Reliability Evaluation of Distribution Network With DG Considering the Reliability of Protective Devices Affected by SFCL

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***Abstract*—This paper proposes a reliability model for a superconducting fault current limiter (SFCL), which is a new alternative in limiting the fault current recently increasing in a network. An evaluation technique for distribution reliability that uses the improved failure rate of all protective devices in a network, depending on the location of the SFCL, is also proposed. As a result, it is expected that the SFCL makes the reliability of adjacent equipment on an existing network improve, and these changes are analyzed. In addition, in order to apply the effect of the intermittent output of renewable-energy sources, distribution reliability indices were redefined in this paper. Case studies verify that the SFCL is effective in reducing fault currents and improving distribution reliability. These effects are analyzed with respect to the location of the SFCL in a case study system.**

***Index Terms*—Power distribution reliability, reliability model, superconducting fault current limiter (SFCL).**

I. INTRODUCTION

RECENTLY, environmental regulations for the reduction of the emission of carbon worldwide have included carbon taxes, and cap and trade systems. In Korea, the renewable portfolio standard mandates utilities, and other load-serving entities procure a significant portion of their customers' electricity needs from renewable power. This regulation has led to an increase in the amount of distributed energy resources in distribution networks [1]–[3]. These networks have also become complex networks to improve distribution system reliability and increase the flexibility and adaptability of network operation.

However, as electric power systems grow and become more interconnected, fault current increases in a network, and this current will exceed the maximum short-circuit capacity of transformers and protective devices. A number of responses to protect power systems have been suggested such as changing operation modes of systems, applying series reactors, replacing breakers and transformers, and rectifying transformer parameters. On the other hands, it was a fact that a superconducting fault current limiter (SFCL) is not an economical solution compared to these conventional methods. However, various aspects of the SFCL has been researched and developed. Recently, even considering the cooling facilities including liquid nitrogen and temperature sensors, the price of the SFCL is about one fifth compared with existing SFCLs. Moreover, the test bed of the SFCL is constructed in a distribution network and is being proven in Korea.

SFCLs are a new type of device that limits fault current in a network using the behavioral characteristics of superconductors [4]–[9]. It can detect a fault current directly in the quench process without any additional devices and limit a fault current by using the resistivity of superconducting materials. Under normal conditions without a fault in a network, the impedance of the SFCL is zero, which means that the SFCL operates without electric loss. In this respect, the SFCL is a promising candidate for the protective device of a high-temperature superconductor apparatus [10]–[13]. For these reasons, various techniques about SFCLs have been researched to improve quench characteristics and stable operations [14]–[17]. However, the effects of installing an SFCL in a network have not been entirely performed in the aspect of changes for distribution reliability and fault current simultaneously. Moreover, the reliability modeling for SFCLs and the analysis of the reliability for a network with an SFCL have not been performed. Therefore, this paper proposes a reliability model for SFCLs and then analyzes the effect of SFCLs in terms of reliability by considering the improved failure rate of adjacent protective devices, which is evaluated by the reduction of fault currents. In addition, an evaluation technique of the reliability for a distribution network with distributed generation (DG) is newly proposed, considering the output state of DG in this paper.

II. STRUCTURE AND RELIABILITY MODEL FOR SFCLs

SFCLs can be usually classified into hybrid and nonhybrid types [18]–[20]. Hybrid SFCLs detect fault current automatically using superconductors and operates fault current limit with additional devices such as conventional switches and the components of capacitors, inductors, or resistors. Otherwise, nonhybrid SFCLs can detect and limit fault currents by only a superconductor in contrast to the structure of the hybrid one; therefore, its structure and operation process is simple [21], [22]. SFCLs are usually fabricated in thin film, wire, or rod, and of the three, the film-type superconductor has the most compact structure. Therefore, various experiments are conducted recently in distribution networks using film-type nonhybrid SFCLs.

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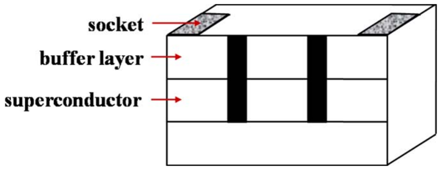

Fig. 1. Structure of a thin-film superconductor.

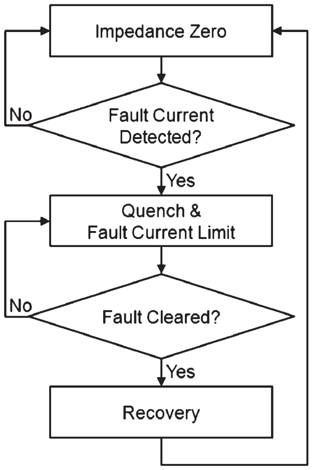

Fig. 2. Operation process for a resistive type of SFCL.

TABLE I
CAUSES AND RESULT OF SFCL WITH FILM-TYPE SUPERCONDUCTOR

Causes		Result
Superconductor & Module	Superconductor	Open
	Buffer Layer	
Socket		
Cooling System		

A. *Cause and Result of* SFCLs

This paper proposes a reliability model for film-type nonhybrid SFCLs, whose structure is shown in Fig. 1.

The operation process of SFCLs is depicted in Fig. 2 when a fault occurs in a network. The “Impedance Zero” is a state where it is connected to the distribution network without electrical power loss during normal conditions.

