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Analysis on Coordination of Over-Current Relay using Voltage Component in a Power Distribution System with a SFCL

Sung-Hun Lim and Seung-Taek Lim

***Abstract*— To reduce the more increased fault current due to the increase of the power generation with the power demand, the superconducting fault current limiter (SFCL) has received attention as one of the effective methods to resolve the fault current problem. However, the operation of the protection device, especially dependent on the amplitude of the fault current, can be affected by the application of the SFCL. For the protection coordination between the SFCL and the over-current relay (OCR), one of the typical protection devices in the power distribution system, the resetting of operational parameters in the OCRs, which can be troublesome, is required. For these resettings of the protection devices, the fault current calculation from the power distribution system considering the impedance of the SFCL is inevitable.**

In this paper, the method using the voltage component as the effective parameter of the OCR for the protection of the power distribution system with the SFCL was suggested. Through the analysis on the simulation results from the modeling of the OCR, the suggested method using the voltage component in the OCR could be confirmed to be more effective compared to the previous resetting method of the OCR.

***Index Terms*— fault current, superconducting fault current limiter (SFCL), over-current relay (OCR), voltage component, protection devices, power distribution system.**

I. Introduction

POWER demand has been growing rapidly and steadily. At the same time, the installation of the distributed generations (DGs) from demand for clean and carbon-free energy has increased the fault current level in the power distribution system. This increase in fault current can exceed the capacity of the circuit breakers (CBs) and this problem has been mentioned as an important issue in high load density areas [1]-[3]. To solve the capacity excess of the CBs, the various solutions have been introduced, for example, replacement of CBs with large capacity CBs, installation of the series reactor, operation between open and loop system and so on. The replacement of the CBs seems to be direct solution but it has the economic feasibility. Other solution causes the power loss in a normal time or needs operating plan and countermeasure for the bidirectional fault current. As the most promising solution to overcome above mentioned problems, the superconducting fault current limiter (SFCL) has been studied [3]-[5].

The SFCLs have no power loss in normal time and fast limiting operation within a quarter cycle without additional sensing device. For the above reasons, SFCLs to commercialize have been studied. However, most of studies have been concentrated on improvement of fault current limiting characteristics or increase of SFCL's limiting capacities [5]-[8]. As SFCL's operation is vitally concerned with the amplitude of the fault current, the operation of the protective relay has no choice but to be affected. Especially, overcurrent relays (OCRs), which are the most commonly used in the power distribution system, can cause the trip delay or malfunction. These delayed operation of the OCRs can interrupt the protection coordination between the protective relays and finally fails in protection of the power distribution system [9]-[14].

In this paper, the OCR using the voltage component was suggested to mitigate the OCR's trip delay caused by SFCL's operation. The radial 22.9 [kV] power distribution system with the SFCL for PSCAD/EMTDC simulation was composed and the operation of the OCR using the voltage component was analyzed. The suggested OCR using the voltage component could be confirmed to be more effective compared to the previous coordination method of the OCR.

II. Existing OCR and Proposed OCR

A. Existing OCR

The OCR operated by the fault current amplitude is the most commonly used protection device in the power distribution system. Generally, the trip time (T_{trip}) of the OCR can be expressed as the equation (1), which is inversely proportional to the current index (M), the ratio of the input current (I_f) versus the pick-up current (I_{pickup}) as shown in equation (2).

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

$$M = \frac{I_f}{I_{pickup}} \quad (2)$$

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Here, TD, as called time dial, is the proportional coefficient and *A*, *B* and *p* are the prescribed constants to describe the OCR's operational characteristic, respectively. The input current (I_f) is the root-mean-square (RMS) value. The trip time versus the fault current of the OCR in Eq. (1) can be displayed with curve, called as the time-current curve (TCC).

As expected from Eq. (1), in case that the fault current is higher, the OCR will trip within the short time. On the other hand, the OCR's trip takes long time in case that the fault current is low. Therefore, the operation of the SFCL, which is applied into the distribution system for the reduction of the fault current, would cause the trip delay of OCRs.

