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Study on Application of Superconducting Fault Current Limiter Considering Risk of Circuit Breaker Short-Circuit Capacity in a Loop Network System

Jin-Seok Kim*, Sung-Hun Lim† and Jae-Chul Kim**

Abstract – This paper suggests an application method for a superconducting fault current limiter (SFCL) using an evaluation index to estimate the risk regarding the short-circuit capacity of the circuit breaker (CB). Recently, power distribution systems have become more complex to ensure that supply continuously keeps pace with the growth of demand. However, the mesh or loop network power systems suffer from a problem in which the fault current exceeds the short-circuit capacity of the CBs when a fault occurs. Most case studies on the application of the SFCL have focused on its development and performance in limiting fault current. In this study, an analysis of the application method of an SFCL considering the risk of the CB's short-circuit capacitor was carried out in situations when a fault occurs in a loop network power system, where each line connected with the fault point carries a different current that is above or below the short-circuit capacitor of the CB. A loop network power system using PSCAD/EMTDC was modeled to investigate the risk ratio of the CB and the effect of the SFCL on the reduction of fault current through various case studies. Through the risk evaluations of the simulation results, the estimation of the risk ratio is adequate to apply the SFCL and demonstrate the fault current limiting effect.

Keywords : Superconducting Fault Current Limiter (SFCL), Protective coordination, Protective devices.

1. Introduction

Because of the increased demand for power, conventional power systems have evolved into more complex systems, such as the mesh-type and loop-type systems, to provide a stable power supply. However, the complexity of these power systems has created several problems. Among these problems, the short-circuit current has increased relative to past power distribution systems and has exceeded the short-circuit capacities of the circuit breakers (CBs) [1-6].

To mitigate the short-circuit current problem, several methods are being employed that use a series current limit reactor, a high-impedance power transformer, and other components.

However, these methods have other disadvantages, such as voltage sag and power loss during a normal state.

Recently, the superconducting fault current limiter (SFCL) has been recognized as a promising component that can be utilized to attenuate the increase of a short-circuit current without the aforementioned problems because the SFCL has no impedance under normal conditions. However, until now, studies of the application of the SFCL have been focused on the improvement of its performance, increase of its capacity, and the analysis of protective coordination of the protective devices that were operated by a fault current with or without the application of the SFCL [6-15].

To introduce the SFCL into a power system, it is proposed that the selection method of the SFCL's location considers the proportion of the fault current flowing through the SFCL. The use of this application scheme using the SFCL is linked to an improvement of its effect and determination of its configuration.

In this study, an investigation of the effect of the application method of the SFCL on the breaking capacities of the interruptive devices in a power system was performed. To estimate the ratio between the CB's short-circuit capacity and fault current, the use of the fault current index (FCI) factor was suggested. The FCI factor using a PSCAD / EMTDC simulation was investigated through various case studies according to the application location of the SFCL.

2. Application Method of SFCL

To apply the SFCL to a practical power system and achieve protective coordination, an application method that appropriately limits the fault current without placing a

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† Corresponding Author: Dept. of Electrical Engineering, Soongsil University, Korea. (superlsh73@ssu.ac.kr)
* Dept. of Electrical Engineering, Soongsil University, Korea. (redwolf832@ssu.ac.kr)
** Dept. of Electrical Engineering, Soongsil University, Korea. (jckim@ssu.ac.kr)

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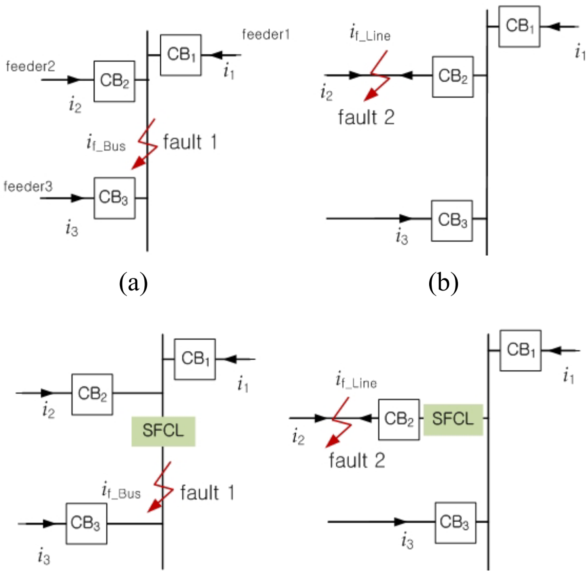
burden on the SC element is required.

