Optimal Placement of Superconducting Fault Current Limiters (SFCLs) for Protection of an Electric Power System with Distributed Generations (DGs)

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Abstract—**Power flow patterns and fault current levels are influenced by the introduction of distributed generations (DGs) in an electric power system. In particular, the change in the fault current levels caused by DG installation may require a change in the coordination of relays to prevent their misoperation. When DGs are installed in an electric power system, superconducting fault current limiters (SFCLs) can be used to help reduce the fault currents within the breaking capacity of the protective devices. In this paper, multiple criteria such as the number of SFCLs, fault current reduction, and the total operating time of the relays are considered in order to determine the optimal placement of SFCLs for protection of an electric power system with DGs, and a scenario optimization based approach is used to solve the multi-criteria SFCL placement problem. Numerical simulations are also carried out to demonstrate the effectiveness of the proposed approach.**

Index Terms—**Distributed generation (DG), relay coordination, superconducting electric power, superconducting fault current limiter, system studies for superconducting devices.**

I. INTRODUCTION

POWER FLOW patterns and fault current levels are influenced by the introduction of distributed generations (DGs) in an electric power system. In particular, the change in the fault current levels caused by DGs may require new protective devices with higher breaking capacities and/or modification of the relay coordination to prevent misoperation of the relays.

Various methods such as the disconnection of all DGs in the event of a power system fault, the use of fault current limiters (FCLs) [1], and the use of an adaptive relay [2] have been proposed to solve the problems caused by DGs. In the past several years, there has been growing interest in the use of superconducting fault current limiters (SFCLs) [3]–[5] as an alternative to FCLs to limit the fault current in the event of a power system fault.

When DGs are installed in an electric power system, SFCLs can be used to help reduce fault currents to within the breaking capacity of the protective devices. However, it is not economically desirable to place expensive SFCLs for individual DGs to be installed. Several methods have been developed for determining the optimal placement of SFCLs in an electric power system. Some of the criteria used for determining the optimal placement of SFCLs include the total SFCL capacity [6], sensitivity [7], and fault current reduction [8]. In addition, the operation of relays needs to be considered along with these criteria when determining the optimal placement of SFCLs for protection of an electric power system with DGs. Therefore, this optimal placement of SFCLs needs to be formulated as a multiple-attribute decision-making (MADM) [9] problem.

In order to solve MADM problems, it is necessary to identify the appropriate weight for each criterion. In general, the weighting methods used to find the appropriate weight for each criterion can be divided into two categories: subjective methods and objective methods. An objective method such as an entropy measure (EM)-based weighting method [10] is more commonly used for determining the appropriate weight for each criterion, since there is difficulty in obtaining reliable weights with a subjective method.

This paper presents a scenario optimization based approach for determining the number and locations of SFCLs for protection of an electric power system with DGs. Multiple criteria such as the number of SFCLs, fault current reduction, and the total operating time of relays are considered. A scenario optimization [11] is used to handle the multi-criteria SFCL placement problem, and an EM-based method is also used to select the weight for each criterion.

II. MULTI-CRITERIA SFCL PLACEMENT PROBLEM

A. Placement of SFCLs in an Electric Power System

While various SFCLs such as resistive SFCLs [3], hybrid resistive SFCLs [4], and inductive SFCLs [5] have been developed, hybrid resistive SFCLs are considered in this study. The operation scheme of a hybrid resistive SFCL is illustrated in Fig. 1. The load current is less than the critical current during normal operation, when switch S1 is open and switch S2 is closed. In this state, the load current flows through the high-temperature superconductor, which is in a superconducting state. On the other hand, when a fault occurs, switch S1 is closed and switch S2 is open, and the fault current flows through the current-limiting resistor, which has a higher impedance.