B. Resetting method

To keep the trip time of the OCR due to the application of the SFCL, the resetting of time dial (TD) or pick-up current (I_{pickup}) in the OCR is required. Fig. 1 shows TCCs for two resetting methods to maintain the trip time of the OCR in case that the SFCL is applied.

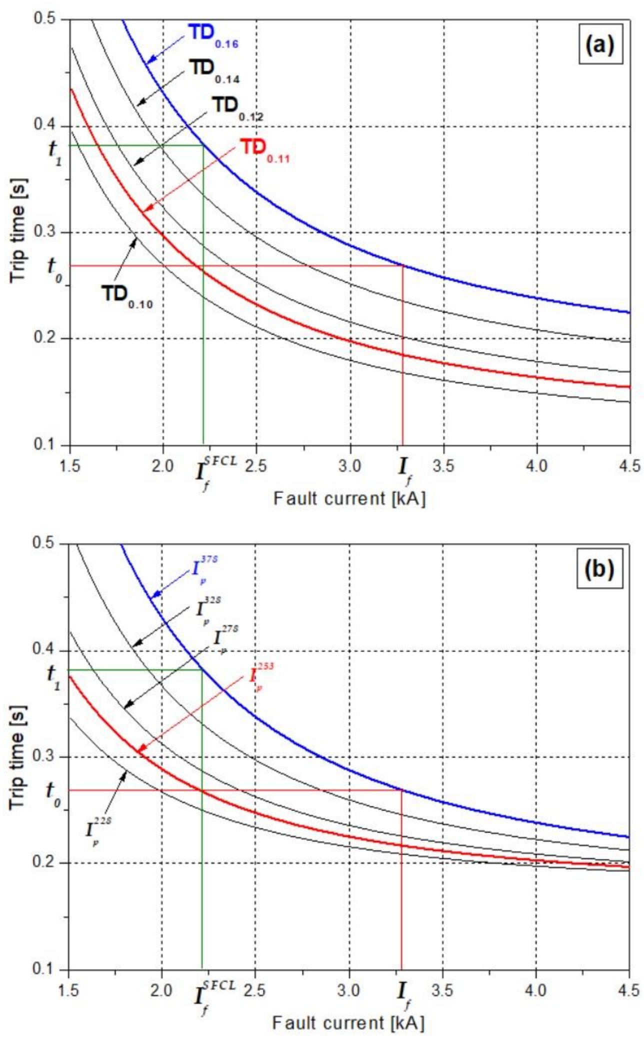

Fig. 1. Typical OCR resetting methods to maintain the trip time when trip delay occurs in case that the SFCL is applied (a) time dial resetting (b) pick up current resetting

In Fig. 1(a), each TCC's subscript indicates the setting value of the TD and TCC moves down by setting TD value into lower one. When fault current decreases from I_f to I_f^{SFCL} by the SFCL, the OCR's trip time in $T_{0.16}$ curve is delayed from t_0 to t_1. The resetting of TD, one of the operational parameters of the OCR, to 0.11 from 0.16 can keep the original OCR's trip time in t_0, which is the same time of the case without the SFCL. However, in case that the SFCL is not operated or removed, the malfunction of the OCR, not operated in the presetting point, can occur.

Similar to the TD setting as described in Fig. 1(a), the resetting of I_{pickup} considering the operation of the SFCL can prevent the operational point of the OCR in the TCC from moving into other point as shown in Fig. 1(b). Each TCC's upper suffix indicates the setting value of I_{pickup} and TCC moves down by setting I_{pickup} value into lower one. In case that the OCR's trip time is delayed due to the application of the SFCL, the resetting of the I_{pickup}, which was preset in 378, into 253 can make the OCR's trip time unchanged or fixed in t_0. With I_{pickup} resetting, the trip delay of the OCR by the SFCL can be avoided. However, it needs to be carried out to be complied with the setting standard of the protective relay.

In recent power distribution system requiring the high quality power, if the trip time of the OCR is not unchanged regardless of the application of the SFCL, the coordination of the OCR is not necessary and more effective for the SFCL's application to protect the power distribution system power system.

