An Optimal Location for Superconducting Fault Current Limiter Considering Distribution Reliability

Sung-Yul Kim, In-Su Bae and Jin-O Kim

***Abstract*-- As electric power demand has constantly been increasing, more bulk power systems have been installed in a network. For environmental and technical reasons, the amount of distributed resources is increasing considerably in a distribution network. Therefore, distribution networks have become more complex mesh networks, which improve the reliability of distribution system and the flexibility of network operation. These changes cause fault current to increase. As a result, the fault current will exceed the rated capacity of a circuit breaker in a network. In order to solve this problem, replacing breaker, changing operation mode of system and rectifying transformer parameters can be taken into account. Considering technical and economical aspects, however, one of the most promising power apparatuses is a superconducting fault current limiter(SFCL).**

Recently, various superconducting devices have been developed in the field of power system. Especially, through constant researches, SFCLs have been put to practical use in distribution network as well as in transmission network.

This paper proposes a methodology for determining the optimal location of an SFCL. The location is determined by considering the decrement of fault current flowing from each component and the increment of reliability changing with the customer type. With case studies on method of determining the optimal location for an SFCL applied to a radial network and a mesh network respectively, it is proved that the proposed method is feasible.

***Index Terms*—optimal location, superconducting fault current limiter, distribution reliability.**

I. Introduction

A distribution network is currently being constructed with mesh structure. This construction helps distribution network improve the reliability and flexibility of power delivery. As electric demand increases constantly however, distribution network impedance has become lower due to construction equipment, and the problems of fault current are expected to become more serious. Moreover international environmental regulations of the leaking carbon become effective to keep pace with the global efforts for low-carbon paradigm, and high quality reliable power is needed for particular customers. These contribute to spread out the business of distributed generation(DG). It will accelerate the problem of fault current in network. As the circuit breakers in the power systems no longer cope with enlarging fault current in the near future, a lot of ideas to protect the power system have been suggested such as replacing breaker, changing operation mode of system, applying series reactor, replacing transformers and rectifying transformer parameters. Considering their technical, political and economic difficulties, the superconducting fault current limiter(SFCL) is one of the most promising power apparatus. [1,2,3]

Superconductivity is a phenomenon occurring in certain materials generally at very low temperatures, characterized by exactly zero electrical resistance and the exclusion of the interior magnetic field as the Meissner effect. The material has this characteristics is regarded as superconductor. A SFCL is a new-type device which limits the prospective fault current when a fault occurs in a network using the behavioral characteristics of superconductors. It can detect a fault current directly as the quench process without any additional devices and limit a fault current by resistivity of superconducting materials. Otherwise in normal condition, the resistance of SFCL is almost zero, so most of the current flows through a circuit without electric power loss. In spite of these marvelous merits, it is yet to be perfectly solved such as a size and price of SFCL and adjustment of existing protective relay system.

II. The Properties of Superconducting Fault Current Limiter

The major roles of SFCL are to limit fault current quickly and complete recovery of superconductivity when a fault occurs. According to characteristics of SFCL quenching, it can be subcategorized into resistive, inductive and commutated. [4,5] This paper presents the characteristics and operation process of a resistive SFCL.

The quench and recovery characteristics of resistive SFCL are presented in Fig. 1. and Eq. (1)

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978-1-4244-6551-4/10/$26.00

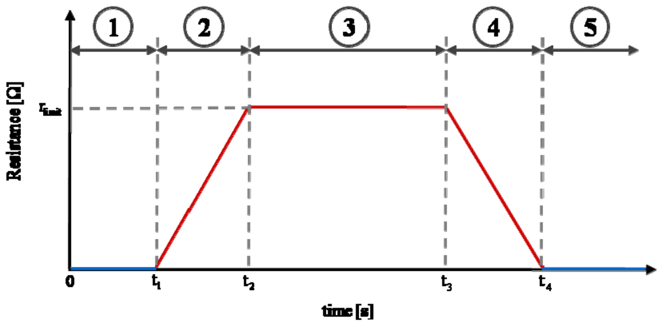

Fig. 1. The resistive characteristics of SFCL

$$f(\mathrm{t}) \begin{cases} 0 & (\mathrm{t} < \mathrm{t}_1 \ , \mathrm{t} \geq \mathrm{t}_4) \\ \mathrm{r}_{\mathrm{limit}} \cdot (1 - e^{-k_1 t}) & (\mathrm{t}_1 \leq \mathrm{t} < \mathrm{t}_2) \\ \mathrm{r}_{\mathrm{limit}} & (\mathrm{t}_2 \leq \mathrm{t} < \mathrm{t}_3) \\ \mathrm{r}_{\mathrm{limit}} \cdot e^{-k_2 t} & (\mathrm{t}_3 \leq \mathrm{t} < \mathrm{t}_4) \end{cases} \tag{1}$$