The candidate sites for installing SFCLs in an electric power system need to be determined first. In this paper, all possible locations are considered as candidate sites for installing a SFCL, as shown in Fig. 1. These include the high-voltage (HV) side of the system, the DG, or the line. In order to reduce

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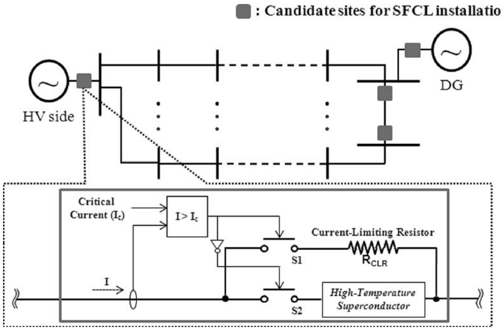

Fig. 1. Operation scheme of hybrid SFCL and candidate sites for installation.

the fault current levels throughout the system, a SFCL could be located on the HV side of the system or at the DGs. It is also possible to install an SFCL on a line near a bus to reduce the fault current to lower than the breaking capacity of the protective devices on the line.

B. Multi-Criteria SFCL Placement Problem Formulation

The addition of DGs to a power system can increase the fault current levels and thereby affect the relay coordination. The increase in the maximum fault current due to the presence of new DGs may make new protective devices with higher breaking capacities necessary. In addition, modification of the relay coordination may also be required, since the changes in the fault current patterns caused by the DGs can affect the relay coordination. The strategic placement of SFCLs can help reduce the maximum fault current to within the breaking capacity of the protective devices. However, the SFCL placement can also have an impact on the relay coordination by altering the fault currents. Therefore, a new relay coordination is needed after the placement of SFCLs to prevent any misoperation of the relays due to the DGs.

In this paper, the total operating time of the primary relays is considered in determining the optimal placement of SFCLs for protection of an electric power system with DGs. Furthermore, it is also necessary to optimize the number of SFCLs to be installed, since the installation and operation costs of SFCLs increase with the number of SFCLs. Hence, other criteria such as the number of SFCLs and the fault current reduction also need to be considered simultaneously.

In this study, the multi-criteria SFCL placement problem is decomposed into a scenario subproblem and a tracking problem. Then, scenario optimization is applied to obtain a solution to the scenario subproblem for all scenarios and to solve the tracking problem to determine the best scenario. In this subsection, the scenario subproblem and tracking problem for the optimal placement of SFCLs are formulated as the following (1)–(10).

1) Scenario Subproblem—Overcurrent Relay Coordination:

a) Objective function: The overall operating time of the primary relays varies depending on the placement of SFCLs. The objective function related to the total operating time of the primary relays, i.e., Z_1^s, can be expressed as follows:

$$\text{Minimize} \quad Z_1^s = \sum_{i=1}^{N_{\mathrm{PR}}} t_i^s \tag{1}$$

where N_{PR} is the number of primary relays; and t_i^s is the operating time of the i-th primary relay in scenario s.

b) Overcurrent relay coordination constraint:

– *Coordination Time Interval Requirement*

$$t_{j,i}^s - t_i^s \ge \Delta t^{\min} \tag{2}$$

$$t_i^s = \left[\frac{A}{(M)^C - 1} + B\right] \mathrm{TDS}_i^s,$$
$$M = \frac{I_{f,i}^{\max,s}(z_{\mathrm{DG}}, z_{\mathrm{SFCL}})}{I_{\mathrm{pickup},i}^s} \tag{3}$$

where t_i^s and $t_{j,i}^s$ denote the operating time of the i-th primary relay and the j-th backup relay for the i-th primary relay in scenario s, respectively; $\Delta t^{\min}$ is the coordination time interval (CTI), which is usually assumed to be between 0.2 s and 0.5 s; $I_{\mathrm{pickup},i}^s$ and TDS_i^s are the pickup current and time dial setting of the i-th relay in scenario s, respectively; $I_{f,i}^{\max,s}(z_{\mathrm{DG}}, z_{\mathrm{SFCL}})$ is the maximum fault current seen by the i-th relay incorporating the transient impedance z_{DG} of the DG and the impedance z_{SFCL} of the SFCL in scenario s; M is the ratio of maximum fault current to the pickup current; and A, B, and C are characteristic parameters of the relay.