References [10] and [11] presented a method to select the SFCL's location considering the current ratio between the amount of fault current through SFCL and the amount of total fault current through the fault point when the SFCL is installed on the bus tie. However, the SFCL can be introduced at various positions, including the secondary windings on the side of the transformer, an out-going point of the feeder, or a neutral line. According to the method described in [10] and [11], the location is restricted to one position and the SFCL is required to have a high capacity so that it can accommodate a very high level of fault current, which is due to most fault current flowing through the SFCL in the worst case.

To improve the method of placement of the SFCL, the application method of the SFCL was studied considering the breaking capacity of the CB among electrical devices on a power system. There are manufacturing standards for the fault current for applications with power systems. Therefore, in order to determine the appropriate location of the SFCL, the ratio between the CB's short-circuit capacity and the fault current, called the FCI factor, is proposed as a metric.

Fig. 1 shows the flow path of the current when a fault occurs at two different locations. The fault current path of three feeders, which are each joined to the bus-bar with an intervening CB with an SFCL connected in series, should be able to handle both input and output currents.



(a) (b)

(c) (d)

Fig. 1. Current path when a simple fault occurs in case that the SFCL is attached to bus-tie: (a) Case without SFCL where fault occurs at bus-tie; (b) Case without SFCL where fault occurs at feeder 2; (c) Case with SFCL on bus-tie where fault occurs at bus; (d) Case with SFCL on feeder 2 where fault occurs at feeder 2.

First, if a fault occurs on the bus-tie without the SFCL, as seen in Fig. 1(a), the equation of the total fault current on the fault point can be expressed as follows:

$$i_{\mathrm{fault1}} = i_1 + i_2 + \mathrm{i}_3, \tag{1}$$

where i_{fault1} is the total fault current at the fault point, and i_1, i_2, and i_3 are the fault currents flowing through each feeder, respectively. As a result of (1), the fault current could exceed the CB's short-circuit capacity. However, the fault current flowing through the CB, which is designed to endure the fault current from each feeder's fault sufficiently without exceeding the breaking capacity of each CB, is represented as follows:

$$i_{\mathrm{CB1}} = i_1,\ i_{\mathrm{CB2}} = i_2,\ i_{\mathrm{CB3}} = i_3, \tag{2}$$

where i_{CB1}, exactly equal to i_1 because CB1 is installed on feeder 1 to protect itself, is the fault current through CB1. Therefore, to separately investigate the fault current corresponding to each CB, any current that exceeds its short-circuit capacity must be considered.

Otherwise, if a fault occurs on feeder 2 without the SFCL, as shown in Fig. 1(b), the expression of the total fault current is similar to (1) because all currents flow through the fault point. The expression is presented as follows:

$$i_{\mathrm{fault2}} = i_1 + i_2 + i_3 \tag{3}$$

In spite of an identical total fault current at the fault point, when analyzing the fault current flowing through the CB, a different equation from (2) must be utilized, which is described as follows:

$$i_{\mathrm{CB1}} = i_1,\ i_{\mathrm{CB2}} = i_1 + i_3,\ i_{\mathrm{CB3}} = i_3 \tag{4}$$

From (4), when analyzing the fault current corresponding to each CB, the fault current flowing through CB2 was increased because of the summation of both i_1 and i_3 from the bus to the fault point, though the fault currents flowing through CB1 and CB2 were not changed by the bus fault state. If the total current of the feeder has a maximum magnitude equal to the fault current when a fault occurs at fault point 2, CB1 and CB2 could be interrupted, but CB3 would not because of its remaining breaking capacity.