The SFCL can be out of order when the large fault current is injected into the SFCL commonly compared to the values of parameter setting in the initial stage. The fault of the SFCL mainly occurs on a buffer layer, superconductor, socket, or cooling system, and it makes the SFCL open at the corresponding point. The causes and result of nonhybrid SFCLs with film-type superconductor is given in Table I.

B. *Reliability Model of the SFCL*

Under normal conditions, the SFCL is rarely separated from a network, which is caused by the preliminary inspection of cooling devices, which can allow superconductors to maintain their superconductivity. Most of the faults for the SFCL are mainly due to the effects of the fault in a network itself. Considering a fault from the SFCL or the other components in a network, therefore the reliability model for the SFCL can be constructed with four states, and it is shown in Fig. 3.

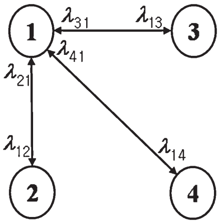

Fig. 3. Four-state reliability model for nonhybrid SFCL.

States 1 and 3 indicate that the SFCL operates perfectly under normal and abnormal conditions, respectively, where abnormal conditions mean that a fault occurs in a network. State 2 is determined as the operation of the SFCL that fails under normal conditions. The main source of this problem is the cooling devices. State 4 results from the fault of the superconductor or module or socket when a fault occurs in a network. The value of λ_{13} is the success rate where the SFCL operates perfectly after detecting a fault. The value of λ_{14} is the failure rate where the SFCL fails to limit fault current in a network, and λ_{41} is the repair rate from State 4 to State 1. If the SFCL fails to limit the fault current, the SFCL itself will be open consequently due to a fault in the network. After a fault including the malfunction of the SFCL itself and a fault in the network are cleared and repaired, the SFCL operates perfectly under normal conditions. The λ_{41} can be determined by the maximum value of repair times for the network or SFCL, as given in (1). The value of λ_{31} is the repair rate of the network. After a fault in the network is cleared, the SFCL in State 3 can be restored to normal State 1. The transition rates of λ_{12} and λ_{21} are the failure rate caused by the SFCL itself and the repair rate of the SFCL itself without any fault in a network, respectively. All the transition rates can be summarized as follows:

$$\begin{aligned}
\lambda_{12} &: \text{failure rate of the SFCL itself} \\
&\quad \text{under normal conditions} \\
\lambda_{21} &: \text{repair rate of the SFCL itself} \\
&\quad \text{without any fault in a network} \\
\lambda_{13} &: (\text{failure rate of a network}) \\
&\quad * (\text{prob. of being in state3}) \\
\lambda_{31} &: 1/(\text{mean time to repair}) \\
\lambda_{14} &: (\text{failure rate of a network}) \\
&\quad * (\text{prob. of being in state4}) \\
\lambda_{41} &: 1/\text{Max}(\text{mean time to repair}, \\
&\qquad \text{repair time of the SFCL}). \qquad (1)
\end{aligned}$$

III. RELIABILITY EVALUATION OF PROTECTIVE DEVICES AFFECTED BY THE SFCL

When a new device is connected in series to a system, the reliability of the system commonly deteriorates. The SFCL, in contrast, not only decreases the stresses on most of the devices in a network but also reduces the frequency of the excessive fault current, thereby often improving the failure rate of devices

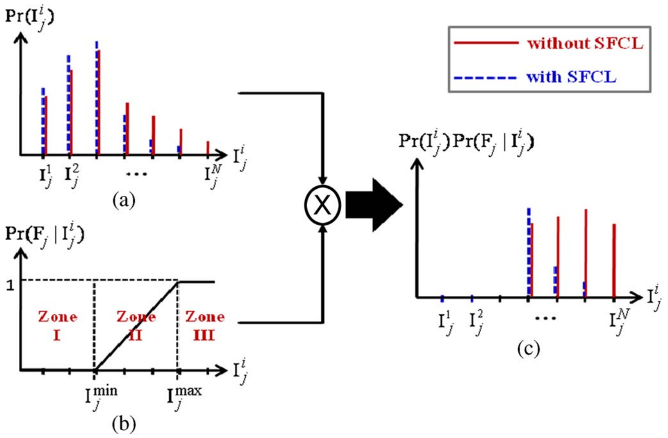

Fig. 4. Process of evaluating the failure probability density of a protective device.

[23]. Therefore, the changes of reliability for existing devices should be estimated in order to evaluate the reliability of distribution networks connected with the SFCL as a new device.

A. *Failure Probability of Protective Devices*

The magnitude of fault currents flowing in a protective device depends on a location where a fault occurs. If the SFCL is installed in a network, the fault currents will be reduced due to the inherent characteristic of the SFCL to limit fault currents in a network. Therefore, the lower currents would be observed more frequently, and the probability density function (pdf) of the fault current would also be shifted to the left side compared with the cases without the SFCL, as shown Fig. 4(a), where I_j^i is the ith rounded magnitude of the fault current passing through the jth protective device when the fault currents are discretized with equal interval.