– *Pickup Current Limits of Relay Unit*

$$I_{\mathrm{load},i}^{\max}(P_{\mathrm{DG}}, Q_{\mathrm{DG}}) \le I_{\mathrm{pickup},i}^s \le I_{f,i}^{\min}(z_{\mathrm{DG}}, z_{\mathrm{SFCL}}) \tag{4}$$

where $I_{\mathrm{load},i}^{\max}(P_{\mathrm{DG}}, Q_{\mathrm{DG}})$ and $I_{f,i}^{\min}(z_{\mathrm{DG}}, z_{\mathrm{SFCL}})$ are the maximum load current considering the active power output P_{DG} and reactive power output Q_{DG} of the DG and minimum fault current through the i-th relay, respectively.

– *Time Dial Setting Limits of Relay Unit*

$$TDS_i^{\min} \le TDS_i^s \le TDS_i^{\max} \tag{5}$$

where $\mathrm{TDS}_i^{\min}$ and $\mathrm{TDS}_i^{\max}$ are the minimum and maximum time dial setting of the i-th relay, respectively.

2) Tracking Problem—Optimal Placement of SFCLs:

a) Objective functions: In addition to the total operating time of the primary relays, the number of SFCLs and the fault current reduction are also considered in finding the optimal placement of SFCLs as follows:

– *Number of SFCLs to be Installed*

The objective function related to the number of SFCLs, i.e., Z_2^s, can be expressed as follows:

$$\text{Minimize} \quad Z_2^s = n_{\mathrm{SFCL}}^s \tag{6}$$

where n_{SFCL}^s is the number of installed SFCLs in scenario s.

– *Fault Current Reduction*

The objective function related to the reduction in average fault current due to the installation of SFCLs, i.e., Z_3^s, can be expressed as follows:

$$\text{Minimize} \quad Z_3^s = \frac{1}{N_F} \sum_{f \in F} \frac{I_{f,\mathrm{after}}^s(z_{\mathrm{DG}}, z_{\mathrm{SFCL}})}{I_{f,\mathrm{before}}(z_{\mathrm{DG}})} \tag{7}$$

where $I_{f,\mathrm{before}}(z_{\mathrm{DG}})$ and $I_{f,\mathrm{after}}^s(z_{\mathrm{DG}}, z_{\mathrm{SFCL}})$ are the fault current before and after SFCL installation in scenario s, respectively, and N_F is the number of elements in the set F of faults.

Considering the multiple criteria in the SFCL placement problem, the combined objective function in the tracking problem can be formulated as follows:

$$\text{Minimize} \quad \left(\frac{w_1 Z_1^s}{\sum\limits_{s \in S} Z_1^s} + \frac{w_2 Z_2^s}{\sum\limits_{s \in S} Z_2^s} + \frac{w_3 Z_3^s}{\sum\limits_{s \in S} Z_3^s} \right) y_s \tag{8}$$

where w_1, w_2, and w_3 are the weights assigned to the overall operating time of the relays, the number of SFCLs, and the fault current reduction, respectively; and y_s is a binary variable that is 1 if scenario s is selected from the set S of scenarios as the best scenario and 0 otherwise.

b) Breaking capacity of protective device constraint:

$$I_{f,i}^{\max,s}(z_{\mathrm{DG}}, z_{\mathrm{SFCL}}) \le I_{f,i}^{\mathrm{BC}} \tag{9}$$

where $I_{f,i}^{\mathrm{BC}}$ represents the breaking capacity of the protective device associated with the i-th relay.

c) Scenario selection constraint:

$$\sum_{s \in S} y_s = 1 \tag{10}$$

III. MULTI-CRITERIA SFCL PLACEMENT METHOD USING SCENARIO OPTIMIZATION WITH ENTROPY MEASURE

In order to solve the multi-criteria SFCL placement problem in Section II, it is necessary to identify the appropriate weight for each criterion. EM [7] is commonly adopted to determine the weight for each criterion and involves computing the entropy for the criterion and selecting the preferred feasible scenarios with the determined weights. For simplicity of notation, the following variable is defined to represent the different criteria of the SFCL placement problem:

$$x_b^s = \begin{cases} n_{\mathrm{SFCL}}^s, & b = 2 \\ \frac{I_{f,\mathrm{after}}^s(z_{\mathrm{DG}}, z_{\mathrm{SFCL}})}{I_{f,\mathrm{before}}(z_{\mathrm{DG}})}, & b = 3 \end{cases} \tag{11}$$

where x_b^s represents the value for the b-th criterion of the SFCL placement problem in scenario s.