To reduce the fault current, when an SFCL with the capability to limit fault current to within the breaking capacity of the CB is introduced, as shown in Fig. 1(c) and (d), the amount of fault current flowing through the CB should be recalculated.

Using the results that include the effects of the SFCL, the equation to describe the degree of risk (DR) from a fault current that is enough to open the CB can be estimated as follows:

$$\text{Degree of Risk (DR)} = \frac{\sum_{x=1}^{n} i_x \ \text{[kA]}}{i_{\text{CB's breaking capacity}} \ \text{[kA]}} \tag{5}$$

where the denominator is the short-circuit breaking capacity of the CB, and the numerator is summation of all currents flowing through the CB from the opposite side of the fault point.

If one of the fault currents from one of the feeders is reduced by the SFCL, DR also decreases. However, the CB stably eliminates the fault current in excess of the CB's short-circuit capacity by limiting the fault current and thus maintaining the operation of the power electrical equipment in the power system. As a result of the estimation of DR with or without the introduction of the SFCL, the location of the SFCL considering the effects of limiting fault current should be determined within a large margin. In addition, in order to involve effects such as insulation and lifetime, whose impacts change according to the magnitude of fault current, weighting factors for different effects are also considered. In this paper, the weighting factor is classified as shown in Table 1, according to the value of the DR [16].

Table 1. Weighting factor according to the DR.

DR	Weight value (W)
$r \le 0.5$	0
$0.5 < r \le 1$	1
$r > 1$	2

Table 2. Setting parameters of SFCL

HTSC element	value	unit
Convergence resistance (R_n)	5	Ω
Time constant (T_F)	0.01	s
Critical current (I_C)	10,000	A
1st and 2nd recovery slopes (a_1, a_2)	-80, -160	1/s
2nd recovery starting resistance (Rr_2)	2.5	Ω

Finally, the equation for the decision of the SFCL's location, which multiplies the DR and weight value, can be presented as follows:

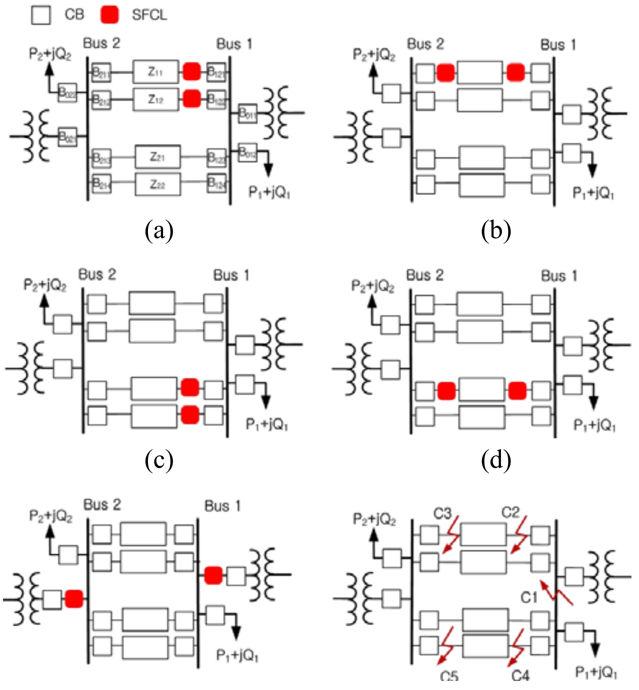
$$\text{Fault Current Index (FCI)} = \text{DR} \times \text{Weight value}. \tag{6}$$

3. Results and Discussion

To select the location of SFCL using the suggested method, a simple power system was configured that consists of a main transformer, power transfer line, and CB to protect the power system, as shown in Fig. 2 with detailed specifications of the power system and current distribution at normal condition in Tables 3 and 4. In Fig. 2(a)-(e), five cases are studied in which the FCI factor is estimated in order to determine the best location of the SFCL. Formations such as two SFCLs on both sides of the same line, one SFCL on one side of two lines, and one SFCL on each second winding side of two main transformers are presented. The operating characteristics of the SFCL are fixed and the analysis is performed according to several fault points located on the line near the bus and on the bus, as shown in Fig. 2(f). The detailed configurations of the power system and the parameters of the SFCL for these cases are shown in Tables 1 and 2.