Generally, the failure probability of protective devices can be affected by the magnitude of fault currents flowing in the corresponding protective device, as shown Fig. 4(b). In Zone I, the fault current passing through the jth protective device is smaller enough than the lower failure threshold current $I_j^{\min}$, and this device can interrupt the fault without any failure. This means that the failure probability of device is zero. On the other hand, in Zone III, the fault current exceeds the upper failure threshold current $I_j^{\max}$, and this device cannot operate successfully with failure probability 1. Zone II has the probability between 0 and 1.

The lower and upper failure threshold currents can be represented, respectively, as follows:

$$I_j^{\min} = I_j^i\big|_{i=\mathrm{Max}\{i \mid \Pr(F_j|I_j^i)=0\}} \tag{2}$$

$$I_j^{\max} = I_j^i\big|_{i=\mathrm{Min}\{i \mid \Pr(F_j|I_j^i)=1\}} \tag{3}$$

where event F_j is given as the failure of the jth protective device, and the conditional probability $\Pr(F_j|I_j^i)$ is defined as follows:

$$\Pr\left(F_j|I_j^i\right) = \frac{\Pr\left(F_j \cap I_j^i\right)}{\Pr\left(I_j^i\right)}. \tag{4}$$

Applying the total probability theorem, therefore, the failure probability of the jth protective device is defined by using the failure probability density of a protective device, as shown in Fig. 4(c).

The following equation shows that the failure probability of the jth protective device should be improved by installing the SFCL due to the shifting effect to the left side in the pdf of the fault current:

$$\Pr(F_j) = \sum_{i=1}^{N} \Pr\left(I_j^i\right) \Pr\left(F_j|I_j^i\right). \tag{5}$$

B. *Reliability of Protective Devices*

There are various reasons causing the fault in a protective device such as degraded operation, worn, arcing, and fault current. It is assumed that these reasons are independent of each other, and then, the failure rate of the jth protective device is given as

$$\lambda_{0,j} = \lambda_{0,j}^{\text{fault current}} + \lambda_{0,j}^{\text{degraded operation}} + \lambda_{0,j}^{\text{worn}} + \lambda_{0,j}^{\text{arcing}} \cdots \tag{6}$$

where subscript 0 means the network before the SFCL is installed.

The effect of fault current reduction in a network differs according to a location for installing the SFCL, and also, the failure rate of the adjacent devices is strongly affected by a location of the SFCL. The failure probability of the jth protective device before and after the SFCL is installed in the kth line can be determined as follows, respectively, and these are induced from (5)

$$\Pr(F_{0,j}) = \sum_{i=1}^{N} \Pr\left(I_{0,j}^i\right) \Pr\left(F_{0,j}|I_{0,j}^i\right) \tag{7}$$

$$\Pr(F_{k,j}) = \sum_{i=1}^{N} \Pr\left(I_{k,j}^i\right) \Pr\left(F_{k,j}|I_{k,j}^i\right). \tag{8}$$

As the SFCL reduces the magnitude of fault currents, the improved failure rate of the jth protective device after the SFCL is installed on the kth line is given as

$$\eta_{k,j} = 1 - \Pr(F_{k,j}) / \Pr(F_{0,j}). \tag{9}$$

As a result, the failure rate of the jth protective device after the SFCL is installed in the kth line is determined as follows:

$$\lambda_{k,j} = \lambda_{0,j} - \lambda_{0,j}^{\text{fault current}} \cdot \eta_{k,j}. \tag{10}$$

IV. RELIABILITY EVALUATION OF DISTRIBUTION NETWORK WITH DG

Fig. 5 depicts the simple case in order to explain the reliability of distribution with DG, which is proposed in this paper. Table II presents customer data of this simple system, and it is assumed that DG can operate independently.

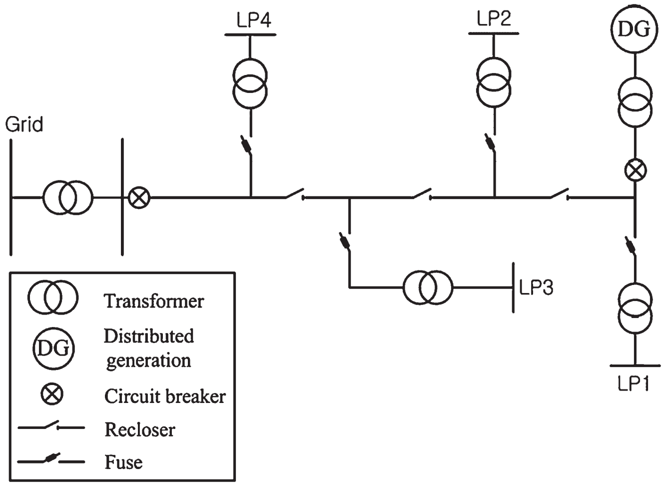

Fig. 5. Distribution network with DG.