C. OCR using Voltage Component

The existing OCR is operated or tripped just by the amplitude of the fault current as seen in Eq. (2). On the other hand, the suggested OCR using voltage component is operated by not only the amplitude of the current (I_f) but also the voltage amplitude across the SFCL (V_{SFCL}) as expressed in Eq. (3).

$$M = \frac{I_f + \alpha \cdot V_{SFCL}}{I_{pickup}} \tag{3}$$

Here, V_{SFCL} and α indicate the root-mean-square (RMS) value of the voltage induced in the SFCL and the adjusting coefficient, respectively. As seen in Eq. (3), in case of the fault occurrence, the fault current (I_f) more decreases compared to the case without the SFCL. Instead, the voltage across the SFCL (V_{SFCL}) induces, which is contributed to compensate the decrease of the fault current caused by application of the SFCL. Therefore, the trip time delay of the existing OCR due to the decrease of the current index in Eq. (2) is expected to be suppressed by adding the voltage component into the existing OCR through the proper α selection as described in Eq. (3).

III. Simulation and Result

A. Simulation Configurations

PSCAD/EMTDC was used for the simulation modeling of the OCR using the voltage component. Fig. 2 shows the

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schematic simulation circuit of the power distribution system to analyze the operation of the OCR using the voltage component. The simulation circuit is composed of CB operated by OCR, SFCL, main transformer (MTR), distribution line ($\mathbf{Z}_1$, $\mathbf{Z}_2$) and loads. Specific parameters are presented in Table I. As the OCR's operational characteristic, the KEPCO's very inverse characteristic was chosen and the OCR's setting parameters were listed in Table II. The three-phase permanent fault was applied between Z_1 and Z_2 in 0.3 [s] as shown in Fig. 2.

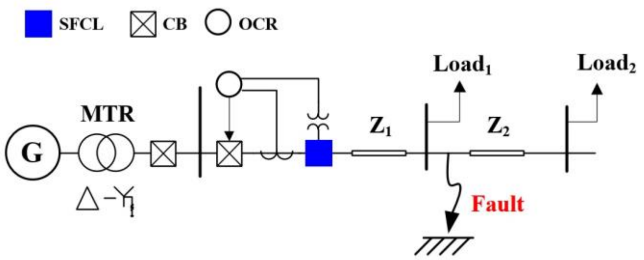

Fig. 2. Schematic simulation circuit of the power distribution system to analyze the operation of the OCR using voltage component

TABLE I
PARAMETERS OF POWER DISTRIBUTION SYSTEM

Component	Parameter	Unit
Power Source	154 j1.0	[kV] [%Ω]
Main transformer (MTR)	60 154/22.9	[MVA] [kV]
Distribution line ($\mathbf{Z}_1$, $\mathbf{Z}_2$)		
Line Impedance (ACSR 160mm^2)	Z_1 = 3.86+j7.42 Z_0 = 9.87+j22.68	[%Ω/km] [%Ω /km]
Feeder Length	$l_1 = l_2 = 4$	[km]
Load$_1$ & Load$_2$	$P_{L1} = P_{L2} = 5$ $Pf_{L1} = Pf_{L2} = 0.95$	[MW] -
System Base	100 22.9	[MVA] [kV]

TABLE II
PARAMETERS OF SFCL AND OCR

Device	Designed (Setting) Value	Unit
OCR	$I_{\text{pickup}} = 0.378$ $TD = 0.16$ α = 0.3954	[kA] - -
SFCL	$I_C = 1.5$ $Z_{CLR} = j2$	[kA] [Ω]

As the SFCL model, the trigger type SFCL was considered as shown in Fig. 3, which has been studied for long time in Korea for field test [5]-[8]. The trigger type SFCL consists of superconducting module (SC), fast switch (SW), current limiting reactor (CLR) and control circuit. The line current flows through the SC in normal time. In the initial fault time directly after the fault happens, SW is open in case that the voltage of the SC (v_{SC}) generates. Consequently, the SC acts as fault current detecting sensor not as limiter and the CLR acts as a fault current limiter. The designed parameters of the trigger type SFCL are presented in Table II.

