current of the flux-lock type SFCL as the input current, can be maintained to be the same value as the OCR operated by the feeder current in case that the flux-lock type SFCL is not installed. In addition, the operation time of the OCR can be expected to be adjusted through the variation of the design parameters such as the turn number's ratio of the coil 3 to the coil 1 and the winding direction of coil 1 and coil 2.

To analyse the effect of the design parameters of the flux-lock type SFCL on the operation time of the OCR, the variation of the OCR's operation time according to the turn number's ratio between the coil 1 and the coil 3 was investigated.

Figs. 6 and 7 show the current limiting and interrupting characteristics of the flux-lock type SFCL with OCR operated by the current of its coil 3 according to the turn number's ratio between the coil 1 and the coil 3 in two winding directions (subtractive polarity winding and additive polarity winding). In both winding directions, as the turn number's ratio between the coil 1 and the coil 3 (N_3/N_1) increases, the operation time of the OCR can be seen to be increased. On the other hand, the amplitude of the limited feeder current before the fault is removed by the interrupting operation of the CB can be seen to be almost the same. Therefore, through the adjustment of the turn number's ratio between the coil 1 and the coil 3, the operation time of the OCR to trip the CB is expected to be set to be the same value

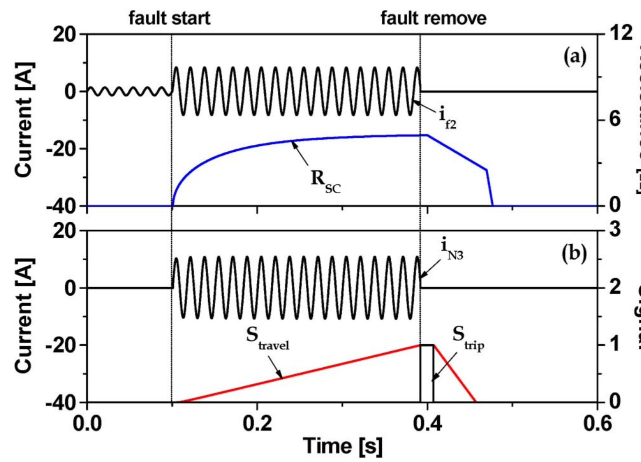

Fig. 5. Current limiting and interrupting characteristics of the flux-lock type SFCL with OCR using the current of its coil 3 as input current. (a) Feeder current (i_{f2}) and resistance curve of HTSC element (R_{SC}) comprising the flux-lock type SFCL. (b) Current of coil 3 (i_{N3}), trip and travel signals of OCR (S_{trip}, S_{travel}).

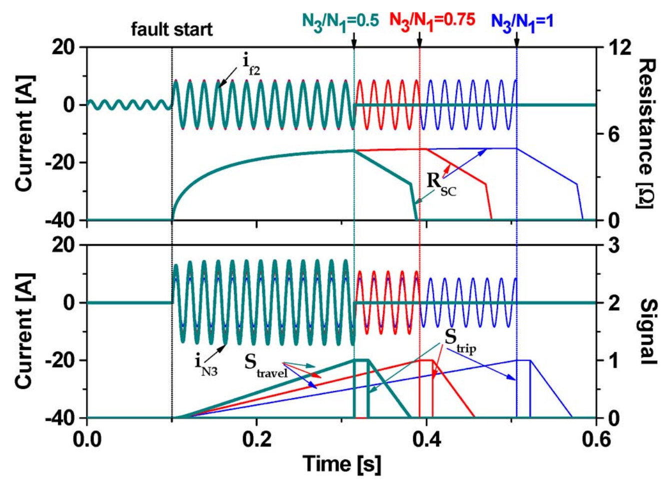

Fig. 6. Current limiting and interrupting characteristics of the flux-lock type SFCL with OCR operated by the current of its coil 3 in case of the subtractive polarity winding. (a) Feeder current and resistance curve of HTSC element comprising the flux-lock type SFCL. (b) Current of coil 3, trip and travel signals of OCR.

as the case that the flux-lock type SFCL is not applied into the feeder and can be confirmed to keep the protection coordination of the flux-lock type SFCL with the OCR operated by the coil 3's current as its input current.

IV. Conclusions

In this paper, as the method to keep the protection coordination of the flux-lock type SFCL with the OCR when it was introduced into the power distribution system, the flux-lock type SFCL with the OCR, which was operated by the current of its coil 3, was proposed.

The fault current limiting and interrupting characteristics of the flux-lock type SFCL with the OCR, which was operated by its feeder current, were compared with those of the suggested flux-lock type SFCL with the OCR.