Table 3. Parameters of the power system

Source	value	unit
Bus 1	6,080 + j720	MVA
Bus 2	180 + j900	MVA
Line impedance	**value**	**unit**
$Z_{11} = Z_{12}$	1.07 + j 15.4	Ω
$Z_{21} = Z_{22}$	0.77 + 11.84	Ω
Load capacity	**value**	**unit**
$P_1 + jQ_1$	48.2 + j13.3	MVA
$P_2 + jQ_2$	5870.9 + j1134.7	MVA



(a) (b) (c) (d) (e) (f)

Fig. 2. Configurations of power system for case studies to determine the best location for the SFCL through estimation, considering the CB's breaking capacity.

From the computer simulation using the parameters in Tables 1 and 2, five cases were analyzed. Table 3 lists the fault currents at various locations of the fault point when the entire fault current flows through the CB and lists the FCI in the case where the short-circuit breaking capacity of the CB is 40 kA without the SFCL.

In Table 5, the cases (C1, C2, C3, C4, and C5) indicate the fault points shown in Fig. 2(f). The numbers in the subscripts of the measurement points represent the position of the CB, where the first number denotes the output bus, the second number denotes the input bus, and the last number denotes the CB's code. For example, B121 is

Table 4. Current distribution in normal condition

→	CB	Current	CB	Current
Flowing through CB	B_{011}	13.02	B_{021}	2.98
	B_{012}	0.1	B_{022}	9.94
	B_{121}	2.41	B_{211}	2.41
	B_{122}	2.41	B_{212}	2.41
	B_{123}	4.05	B_{213}	4.05
	B_{124}	4.05	B_{214}	4.05

Table 5. Fault current in three-phase short-circuit fault without SFCL and estimation results of FCI when CB breaking capacity is 40 kA.

Cases Fault current	measurement point	C1	C2	C3	C4	C5
At fault point	i_{fault}	62.47	62.47	56.82	62.47	51.12
flowing through CB	B_{011}	22.18	22.18	16.07	22.18	15.95
	B_{121}	11.11	55.34	16.91	11.11	8.98
	B_{122}	11.11	11.11	16.91	11.11	8.98
	B_{123}	8.59	8.59	7.13	56.66	17.03
	B_{124}	8.59	8.59	7.13	8.59	17.03
	B_{021}	22.18	22.18	16.07	22.18	15.95
	B_{211}	11.1	11.1	41.94	11.1	8.97
	B_{212}	11.1	11.1	16.92	11.1	8.97
	B_{213}	8.58	8.58	7.12	8.58	35.2
	B_{214}	8.58	8.58	7.12	8.58	17.04
∑FCI		2.49	5.17	3.34	5.32	1.96

located on a line near bus 1 through which current flows from bus 1 to bus 2, and it is the first CB among 6 CBs near bus 1. According to the results from the simulation, in spite of the current at all of the fault points exceeding the CB's short-circuit breaking capacity of 40 kA, the short-circuit breaking capacity of only a small number of CBs was exceeded.

Using the fault current, the FCI could be calculated by (6), which is the product of the DR of (5) and the weighting factor of Table 1. Among the values of the summation of the FCI, the worst was due to the high fault currents in the cases of C2 and C4 where the CB is not stably operated. To reduce the fault current, the SFCL was applied at various positions, as shown in Fig. 2 (a)-(e).

Table 4 arranges the results of the FCI factor to determine the optimum location to introduce the 5-Ω resistive-type SFCL in the power system. From the results, the FCI is improved in all cases. In cases where the SFCL was installed on the lines, as shown in Fig. 2(a) and (b) or Fig. 2(c) and (d), the table shows a large effect.