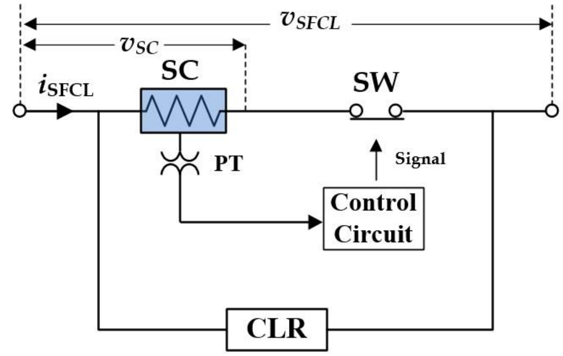

Fig. 3. Structure of the trigger type SFCL.

B. Result and Discussion

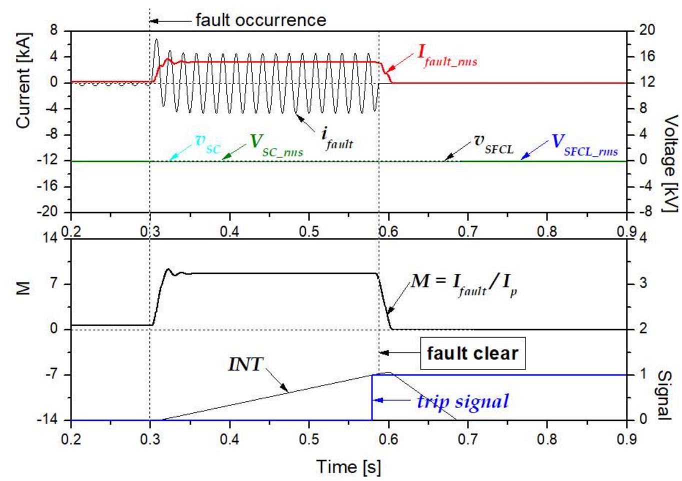

Fig. 4. Fault currents (i_{fault}, i_{fault_rms}), voltages of both the SFCL (v_{SFCL}, v_{SFCL_rms}) and SC (v_{SC}, v_{SC_rms}), index M and INT value of trip signal in case that the existing OCR was applied into the power distribution system without SFCL.

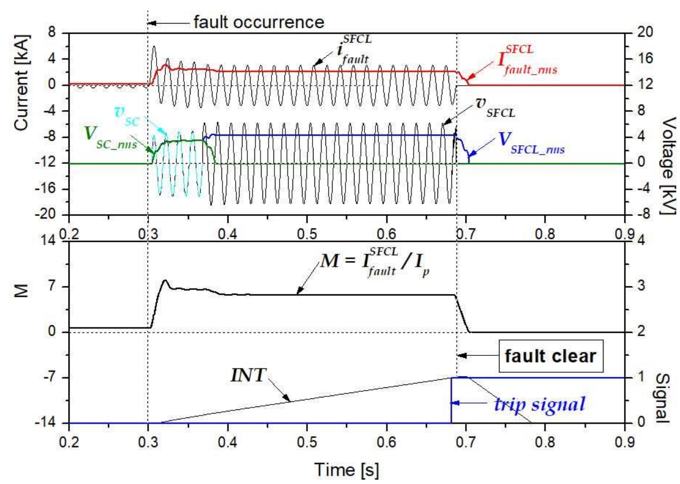

Fig. 5. Fault currents (i_{fault}, i_{fault_rms}), voltages of both the SFCL (v_{SFCL}, v_{SFCL_rms}) and SC (v_{SC}, v_{SC_rms}), index M and INT value of trip signal in case that the existing OCR was applied into the power distribution system with SFCL.

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Fig. 4 shows the instantaneous and the RMS fault currents (i_{fault}, I_{fault_rms}), the instantaneous and the RMS voltages of both the SFCL (v_{SFCL}, V_{SFCL_rms}) and the SC (v_{SC}, V_{SC_rms}) in case that the SFCL was not applied into the power distribution system with the existing OCR. To analyze the operation of the OCR, the index M (Eq. 2) and the integration (INT) value of trip signal are displayed together.

When the INT value reaches at '1', the trip signal from the OCR to open the CB is generated, which makes the fault removed. The fault current increased into about 3.3 [kA_{rms}] and the index M increased into 8.7. According to Eqs. (1) and (2), the fault was removed at around 0.58 [s].