The section ② presents quench characteristics above higher critical current density in case fault current is injected to the faulted network. The shorter it takes to quench, the faster it converges on expected limiting fault current. And the quenching time is determined by slope coefficient k_1. In the section ③, SFCL limits fault current. is determined according to high fault current density of network. Recovery characteristics of SFCL is presented in the section ④. If it takes shorter to recover, the time to reconnect SFCL to network which is in normal condition can be minimized. It is determined by slope coefficient k_2. The section ①, ④ and ⑤ are showing behavior characteristics of superconductor in normal condition without faults whereas ② and ③ are representing those in abnormal condition where over current flows into the network due to faults.

III. An Optimal Location for Superconducting Fault Current Limiter

Considering only reduction of fault current, an optimal location of SFCL is generally LV side on transformer, bus and feeder. If DG is connected in distribution network, feasible region of SFCL will be including additionally DG terminal, it because, fault current is newly injected by DG. However these places which are defined considering only reduction of fault current are not commensurate with an improvement of distribution reliability according to installation of SFCL. Therefore, this paper newly proposes an index of fault current sensitivity by component type and an index of reliability sensitivity by customer type. And using both indices an optimal location of SFCL is determined.

A. Location of SFCL for reduction of fault current

Fault on power system are divided into balanced 3-phase fault and unbalanced fault as single line-to-ground fault, line-to-line fault and double line-to-ground fault. Balanced 3-phase fault occurs infrequently, but it is often the most severe and worst type of fault. Therefore, this fault is used to determine capacity of circuit breakers, setting parameters of protection devices and electric force added to power components. Balanced 3-phase fault is solved on a per-phase basis because the network is balanced. [6]

This paper proposes an index of fault current sensitivity($\mathrm{I}^{\mathrm{FCS}}$) based on reduction of fault current according to a location of installing SFCL. This index represents jth component's fault current deviation between after SFCL is installed in line i and before. Concurrently, this deviation is applied to weighting factor, w_j for jth component which is calculated by component's cost.

$$\mathrm{I}_i^{\mathrm{FCS}} = \sum_{j=1}^{J} \Delta I_{i,j}^{\mathrm{F}} \tag{2}$$

$$\Delta I_{i,j}^{\mathrm{F}} = w_j \cdot (I_{o,j}^{\mathrm{F}} - I_{i,j}^{\mathrm{F}}) \tag{3}$$

$$\mathrm{I}^{\mathrm{FCS}} = \begin{bmatrix} \mathrm{I}_1^{\mathrm{FCS}} & \mathrm{I}_2^{\mathrm{FCS}} & \cdots & \mathrm{I}_I^{\mathrm{FCS}} \end{bmatrix} \tag{4}$$

where i is a line where SFCL is installed. j means jth component among total number of components, J, and $\Delta I_{i,j}^{\mathrm{F}}$ is the amount of fault current deviation for jth component when SFCL is installed in ith line or not. In this equation, i=0 means that SFCL doesn't exist in the network. Therefore $\mathrm{I}_i^{\mathrm{FCS}}$ represents the sum of fault current deviation for each component when SFCL is installed in ith line, and $\mathrm{I}^{\mathrm{FCS}}$ includes index of fault current sensitivity according to all candidate lines for SFCL placement.

This index proposed in this paper is applied to determine an optimal location of SFCL as an essential factor. Higher value of index of fault current sensitivity according to a location of SFCL means more suitable place to install SFCL from a viewpoint of fault current reduction.

B. Location of SFCL for improvement of reliability

When SFCL is installed in distribution network, it can make distribution reliability changed. Therefore, in order to evaluate the effects of SFCL, distribution reliability should be analyzed depending on all location of SFCL placement.

1) Component reliability according to fault current path

Failure rate by fault current which is a factor of failures for a component is different from each other. And fault current of each component will decrease when SFCL is added to a system, it makes failure rate of each component improve. The effect of fault current reduction in a distribution network differs according to a location of SFCL placement.

$$\lambda_{o,k,e} = \lambda_{o,k,e}^{\text{fault current}} + \lambda_{o,k,e}^{\text{degraded operation}} + \lambda_{o,k,e}^{\text{worn}} + \lambda_{o,k,e}^{\text{arcing}} \cdots \tag{5}$$

$$\lambda_{i,k,e} = (1\text{-}\lambda_{o,k,e}^{\text{fault current}} \cdot \eta_{i,k,e}) \cdot \lambda_{o,k,e} \tag{6}$$

Failure rates for event e at kth load before SFCL is installed in a network and after SFCL is installed in ith line are represented in Eqs. (5) and (6), respectively. $\lambda_{o,k,e}^{\text{fault current}}$ means failure rate only caused by fault current for event e at kth load when SFCL doesn't exist in a network, and $\eta_{i,k,e}$ is fault current reduction efficiency of failure rate for event e at kth load when SFCL is installed in ith line.