TABLE II
CUSTOMER DATA

Load Point (LPl)	Number of Customers (N_l)	Average Load [kW] (L_l)
LP1	500	2000
LP2	700	3000
LP3	800	4000
LP4	1000	5000
Total	3000	14000

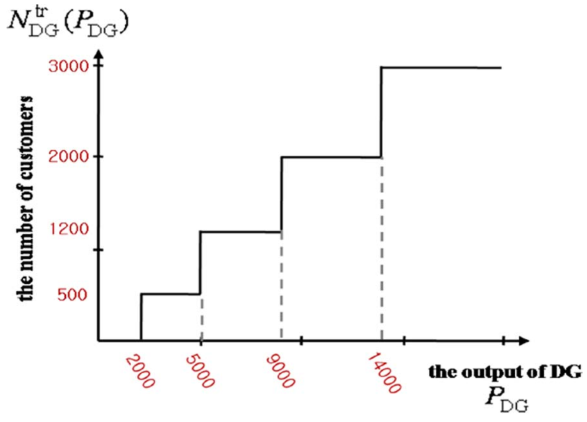

Fig. 6. Number of customers depending on the output of DG.

For example, it is assumed that the output of DG is 6000 kW under abnormal conditions, and then, DG can supply reliable electric energy in LP1 and LP2. However, LP3 cannot be supplied at all from DG in spite of the surplus electric energy, i.e., 1000 kW.

The following equation presents the number of customers to demand reliable electric energy with respect to the output of DG in this simple system using unit function:

$$N^{\mathrm{tr}}_{\mathrm{DG}}(P_{\mathrm{DG}}) = N_1 \cdot U(P_{\mathrm{DG}} - L_1) + \cdots + N_4 \cdot U\left(P_{\mathrm{DG}} - \sum_{l=1}^{4} L_l\right) \quad (11)$$

where P_{DG} means the output of DG, and it can be briefly illustrated in Fig. 6.

As a result, (11) can be generalized into the following:

$$N^{\mathrm{tr}}_{\mathrm{DG}}(P_{\mathrm{DG}}) = \sum_{\forall \text{load point } l} N_l \cdot U\left(P_{\mathrm{DG}} - \sum_{l=1}^{l} L_l\right). \quad (12)$$

The number of customers possibly supplied by DG in responding to a fault is defined as N^{tr}_{f}, which depends on the structure of the network. When a fault occurs in a network, the number of customers who are supplied with energy from DG is estimated by the output of DG and the structure of the network. Therefore, this can be proposed as follows:

$$N^{\mathrm{tr}}_{\mathrm{DG},f}(P_{\mathrm{DG}}) = \min\left\{N^{\mathrm{tr}}_{\mathrm{DG}}(P_{\mathrm{DG}}), N^{\mathrm{tr}}_{f}\right\}. \quad (13)$$

Using the following proposed equations, the system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), and energy not supplied index (ENS), which are commonly used to evaluated the distribution reliability [24], [25], can be redefined as a function of the DG output:

$$\mathrm{SAIFI}(P_{\mathrm{DG}}) = \frac{\sum_{\forall \text{load point } l} N_l - \sum_{\forall \text{fault } f} N^{\mathrm{tr}}_{\mathrm{DG},f}(P_{\mathrm{DG}})}{N_T} \quad (14)$$

$$\mathrm{SAIDI}(P_{\mathrm{DG}}) = \frac{\sum_{\forall \text{fault } f} \sum_{\forall \text{load point } l} r'_l \cdot \left(N_l - N^{\mathrm{tr}}_{\mathrm{DG},f}(P_{\mathrm{DG}})\right)}{N_T} \quad (15)$$

$$\mathrm{ENS}(P_{\mathrm{DG}}) = \sum_{\forall \text{load point } l} L_{a(l)}(P_{\mathrm{DG}}) \cdot r'_l \quad (16)$$

where r'_l means the time to repair the fault on load point l, and $L_{a(l)}(P_{\mathrm{DG}})$ is the average load connected to load point l not supplied with the output of DG.

All power systems are exposed to varying weather conditions. DGs, particularly including wind power and photovoltaic generation, are affected by the weather effects, and these types of generation are incorrectly considered as intermittent energy sources. Therefore, the combination of the output states of DG is determined, considering the effects of weather to evaluate the more accurate reliability of a network [26]–[28], and therefore, SAIFI, SAIDI, and ENS can be expressed using the stochastic output of DG as follows:

$$\mathrm{SAIFI} = \sum_{\forall P_{\mathrm{DG}}} \Pr(P_{\mathrm{DG}}) \cdot \mathrm{SAIFI}(P_{\mathrm{DG}}) \quad (17)$$

$$\mathrm{SAIDI} = \sum_{\forall P_{\mathrm{DG}}} \Pr(P_{\mathrm{DG}}) \cdot \mathrm{SAIDI}(P_{\mathrm{DG}}) \quad (18)$$

$$\mathrm{ENS} = \sum_{\forall P_{\mathrm{DG}}} \Pr(P_{\mathrm{DG}}) \cdot \mathrm{ENS}(P_{\mathrm{DG}}). \quad (19)$$

These SAIFI, SAIDI, and ENS, finally, are used to analyze the distribution reliability, considering the effects of the intermittent output of DGs.