In this section, the EM-based method is proposed in conjunction with scenario optimization to sequentially solve the scenario subproblem and the tracking problem in the multi-criteria SFCL placement problem by selecting the weight for each criterion. The procedures of the proposed method can be summarized as follows:

Step 1) Perform the load flow to obtain the maximum load current in a power system with DGs.

Step 2) Create SFCL placement scenarios with various maximum numbers and locations of SFCLs. The number of scenarios m is given in (12):

$$m = \sum_{k=0}^{N_{\mathrm{SFCL}}} \binom{N_{\mathrm{location}}}{k} \tag{12}$$

where N_{SFCL} represents the maximum number of SFCLs; $N_{\mathrm{locations}}$ denotes the number of candidate locations for the SFCLs to be installed; and k is the number of SFCLs to be installed in each scenario.

Step 3) Calculate the near-end fault currents seen by the primary and backup relays for each scenario and the reduction in the average fault current.

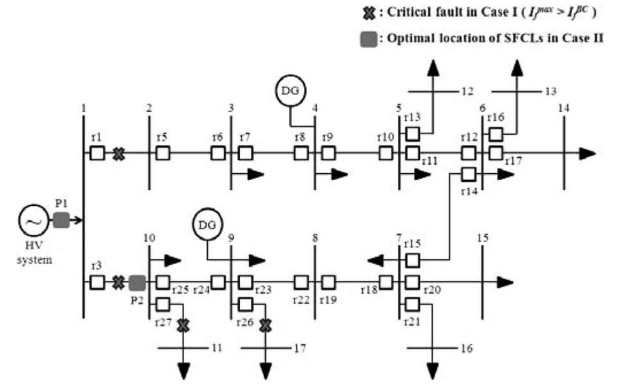

Fig. 2. 17-bus test system with DGs.

Step 4) To facilitate comparison of different criteria, perform normalization of all data in each scenario using

$$P_b^s = \frac{x_b^s}{\sum\limits_{s=1}^{m} x_b^s}, \quad s = 1, 2, \ldots, m, \quad b = 2, 3, \ldots, n \tag{13}$$

where P_b^s represents the normalized value for the b-th criterion; n is the total number of criteria; and m is the total number of scenarios.

Step 5) Determine weight w_b for each criterion by calculating its entropy, i.e., E_b, using

$$E_b = -\frac{1}{\log m} \sum_{s=1}^{m} P_b^s \log P_b^s, \quad s = 1, 2, \ldots, m, \quad b = 2, 3, \ldots, n \tag{14}$$

$$w_b = \frac{1 - E_b}{\sum\limits_{b=1}^{n} (1 - E_b)}, \quad b = 2, 3, \ldots, n. \tag{15}$$

Step 6) Reduce the number of scenarios to only the feasible scenarios within the lowest 10% as ranked using

$$\sum w_b P_b^s, \quad \forall s \in S. \tag{16}$$

Step 7) Solve the scenario subproblem, i.e., the overcurrent relay coordination problem, and then perform the EM method (Step 4 and Step 5) with the data for all criteria including the results obtained from the scenario subproblem.

Step 8) Solve the tracking problem to determine the best scenario, i.e., the number and locations of SFCLs. If all scenarios are found to be infeasible in the tracking problem, extend the region of the feasible scenarios in the scenario subproblem, go back to the Step 7, and repeat the algorithm.

IV. NUMERICAL SIMULATION RESULTS

The proposed method is tested using the 17-bus test system with a rated voltage at 22.9 kV, as shown in Fig. 2. In this study, the HV side of the test system is assumed to be a virtual generator with high capacity. The test system is protected by the directional overcurrent relays. The characteristics of the relays are selected on the basis of the IEEE standard for overcurrent relays [12]. In addition, the circuit breakers (CBs) are assumed to have a 12.5 kA breaking capacity. Two DGs with 10 MVA capacities are installed in the test system. They are connected

TABLE I
TOTAL OPERATING TIME OF RELAYS AND FAULT CURRENT FROM BUS 1 FOR A LINE FAULT BETWEEN BUS 1 AND BUS 2

	Total Operating Time (s)	Fault Current (A)
Case I (w/o SFCL)	12.60	13,844
Case II (w/ SFCL)	14.17	11,905