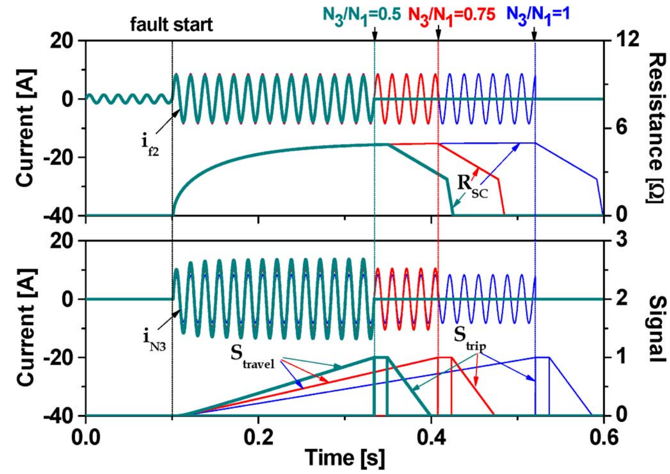

Fig. 7. Current limiting and interrupting characteristics of the flux-lock type SFCL with OCR operated by the current of its coil 3 in case of the additive polarity winding. (a) Feeder current and resistance curve of HTSC element comprising the flux-lock type SFCL. (b) Current of coil 3, trip and travel signals of OCR.

The higher induced current in the coil 3 during the fault period could be shown to be contributed to the operation of the OCR, although the feeder current was decreased by the limiting operation of the flux-lock type SFCL.

References

[1] V. D. Pham, Y. Laumond, T. Verhaefe, A. Fevrier, M. Collet, and M. Bekhaled, "Towards the superconducting fault current limiter," *IEEE Trans. Power Delivery*, vol. 6, pp. 801–808, Apr. 1991.

[2] J. Yu and X. Duan, "A new type of superconducting fault current limiter (SFCL)," in *IEEE/PES Transmission and Distribution Conference and Exhibition 2002: Asia Pacific*, Oct. 2002, vol. 3, pp. 2322–2325.

[3] Y. Jiang, S. Dongyuan, D. Xianzhong, T. Yuejin, and C. Shijie, "Comparison of superconducting fault current limiter in power system," in *IEEE Power Engineering Society Summer Meeting*, Jul. 2001, vol. 1, pp. 43–47.

[4] B. Gromoll, G. Ries, W. Schmidt, H.-P. Krämer, P. Kummeth, and H.-W. Neumüller, "Resistive current limiters with YBCO films," *IEEE Trans. Appl. Supercond.*, vol. 7, no. 2, pp. 828–831, Jun. 1997.

[5] H. Yamaguchi, T. Kataoka, K. Yaguchi, S. Fujita, K. Yoshikawa, and K. Kaiho, "Characteristics analysis of transformer type superconducting fault current limiter," *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 815–818, Jun. 2004.

[6] S. H. Lim, H. S. Choi, and B. S. Han, "Fault current limiting characteristics due to winding direction between coil 1 and coil 2 in a flux-lock type SFCL," *Phys. C*, vol. 416, pp. 34–42, Nov. 2004.

[7] S. H. Lim, H. S. Choi, and B. S. Han, "The improved hysteresis characteristics of flux-lock type SFCL using third winding," *Phys. C*, vol. 406, pp. 37–45, Jul. 2004.

[8] S.-H. Lim, "Fault current waveform analysis of a flux-lock type SFCL according to LC resonance condition of third winding," *J. Electr. Eng. Technol.*, vol. 3, no. 2, pp. 213–217, Jun. 2008.

[9] S.-H. Lim, "Fault current limiting characteristics of separated and integrated three-phase flux-lock type SFCLs," *J. Electr. Eng. Technol.*, vol. 2, no. 3, pp. 289–293, Sep. 2007.

[10] *"User's Guide on the Use of PSCAD,"* MANITOBA-HVDC Research Centre, 2005.

[11] L. Ye and A. Campbell, "Behavior investigations of superconducting fault current limiters in power systems," *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 662–665, Jun. 2006.

[12] L. Ye and K.-P. Juengst, "Modeling and simulation of high temperature resistive superconducting fault current limiters," *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 839–842, Jun. 2004.

[13] M. Majoros, A. M. Campbell, B. A. Glowacki, and R. I. Tomov, "Numerical modeling of heating and current-sharing effects on I-V curves of $Y_1Ba_2Cu_3O_7$ and MgB_2 conductors," *Phys. C*, vol. 401, pp. 140–145, Jan. 2004.

[14] S. H. Lim, S. R. Lee, H. S. Choi, and B. S. Han, "Analysis of operational characteristics of flux-lock type SFCL combined with power compensator," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 131–134, Jun. 2005.

[15] H.-R. Kim, O.-B. Hyun, H.-S. Choi, S.-D. Cha, and J.-M. Oh, "Resistance development in superconducting fault cuernt limiters prior to quench completion," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 2032–2035, Jun. 2003.

[16] H. R. Kim, S. W. Yim, S. Y. Oh, and O. B. Hyun, "Recovery in superconducting fault current limiters at low applied voltages," *IEEE Trans. Appl. Supercond.*, vol. 18, no. 2, pp. 656–659, Jun. 2008.

[17] A. J. Allen and S. Santoso, "Modeling distribution overcurrent protective devices for time-domain simulations," in *IEEE Power Engineering Society General Meeting*, Jun. 2007, pp. 1–6.

[18] Korea Electric Power Corporation, Distribution Practical III 2006.