The process to evaluate the reliability of the distribution network with DGs and SFCL is expressed in Fig. 7 and summarized as four steps:

1) determine the reliability models for SFCL and DG;

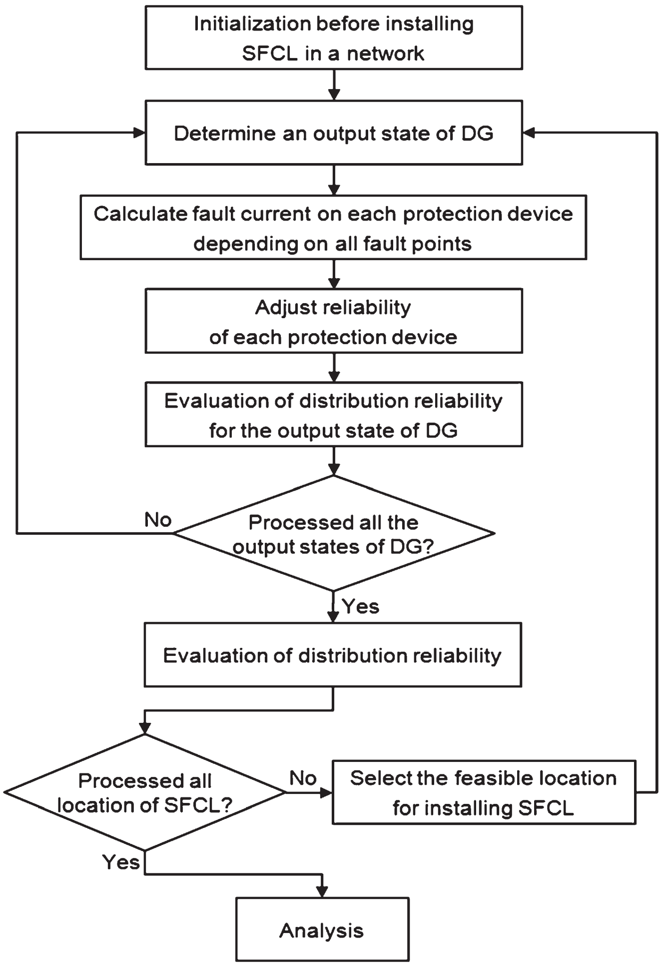

Fig. 7. Flowchart for the evaluation reliability of distribution network with SFCL and DGs.

2) analyze fault currents on each protective device before installing SFCL in a network;
3) analyze fault currents on each protective device with respect to the location of the SFCL, and adjust the failure probability of each protective device, considering the failure density and failure probability function;
4) evaluate the reliability of a network, considering the output state of DGs and the reliability model for the SFCL.

V. CASE STUDY AND DISCUSSION

The case system in Fig. 8 is studied in the distribution network with DGs, which are composed of 3-MW class (DG1, 2) and 20-MW class (DG3). The circuit breaker, line switch, and fuse are considered as protective devices in this case study system. The failure rate of these devices is affected by the fault current reduction, depending on each location of the SFCL.

Without DG in a radial network, the SFCL is generally located in the low-voltage (LV) side on the transformer, bus, or feeder, because the fault current is injected from the LV side on the transformer to the fault point. However, if we consider the effects of DG in a network, then most of fault currents will flow from the LV side on the transformer and also the output terminal of DG to the fault point. Therefore, the location is postulated on the LV side of the main transformer (Case 1), the front side of the feeder with first line (Case 2), and the output terminal of DG3 (Case 3), respectively. Each case study has two subcategories in order to evaluate the effect of the reliability model of the SFCL. The first subcategory (Case #-1) is assumed to have the failure probability of the SFCL to be zero. The reliability model for the SFCL proposed in this paper is applied in the second subcategory (Case #-2), where the probability of being in State 3 of the SFCL reliability model is 0.995 when a fault occurs in a network and the SFCL itself fails with a probability of 0.01 in the normal network.

A. *Base Case: Before Installing SFCL*

The protective devices are assumed to operate with a probability of 0.85, and their reliability and customer data are given in Tables III and IV, respectively.

The number of customers and average load in each load point are given here.

The output states of DGs are considered as wind generations with actual wind data in Korea. The stochastic output model of DG is simplified to six states, and it is calculated in Table V.

In the base case, the distribution reliability indices in each state of DGs such as SAIDI, SAIFI, and ENS are depicted in Fig. 9.

Over State 4 of DG, these indices in Fig. 9 are improved like the simple example in Section 4. The reason is that the electrical load connected to DG1 or DG2 can be served, even if a fault occurs in this network when the output of DG1 and DG2 are over States 4 and 5, respectively. As the output state of DG is increased, $\mathrm{SAIFI}(P_{\mathrm{DG}})$, $\mathrm{SAIDI}(P_{\mathrm{DG}})$, and $\mathrm{ENS}(P_{\mathrm{DG}})$ are also improved. SAIFI, SAIDI, and ENS are finally calculated using the probability being that each output state of DG and these results are shown as "total" in Fig. 9.

B. *Cases 1, 2, and 3: After Installing SFCL*

In Cases 1, 2, and 3, the distribution reliability is calculated by applying the improved failure rate of protective devices with respect to the location of the SFCL. The improved failure rate of each device is adjusted based on the failure probability $(\Pr(F_{0,j}))$ of the protective device before installing the SFCL.