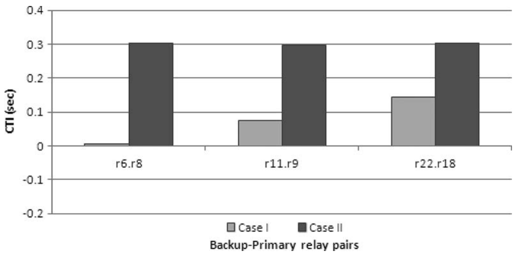

Fig. 3. Comparison of CTIs obtained from Case I and Case II.

to bus 4 and bus 9, respectively. A 22.9 kV, 630 A hybrid resistive SFCL is considered in this study. The critical current and resistance of the current-limiting resistor in the SFCL are assumed to be 1.4 kA and 0.4 Ω, respectively. In addition, N_{SFCL} is assumed to be four.

The presence of DGs results in an increased fault current in the test system. Cases with and without SFCLs installed are compared to show how the SFCL placement influences the fault currents and relay coordination. In this paper, Case I represents the case without installed SFCLs and Case II represents the case with SFCLs of 0.4 Ω installed as determined by the proposed method. A three-phase fault is applied in the test system.

Table I shows the total operating time of the primary relays and the largest fault current on the line for the fault. It can be observed from Table I that the fault current in Case I exceeds the 12.5 kA breaking capacity of the CBs in the test system. The proposed SFCL placement method is applied to determine the number and best locations of the SFCLs for the test system with DGs. The optimal number of SFCLs for Case II is found to be two, and the optimal locations are P1 and P2. On the other hand, it can be seen from Case II in Table I that the fault current is reduced to within the breaking capacity of CBs after two SFCLs are installed at the locations determined by the proposed method. These results show that the SFCL placements determined by the proposed method effectively reduce the increased fault current due to the presence of DGs to within the breaking capacity of the CBs. Table I also shows that the total operating time of the relays for Case II is longer than that for Case I when the existing settings of the relays are maintained.

Fig. 3 shows a comparison of the CTIs obtained from Case I and Case II. As can be seen from Case I in Fig. 3, the directional overcurrent relays do not normally operate when the original relay setting of the test system without DGs is maintained for the test system with DGs. In fact, 3 relay pairs do not meet the CTI requirements. On the other hand, Case II in Fig. 3 shows that the relays satisfy the CTI requirements after two SFCLs are placed at the optimal locations and the modification of the relay coordination is performed.

In order to examine how the resistance of the SFCL influences the outcome of this study, further case studies have been conducted for different resistance values of the SFCL. Table II shows the SFCL placements obtained for different SFCL resistance values. For Case II, two SFCLs of 0.4 Ω are needed to reduce the fault currents to within the breaking capacity of the CBs. In contrast, the optimal number of SFCLs is one for Cases III and IV, and the optimal location is P1. This is because a single SFCL of 1 Ω (or 2 Ω) is enough to reduce the fault currents to within the breaking capacity of the CBs for Cases III and IV.

TABLE II
SFCL PLACEMENT RESULTS FOR DIFFERENT RESISTANCE VALUES OF SFCL

	Resistance of SFCL	The number of SFCLs	Locations of SFCLs
Case II	0.4 Ω	2	P1 and P2
Case III	1 Ω	1	P1
Case IV	2 Ω	1	P1

It can be concluded from these results that the SFCL placement determined by the proposed method can reduce the fault current to within the breaking capacity of the CBs while meeting the CTI requirements of the relays.

V. CONCLUSION

In this paper, multiple criteria such as the number of SFCLs, fault current reduction, and the total operating time of the relays are considered in determining the optimal placement of SFCLs for protection of an electric power systems with DGs. An EM-based method is proposed to select the weight for each criterion and is used in conjunction with scenario optimization to sequentially solve the scenario subproblem and the tracking problem in the multi-criteria SFCL placement problem. The numerical results show that SFCL placement determined by the proposed method can help reduce the fault current to within the breaking capacity of the protective devices while meeting the CTI requirements of the relays.

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