2) Estimation of distribution reliability

Various indices are used to evaluate distribution reliability. [6,7,8] However, all characteristics of a distribution network can't be represented through one of these distribution reliability indices. Therefore, this paper proposes a distribution reliability index which is composed with traditional indices to estimate distribution reliability. It can consider the effects of SAIDI(System Average Interruption Frequency Index), ASUI(Average Service Unavailability Index) and AENS(Average Energy Not Supplied) concurrently from various points of view. The proposed index, WLRI(Weighted-Load Reliability Index) is represented in Eqs. (7) and (8).

$$\mathrm{WLRI}_{i,k} = \sum_{m=1}^{3} w_m \cdot R(m,i,k) \tag{7}$$

$$R(m,i,k) = \begin{cases} \dfrac{\sum_{e\in\forall\ \text{interruption events}} \lambda_{i,k,e} N_k}{\sum_{k=1}^{K} N_k} & (m=1) \\[2ex] \dfrac{\sum_{e\in\forall\ \text{interruption events}} r_{i,k,e} N_k}{8760\cdot\sum_{k=1}^{K} N_k} & (m=2) \\[2ex] \dfrac{\sum_{e\in\forall\ \text{interruption events}} r_{i,k,e} L_k}{\sum_{k=1}^{K} N_k} & (m=3) \end{cases} \tag{8}$$

where w_m is weighting factor by the significance of mth reliability, and $\lambda_{i,k,e}$, $r_{i,k,e}$, N_k, L_k are failure rate, repair time, the number of customers and the amount of load, respectively.

3) a reliability sensitivity index

Reliability sensitivity index is newly proposed to determine a change of distribution reliability according to an installation location of SFCL. A feasible location of SFCL can be resolved via this proposed index for reliability improvement of customers.

$$\mathrm{I}_i^{\mathrm{RS}} = \sum_{k=1}^{K} \Delta\mathrm{WLRI}_{i,k} \tag{9}$$

$$\Delta\mathrm{WLRI}_{i,k} = w_k \cdot (\mathrm{WLRI}_{o,k} - \mathrm{WLRI}_{i,k}) \tag{10}$$

$$\mathrm{I}^{\mathrm{RS}} = \left[\mathrm{I}_0^{\mathrm{RS}}\ \mathrm{I}_1^{\mathrm{RS}}\ \cdots\ \mathrm{I}_{i-1}^{\mathrm{RS}}\ \mathrm{I}_i^{\mathrm{RS}}\right] \tag{11}$$

where $\mathrm{I}_i^{\mathrm{RS}}$ represents reliability sensitivity when SFCL is installed in ith line, and $\Delta\mathrm{WLRI}_{i,k}$ is the amount of weighted-load reliability deviation for kth load before SFCL is installed in ith line and after. w_k is determined by considering CIC(Customer Interruption Cost) of each customer[9] and is applied to the deviation as a weighting factor by the significance of kth load. Higher index of reliability sensitivity according to a location of SFCL means more suitable place to install SFCL from a viewpoint of distribution reliability improvement.

C. Optimal location of SFCL

Finally, an optimal location of SFCL should be determined considering fault current reduction and reliability improvement when SFCL is installed in distribution network. Both effects can be evaluated by indices of fault current sensitivity and reliability sensitivity. Therefore Index of the optimal location of SFCL is expressed as

$$\mathrm{I}_i^{\mathrm{OLS}} = \alpha\cdot\mathrm{I}_i^{\mathrm{FCS}} + \beta\cdot\mathrm{I}_i^{\mathrm{RS}} \tag{12}$$

where α and β are factors to adjust the scale of each index, and the sum of these factors is equal 1.

IV. Case Study and Discussion

Distribution networks connected with DG are used in the following tests. RBTS 2 bus is modified in each case. [10,11] Circuit breaker, line switch and fuse are considered as protection devices in these networks. It is assumed that failure rate of transformer, circuit breaker and line switch is affected by fault current reduction due to SFCL installation and failure rate of fuse is no longer improving after SFCL is installed in a network on the assumption that fuse operates perfectly. Impedance of SFCL to limit fault current is 1pu and balanced 3-phase fault is considered to evaluate effects when SFCL is installed.