In addition, it was better to apply the SFCL on both sides of the same line (Fig. 2(b) and (d)) than to apply it on one side of two lines (Fig. 2(a) and (c)). The average value is useful in analyzing the FCI against the overall fault location when the SFCL was introduced according to the cases in Fig. 2. In this case, the best solution was to introduce the SFCL on both sides of the same line with lower the impedance of the line.

Table 7 lists the amount of fault current on the fault point and the maximum fault current flowing through the CB, which is when the FCI shows its maximum decrease. The maximum fault current includes cases with and without the SFCL and all locations of the SFCL.

Table 6. Summation of FCI in order to determine overall effect in power system according to case studies between application locations of SFCL and fault locations with 5-Ω Resistive-type SFCL.

Cases SFCL location	C1	C2	C3	C4	C5	Ave.
(a)	2.40	2.61	2.81	5.31	1.96	3.016
(b)	2.48	2.60	1.48	5.31	1.96	2.764
(c)	2.41	5.17	3.34	2.72	1.93	3.114
(d)	2.29	5.05	2.83	1.51	0.74	3.194
(e)	2.28	4.87	2.83	5.03	1.95	3.392

Table 7. Fault current at fault point and maximum fault current among various currents flowing through CB when FCI shows maximum reduction with and without SFCL.

		C1	C2	C3	C4	C5
Without SFCL	i_{fault}	62.47	62.47	56.82	62.47	51.12
	$i_{CB\,Max}$	32.87	55.34	41.94	56.66	35.20
With SFCL	i_{fault}	59.35 (95.0%)	46.91 (75.1%)	51.80 (91.1%)	44.39 (71.1%)	45.80 (89.6%)
	$i_{CB\,Max}$	28.07 (85.4%)	40.99 (74.0%)	35.52 (84.7%)	38.52 (67.8%)	29.46 (83.7%)

In Table 7, similar to Table 3, the fault current in all locations exceeded the CB's short-circuit breaking capacity, though the 5-Ω resistive-type SFCL decreased the fault current.

However, it was confirmed that the fault current flowing through the CB that exceeded its short-circuit breaking capacity was reduced compared to the case without the SFCL. If the resistance of the SFCL was increased, the fault current would be decreased to less than the CB's breaking capacity. Therefore, the FCI was better because the fault case at C2 was better with the application method, as shown in Fig. 2(b), and all fault locations could interrupt the short circuit to protect the components of the power system.

By estimating the ratio between the CB's short-circuit capacity and fault current, we could determine the appropriate location of the SFCL and the best application method.

4. Conclusion

In this study, an investigation of the selection of the location and application method of the SFCL was performed considering the breaking capacity of the interruptive devices in the power system. Through the analysis of several case studies considering the fault locations and application methods, the ratio between the CB's short-circuit capacity and the fault current, also known as the fault current index

(FCI) factor, was estimated. By using the FCI factor with PSCAD / EMTDC simulations for the case studies, the location and application method of the SFCL was investigated to keep the fault current under the CB's short-circuit breaking capacity.

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Kim, Jin-Seok He received his B.S. degree from Electrical Engineering at Seoul National Univ. of Science and Technology in 2007 and his M.S. degree from Electrical Engineering at Soongsil Univ. in 2009. Currently, he is studying for his Ph.D. degree at Soongsil Univ. Korea.

Lim, Sung-Hun He received his B.S., M.S., and Ph.D. degrees from Chonbuk National Univ., Korea in 1996, 1998, and 2003, respectively. Currently, he is an Assistant Professor at Soongsil University, Korea. Currently, he is a professor in the Dept. of Electrical Engineering at Soongsil Univ. Korea.

Kim, Jae-Chul He received his B.S. degree from Electrical Engineering at Soongsil Univ. in 1979 and his M.S. and Ph.D. degrees from Seoul National Univ. in 1983 and 1987, respectively. Currently, he is a professor in the Dept. of Electrical Engineering at Soongsil Univ. Korea