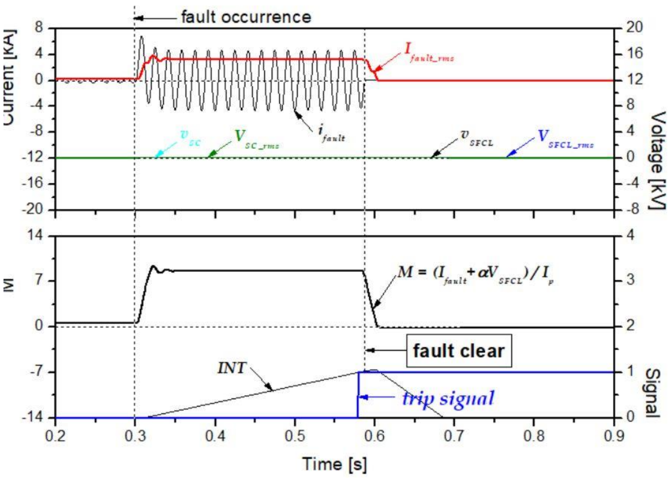

Fig. 6. Fault currents (i_{fault}, i_{fault_rms}), voltages of both the SFCL (v_{SFCL}, v_{SFCL_rms}) and SC (v_{SC}, v_{SC_rms}), index M and INT value of trip signal in case that the OCR using the voltage component was applied into the power distribution system without SFCL.

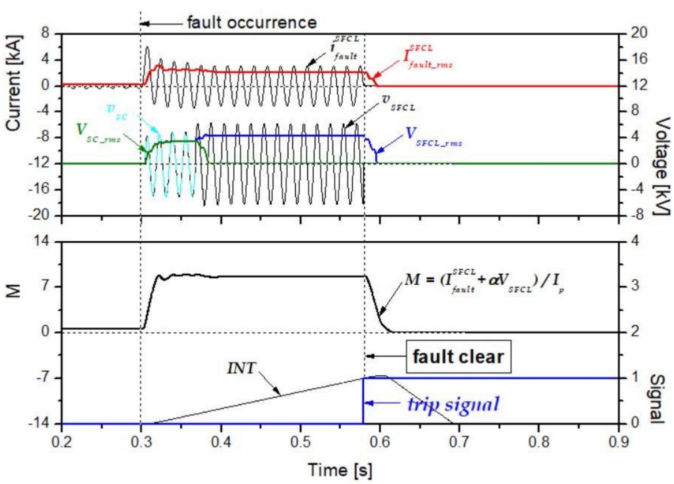

Fig. 7. Fault currents (i_{fault}, i_{fault_rms}), voltages of both the SFCL (v_{SFCL}, v_{SFCL_rms}) and SC (v_{SC}, v_{SC_rms}), index M and INT value of trip signal in case that the OCR using the voltage component was applied into the power distribution system with SFCL.

Fig. 5 shows the instantaneous and the RMS fault currents, the voltages of the SFCL and the SC, the index M and the INT value in case that the SFCL was applied into the power distribution system, which is protected by the existing OCR. By the operation of the SFCL, the fault current can be seen to be decreased from 3.3 [kA_{rms}] to 2.2 [kA_{rms}]. The excess above the preset voltage in the SC is controlled for the SW to be opened. After the SW is opened, the voltage of the SC becomes zero and the voltage of the SFCL approaches the constant value. Index M can be seen to be also decreased into 5.8 because the fault current decreases. Consequently, the trip delay in the OCR about 0.1 [s] compared to the case without the SFCL occurs and the fault is removed at around 0.68 [s].

Figs. 6 and 7 show the fault current and the voltage in the SC and the SFCL together with the index M and the INT value in case that the OCR using the voltage component is applied into the power distribution system for both the case without the SFCL and the one with the SFCL. In the case without the SFCL as seen in Fig. 6, the fault current, the index M and the INT value are the same to the case that the existing OCR is applied, which was analyzed in Fig. 4.

However, in the case with the SFCL as seen in Fig. 7, the index M is almost the same as compared to one in Fig. 6 though the fault current decreases into 2.2 [kA_{rms}]. Finally, the unchanged index M, which affects the operation of the OCR, is observed to clear the fault around 0.58 [s] at the same time as the case without the SFCL. From the above analysis, it was confirmed that the OCR's trip time delay due to the operation of the SFCL could be suppressed by applying the OCR using the voltage component.