In order to calculate fault currents in a network, Monte Carlo simulation is performed, as usual, by randomly choosing one of the locations among all lines. It is assumed that $\lambda_{0,j}^{\text{fault current}}$ is 0.09 and that the failure probability function of protective devices has the lower failure threshold current $(I_j^{\min})$, i.e., 5 pu, and the upper failure threshold current $(I_j^{\max})$, i.e., 20 pu [see Fig. 4(b)]. The failure probability density of protective devices can be induced from this failure probability function and the probability density of each device depending on a location of SFCL, and then, the improved failure rate is calculated using this failure probability density of protective devices before and after the SFCL is installed in a network. For example, Fig. 10 provides the process in order to evaluate the improved failure rate of CB2 in each case. The probability density of CB2 via fault currents is shown in Fig. 10(a)–(d). These data are

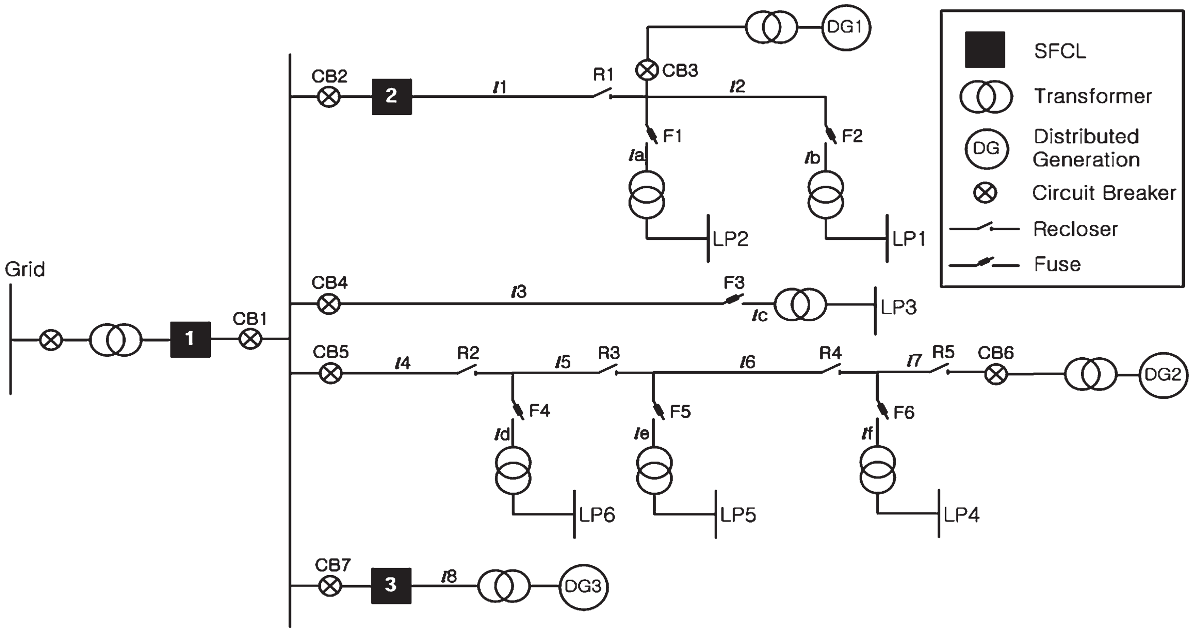

Fig. 8. Case study system.

TABLE III
RELIABILITY DATA FOR PROTECTIVE DEVICES

Protection Device	Repair Time [hour]	Switching Time [hour]
Circuit Breaker	1	
Recloser	1	0.01
Fuse	0.5	

TABLE IV
CUSTOMER DATA

Load Point	Number of Customers (N_l)	Average Load [kW] (L_l)
LP1	1000	1500
LP2	800	4500
LP3	700	9000
LP4	100	2000
LP5	50	1000
LP6	250	6000
Total	2900	24000

TABLE V
DG DATA OF SIX-STATE MODEL

State	1	2	3	4	5	6
The output of DG [pu]	0	0.2	0.4	0.6	0.8	1.0
Probability	0.101	0.095	0.190	0.188	0.098	0.327

convolved with the failure probability function. As a result, the failure probability density of CB2 is shown in Fig. 10(e)–(h), and the improved failure rates of CB2 in each case are calculated by (7)–(9). All the improved failure rates in each case are depicted in Fig. 11.

These improved failure rates confirm that the failure rates for most of protective devices are improved. In particular, the improved failure rate of the device nearby SFCL (CB1, CB2, and CB7 for cases 1, 2, and 3, respectively) is equal to 1, which means that the SFCL perfectly removes the sources of malfunctioning of the device from the fault currents over the lower failure threshold current. The process of this result, for instance, is validated in Fig. 10(c) and (g). On the other hand, the magnitude of fault currents on some devices such as R3, R4, and F6 increases compared to that without SFCL in a network, because the impedance near these devices decreases relatively, depending on the location of the SFCL and the structure of the network.

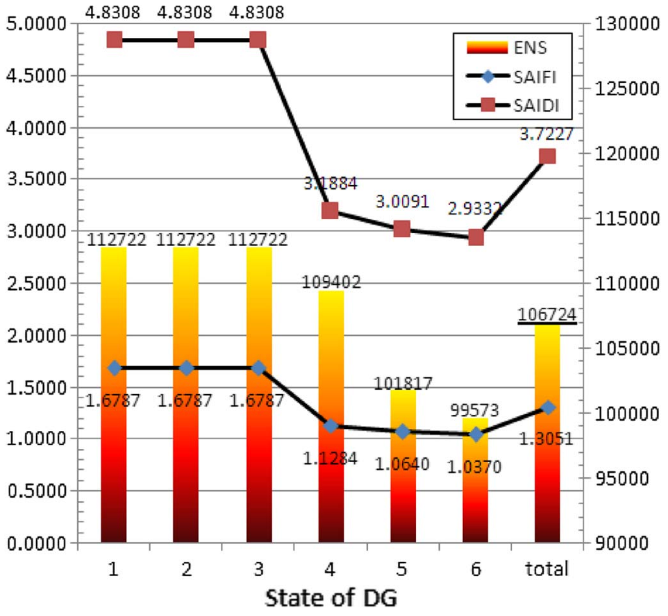

Fig. 9. Base case: Distribution reliability indexes in each state of DGs.