A. Case I : a simple radial network

The network which is connected with a DG is used to determine the optimal location of SFCL. The structure is a simple radial network shown in Fig. 2. DLF method is used to calculate power flow in the network as preparation for evaluating fault current. [12]

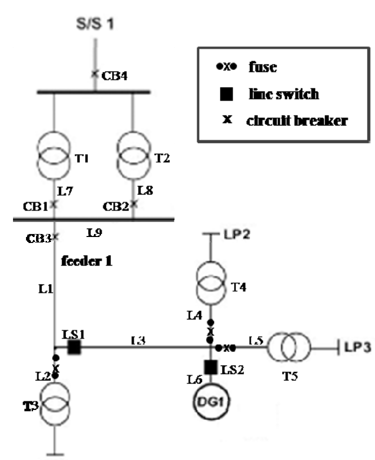

Fig. 2. Case I: modified RBTS 2 bus

Customer, component reliability, system data and output of DG are shown in Tables 1,2 and 3, respectively.

Table 1. Customer data

k	load	type	peak load		number of customers	w_k
			[kW]	[kVAR]		
1	LP1	residential	932	450	250	0.7
2	LP2	residential	874.2	400	200	0.7
3	LP3	residential	918.4	450	240	0.8

Table 2. Reliability and system data

component	failure rate	repair time	switching time
154/22.9[kV]	0.015 [f/yr]	15	
22.9/0.230[kV]	0.015 [f/yr]	10	
22.9[kV] bus	0.001 [f/yr]	2	
22.9[kV] line	0.065 [f/km yr]	5	
circuit breaker	0.006 [f/yr]	4	1
line switch	0.01 [f/yr]	3	0.5

Table 3. The output of DG

DG	generation	
	[kW]	[kVAR]
DG1	1000	700

It is assumed that failure rates of circuit breaker, line switch and 154/22.9 [kV] transformer only caused by fault current are 0.0018, 0.002 and 0.00525, respectively. Balanced 3-phase fault is simulated to entire lines in a network. Fault current for each component is analyzed at that time according to a location for SFCL placement. Then, component's failure rate can be estimated.

The result of fault current sensitivity which is considering significance of each component and reliability sensitivity which is considering significance of each customer is shown in Table 4.

Table 4. Indices of fault current sensitivity and reliability sensitivity

i	location of SFCL	I^{FCS}	I^{RS}
1	L1	24.5759	0.00840970
2	L3	18.4639	0.00559263
3	L6	13.2230	0.00248238
4	L7	5.8878	0.00450170
5	L8	5.8853	0.00450170
6	L9	4.4638	0.00450173

where α and β are the coefficients to adjust scale of each index, and their values are 0.99959, 0.00041, respectively calculated by using the sum of each index. Therefore, from Table 4, an index of optimal location of SFCL, I^{OLS} can be calculated as shown in Table 5.

Table 5. Case I: an index of optimal location of SFCL

i	location of SFCL	I^{OLS}
1	L1	0.01857
2	L3	0.01323
3	L6	0.00795
4	L7	0.00694
5	L8	0.00691
6	L9	0.00635

Without DG in a radial network, SFCL is generally located in LV side on transformer, bus or feeder because fault current is injected from LV side on transformer to fault point. However if we consider the effects of DG in a network, then most of fault current will flow from LV side on transformer and DG to fault point. Considering fault current reduction of components and reliability improvement of customers, the result of this case I shows line L1 which is feeder nearby LV side on transformer and bus is the optimal location to install SFCL.

B. Case II: a mesh network

In Case I, proposed method to determine the optimal location of SFCL is implemented in a simple radial network. In case II, this method is applied to a more complex system composed with a mesh network where feeders 1 and 2 are connected each other and a radial network from feeder 3. Fig. 3. shows a mesh network connected with DGes. Newton-Raphson method is used to calculate power flow in the network as preparation for evaluating fault current. [13,14]