IV. Conclusion

In this paper, the OCR using the voltage component for the application of the SFCL into the power distribution system was suggested. The application of the SFCL in the distribution system causes the OCR's trip delay since the fault current relevant to trip time is reduced. There are some methods, like resetting (TD, I_{pickup}) of the OCR to prevent the trip delay, but those have a possibility of the malfunction in normal state or setting standard. In the OCR using the voltage component, by adding the voltage component to OCR, the trip delay caused by application of the SFCL could be decreased and the problems caused by resetting was confirmed to be solved.

In the future, the study to improve the protection coordination between the protective relays by the OCR using the voltage component will make progress.

References

[1] J. C. Das, "Limitations of fault-current limiters for expansion of electrical distribution systems," *IEEE Trans. Ind. Appl.*, vol. 33, no. 4, pp. 1073–1082, Jul./Aug. 1997.

[2] T. Sato, M. Yamaguchi, T. Terashima, S. Fukui, J. Ogawa, H. Shimizu, and T. Sato, "Study on the effect of fault current limiter in power system with dispersed generators," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 2331–2334, June, 2007.

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

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

[5] S. Lee, J. Yoon, B. Yang, Y. Moon, and B. Lee, "Analysis model development and specification proposal of 154 kV SFCL for the

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TASC.2019.2904668, IEEE Transactions on Applied Superconductivity

application to a live grid in South Korea", *Phys. C: Supercond*, vol. 504, no. 15, pp. 148-152, Sep. 2014.

[6] O. B. Hyun, S. W. Yim, S. D. Yu, S. E. Yang, W. S. Kim, H. R. Kim, G. H. Lee, J. W. Kim and K. B. Park, "Long-Term Operation and Fault Tests of a 22.9 kV Hybrid SFCL in the KEPCO Test Grid", *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 2131-2134, June, 2011.

[7] H. R. Kim *et al.*, "Development and grid operation of superconducting fault current limiters in KEPCO," *IEEE. Trans. Appl. Supercond.*, vol. 24, no. 5, Oct. 2014, Art. no. 5602504.

[8] Sung-Hun Lim, and Seung-Taek Lim, "Current Limiting and Recovery Characteristics of a Trigger-Type SFCL Using Double Quench," *IEEE. Trans. Appl. Supercond.*, vol. 28, no. 3, April, 2018, Art. no. 5601305.

[9] B. Li, C. Li, F. Guo, and Y. Xin, "Overcurrent protection coordination in a power distribution network with the active superconductive fault current limiter," *IEEE. Trans. Appl. Supercond.*, vol. 24, no. 5, pp. 1-4, 2014.

[10] C. Li, B. Li, F. Guo, J. Geng, X. Zhang, and T. Coombs, "Studies on the active SISFCL and its impact on the distance protection of the EHV transmission line," *Protection and Control of Modern Power Systems*, vol. 1, no. 1, pp. 18, 2016.

[11] J. S. Kim, S. H. Kim, and J. C. Kim, "Study on Application Method of Superconducting Fault Current Limiter for Protection Coordination of Protective Devices in a Power Distribution System", *IEEE Trans. Appl. Supercond*., vol. 22, no. 3, Jun. 2012, Art. no. 5601504.

[12] B. Li, C. Li, and F. Guo, "Application studies on the active SISFCL in electric transmission system and its impact on line distance protection," *IEEE. Trans. Appl. Supercond.*, vol. 25, no. 2, pp. 1-9, 2015.

[13] B. Li, C. Li, F. Guo, and Y. Xin, "Overcurrent protection coordination in a power distribution network with the active superconductive fault current limiter," *IEEE. Trans. Appl. Supercond.*, vol. 24, no. 5, pp. 1-4, 2014.

[14] B. Li, C. Li, F. Guo, Y. Xin, C. Wang, and X. Pang, "Coordination of superconductive fault current limiters with zero-sequence current protection of transmission lines," *IEEE. Trans. Appl. Supercond.*, vol. 24, no. 5, pp. 1-5, 2014.