The average improved failure rates are 0.23 in Case 1, 0.17 in Case 2, and 0.10 in Case 3. Considering only the effect of the fault current reduction, therefore the LV side of the main transformer (Case 1, which has the largest improved failure rates) is the optimal location for the SFCL with respect to fault current reduction.

The proposed methodologies for reliability evaluation of distribution network with SFCL and DGs were performed

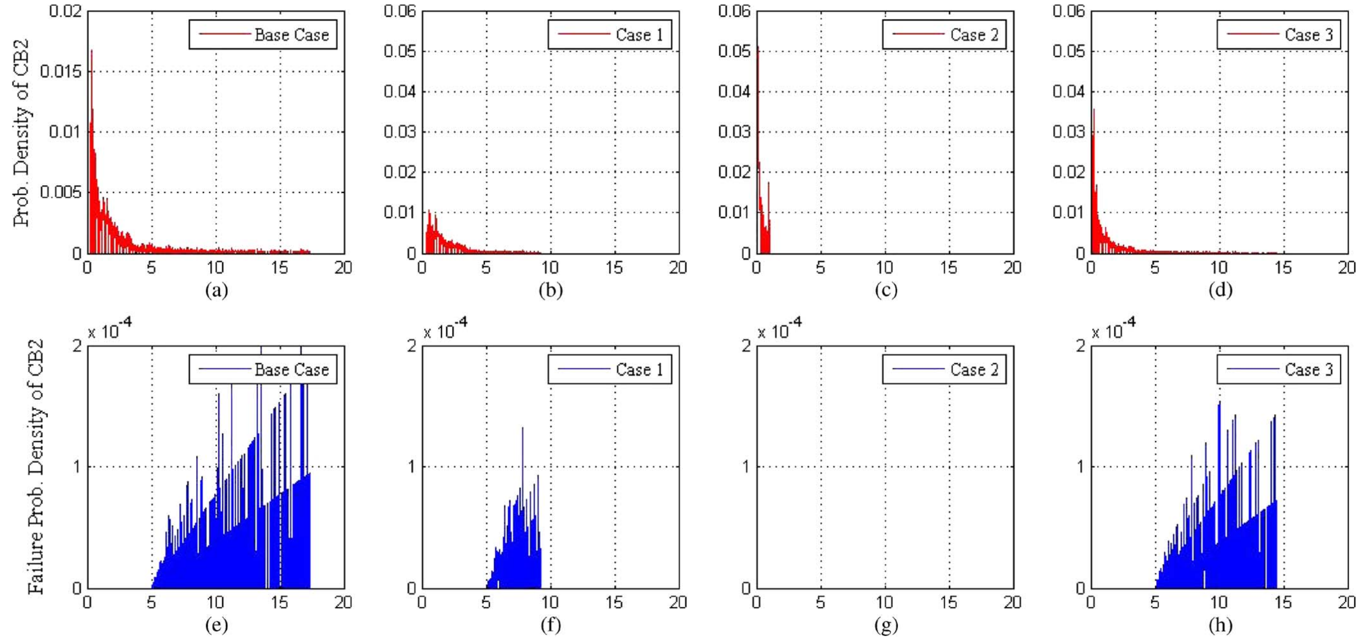

Fig. 10. (a)–(d) Probability density of CB2 case by case. (e) and (f) Failure probability density of CB2 case by case.

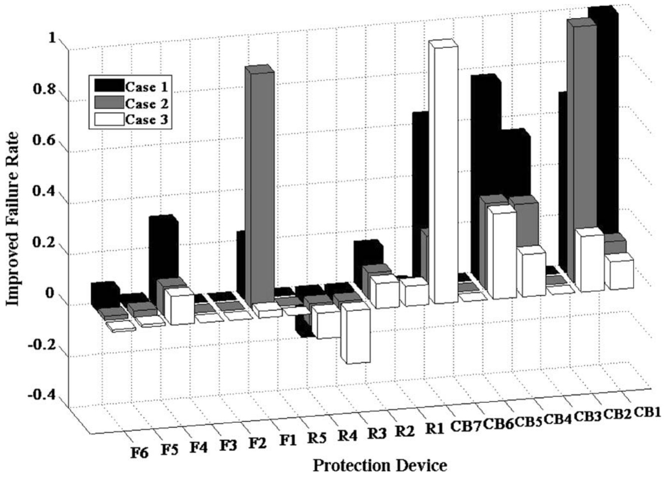

Fig. 11. Improved failure rate of protective devices case by case.