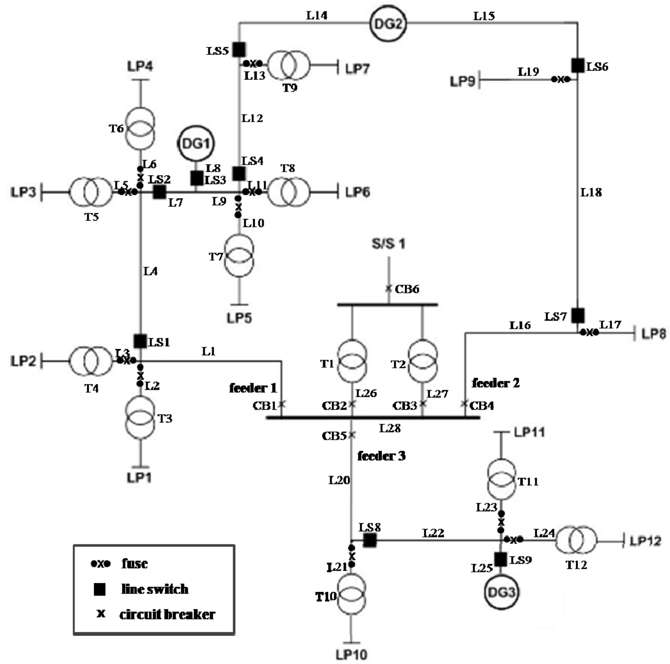

Fig. 3. Case II: Modified RBTS 2 bus

Customer data is shown in Table 6. Data in Table 2 are applied to this network as reliability and system data.

Table 6. Customer data

k	load	type	peak load		number of customers	w_k
			[kW]	[kVAR]		
1	LP1	residential	866.8	400	210	0.5
2	LP2	residential	920.4	450	210	0.5
3	LP3	residential	824.2	400	210	0.6
4	LP4	commercial	750	300	10	1.5
5	LP5	commercial	690	300	10	1.2
6	LP6	commercial	814	400	10	1.0
7	LP7	commercial	740	370	10	1.5
8	LP8	large user	1627.9	800	1	1.6
9	LP9	large user	1872.1	900	1	1.7
10	LP10	residential	932	450	250	0.7
11	LP11	residential	874.2	400	200	0.7

12	LP12	residential	918.4	450	240	0.8

The output of DGes is shown in Table 7.

Table 7. The output of DGes

DG	generation	
	[kW]	[kVAR]
DG1	800	600
DG2	1200	800
DG3	1000	700

It is assumed that failure rates of circuit breaker, line switch and 154/22.9 [kV] transformer only caused by fault current share the same value in case I.

The coefficients to adjust scale of each index, α and β are 0.99941, 0.00059, respectively, calculated by using the sum of each index. As a result, index of fault current sensitivity, reliability sensitivity and the optimal location of SFCL are depicted as shown in Fig. 4.

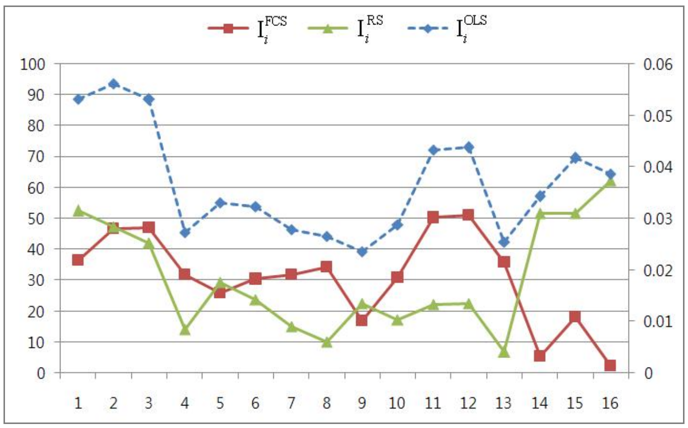

Fig. 4. Case II: indices for candidate locations of SFCL

Considering simply reduction of fault current for SFCL placement, to install a SFCL on feeder 3 is more effective than feeders 1 and 2 because these feeders are connected each other and it makes another path of fault current. Taking into account reliability improvement with index of reliability sensitivity, the bus nearby LV side on transformer is the most feasible location for SFCL installation. In conclusion, considering both sides of fault current and reliability, line L4 is an optimal location for SFCL placement, then lines L1, L7 and L22 are better choices for SFCL placement. Line L4 is close to DG1 and feeder 1. Most of fault current by all tested balanced 3-phase fault flows on the path, L4, and it makes component's reliability improved.

V. Conclusion

This paper proposes indices of fault current sensitivity and reliability sensitivity according to SFCL installation. It also proposes the method of determining the optimal location by considering not only reduction of fault current but improvement of distribution reliability when SFCL is installed in a distribution network. With case studies on method of determining the optimal location for SFCL applied to a radial and a mesh network which are connected to DG, a more sensitive location for SFCL placement to reduce fault current and improve reliability has been determined. The test results have demonstrated that the proposed method is efficient and feasible.

This work has been supported by KESRI(R-2008-38), which is funded by MKE(Ministry of Knowledge

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