TABLE VI
DISTRIBUTION RELIABILITY INDICES IN EACH CASE

	Case	SAIFI	SAIDI	ENS
	Base	1.3051	3.7227	106724
Case #-1	**1-1**	**1.1923**	**3.6155**	**103697**
	2-1	1.2260	3.6479	104195
	3-1	1.2529	3.6728	105368
Case #-2	**1-2**	**1.2241**	3.7175	106604
	2-2	1.2474	3.7162	**105203**
	3-2	1.2556	**3.6746**	105384

by considering the improved failure rate of devices and the stochastic output of DGs. Table VI shows the result of distribution reliability indexes in this case study.

When the SFCL operates perfectly (Case #-1), the LV side (Case 1-1) is probably the optimal location for the SFCL in the table, followed by the front side of the feeder with the first line (Case 2-1) and the output terminal of DG3 (Case 3-1). These results mean that the location for the SFCL in Case 1 has the greatest effect on the reduction of fault currents over the lower failure threshold current. In addition, these analyses are entirely consistent with the order of the average improved failure rates in all cases.

Considering the proposed reliability model of the SFCL (Case #-2), ENS is the most improved when the SFCL is located in the front of the feeder (Case 2-2). In terms of SAIFI and SAIDI, the LV side of the main transformer (Case 1-2) and the output terminal of DG3 (Case 3-2), respectively, are the optimal points. These results are more suitable, compared with the results of Case #-1 because of considering not only the effects of fault current reduction in each case but also the effects of the fault of the SFCL itself as a device connected newly in each case.

Generally, the fault of the SFCL itself can deteriorate distribution reliability in a network. However, the analysis in the case study proves that the SFCL may lead to improvement of failure rates in each adjacent protective device. This also means that installing SFCL may help improve distribution reliability. Therefore, it is necessary for analysis distribution reliability to be affected by the reliability model of the SFCL and the improved failure rate additionally. In order to analyze the changes in distribution reliability according to the improved failure rate, it is assumed that the identical improved failure rate in each device is adjusted, instead of applying different improved rates, as shown in Fig. 11. SAIFI and SAIDI in Case 1 are evaluated by this assumption and depicted in Fig. 12.

As shown in Fig. 12, SAIFI and SAIDI are improved proportionally to the improved failure rate of protective devices. Both indexes with SFCL, which operates perfectly (Case 1-1), are generally improved over the range of the entire improved failure rate, compared with the base case. This result is due to not only absolutely no fault for the SFCL itself but also the improved failure rate of adjacent protective devices.

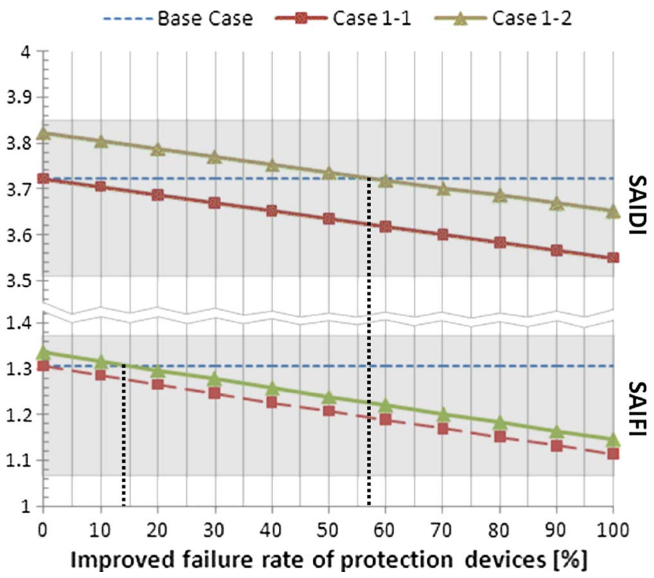

Fig. 12. SAIDI and SAIFI versus the improved failure rate.

Considering the reliability model for practical SFCL, which is proposed in this paper (Case 1-2), SAIFI is improved compared with the base case when the improved failure rate is 14% or over only and SAIDI is improved over 57%. In other words, there exists an equilibrium point at which the reliability index with the SFCL is equal to that without the SFCL according to the improved failure rate of protective devices in each case. In order to improve the distribution reliability with SFCL compared with that without SFCL, therefore it is important to have the improved failure rate over this equilibrium point, and it can be realized by searching for the feasible location of the SFCL where the improve failure rate is as high as possible.

VI. CONCLUSION

Recently, various technologies using the characteristics of superconductivity have been deployed on a commercial scale. One of the most promising facilities applying these technologies is SFCLs. This paper has proposed a reliability model for SFCLs in order to accurately evaluate the reliability of a distribution network where an SFCL is located. Then, the failure rate of adjacent protective devices is reestimated, considering the reduction in the fault current. Additionally, SAIFI, SAIDI, and ENS are newly redefined when a network is composed of DG, which generates electrical energy intermittently. When a fault occurs in a network, the number of customers who are supplied electric energy with respect to the output of DG is suggested.

As a new device is connected in series to a system, the reliability of the entire system usually deteriorates [26]. However, in our method, the results from case studies confirm that the SFCL can help improve the distribution reliability. We ascertain that the equilibrium points for each distribution reliability index exist, considering a network with and without SFCL. Therefore, this paper confirms the potential of SFCLs in the aspect of distribution reliability.

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