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Optimal coordination of overcurrent protection in the presence of SFCL and distributed generation

Saeed ASGHARIGOVAR[1,2,*], **Heresh SEYEDI**[1], **Shahram PARCHEHBAF DIBAZARI**[3]
[1]Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
[2]Department of Electrical Engineering, İstanbul Technical University, İstanbul, Turkey
[3]Department of Electrical Engineering, Ahar Branch, Islamic Azad University, Ahar, Iran

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Abstract: As power demand is increased, power generation and especially distributed generation (DG) are being developed. Therefore, power distribution systems become increasingly complicated and short circuit level in distribution grids is being augmented. Thereby, installation of a superconducting fault current limiter (SFCL) is a logical solution to decrease the fault current level in a distribution network. Preventing distribution system degradation by high fault currents, lower equipment ratings, and economic issues are the advantages of SFCL in distribution grids. However, SFCL installation causes delayed operation of the existing overcurrent protection and requires recoordination of the relays. In addition, disconnecting the SFCL from the distribution circuit due to maintenance leads to miscoordination between the overcurrent relays. In this research work, a genetic algorithm (GA) is used to achieve optimal protection coordination in the presence of both SFCL and DG. Furthermore, the uncertainty associated with the connection status of SFCL and DGs, which are reflected in the protection coordination, is investigated in detail. Moreover, various overcurrent relay characteristics, such as long-time inverse, extremely inverse, very inverse, and normally inverse, are used in a test power system, and remarkable computation results will be shown and discussed in the next parts of the paper.

Key words: Distributed generation (DG), distribution network, genetic algorithm (GA), optimal coordination, overcurrent protection, superconducting fault current limiter (SFCL)

1. Introduction

Overcurrent protection is the main protection system in power distribution networks [1]. Owing to increasing power demand in recent years, employing distributed generation (DG) in distribution systems is a reasonable solution to supply consumers. However, augmenting the short circuit level in distribution networks due to high penetration of DG is inevitable. The consequent need for higher equipment ratings and encountering miscoordination of overcurrent relays are the main disadvantages of DG installation, which is mainly associated with the increased short circuit level [2–5].

In recent years, power system researchers have encouraged the utilization of superconducting fault current limiters (SFCLs) to cope with high fault current levels in distribution systems [6–13]. Using lower equipment ratings due to decreasing short circuit level by utilizing SFCL in distribution systems is one of the main advantages of SFCL. Undoubtedly, equipment with low ratings is cheaper than high ratings equipment and results in reducing investment that is economically beneficial for distribution companies. In [6], the effect of

*Correspondence: s.asghari66@gmail.com

fault current limiter in distribution system with DG has been studied and increasing fault current, as well as instantaneous voltage sag, has been considered. Furthermore, an approach for restoration of directional overcurrent relay coordination in DG systems has been proposed in [7]. In this method, using fault current limiter, settings of relays do not need to be modified. In [8], protection coordination of a flux-lock SFCL with overcurrent relay has been investigated, and the third coil of the flux-lock SFCL has been selected to supply the relay current. In addition, a study on protection coordination between the SFCL and protective devices, such as recloser and overcurrent relay, has been performed in [9]. In [10], an optimization of multi-SFCL and superconducting magnetic energy storage (SMES) units for transient stability enhancement in a multimachine power system based on kinetic energy control has been presented. Moreover, to minimize the effects of DGs, a SFCL-based technique is proposed in [11]. This method is based on optimal impedance determination. In [12], the influence of an active saturated iron-core superconducting fault current limiter (SISFCL) on the conventional overcurrent protection system has been presented. Furthermore, in some research works placement and coordination of the SFCL with protection system have been performed using optimization techniques [2,13].

In addition to the SFCL, optimal values for pickup currents (I_{pickup}) and time dial settings (TDS) of overcurrent relays to achieve the minimum possible operating time of the relays is one of the important factors that have been considered recently [14–19]. In [14], an algorithm based on improved group search optimization for coordination of directional overcurrent relays has been proposed. Furthermore, an analytic approach and an iterative numerical solution for optimal coordination of overcurrent relays have been presented in [15]. In [16], an adaptive differential evolution (ADE) algorithm to solve the nonlinear coordination problem of directional overcurrent relays has been proposed. Moreover, a hybrid GA and nonlinear programming (NLP) approach for coordination of overcurrent relays has been presented in [17]. In [18], biogeography-based optimization algorithms have been utilized for coordination of overcurrent relays. In addition, the simplex optimization algorithm has been employed to coordinate overcurrent relays considering future DG installations in [19].

In this paper, a deep study on the impacts of uncertainty in connection status of distribution grid equipment (i.e. SFCL and DG) on overcurrent protection is performed. Owing to uncertainty related to the connection status of SFCL and DGs, fault current level becomes changing and uncertain and, consequently, confronting miscoordination or delayed operation in the protection system is predictable. Thus, recoordination of overcurrent protection after each reconfiguration of the power grid is inevitable. Therefore, as one of the most useful and effective optimization methods in protection systems, a genetic algorithm (GA) is employed to obtain the optimal I_{pickup} and TDS values of the overcurrent relays and coordinate them with the minimum possible operating time after the occurrence of each reconfiguration related to uncertainty in the connection status of SFCL or DG. Consequently, the remarkable impacts of connecting and disconnecting of the SFCL and DG on the overcurrent protection in different conditions and various types of overcurrent relays will be discussed.

2. Optimal coordination of overcurrent relays

Coordination of overcurrent relays in a distribution network equipped with DG is formulated as an optimization problem. It is clear that the optimization problem includes an objective function (OF) and various constraints and bounds.

2.1. Objective function

The minimization of operating time of overcurrent relays for their primary protective zone and satisfying the coordination of the backup zone with a downstream relay at the same time are the objectives of the optimization problem in distribution systems. In fact, the settings of relays, i.e. TDS and I_{pickup}, should be set in order to provide minimum operating time. Therefore, the objective function could be defined as follows:

$$\text{Objective function } = \sum_{i=1}^{N_{relays}} T_i \tag{1}$$

where T_i is the operating time of overcurrent relay i for faults occurring at its primary zone, and N_{relays} is the number of relays in a distribution grid. According to IEC standard, the operating time of overcurrent relays is obtained as follows [20]:

$$T_i = \frac{TDS_i \times \propto}{(I_{SC-i}/I_{pickup-i})^{\mathrm{n}} - 1} \tag{2}$$

where TDS_i is the time dial setting of the ith relay, I_{sc-i} stands for the fault current seen by the ith relay, $I_{pickup-i}$ represents the pickup current of the ith relay, and α and n are constant values of different types of overcurrent relays according to Table 1.

Table 1. Constant values for different types of overcurrent relays [14].

Characteristic type	α	n
Long-time inverse	120	1
Extremely inverse	80	2
Very inverse	13.5	1
Normally inverse	0.14	0.02

2.2. Constraints

Constraints in an optimal coordination problem are divided into 2 types. The first type of constraints is related to overcurrent relay setting boundaries. In this regard, the optimization results must satisfy inequalities (3) and (4).

$$TDS_i^{\min} \leq TDS_i \leq TDS_i^{\max} \tag{3}$$

$$I_{pickup-i}^{\min} \leq I_{pickup-i} \leq I_{pickup-i}^{\max} \tag{4}$$

In this paper, TDS_i is considered between 0.05 and 1. Moreover, it is clear that $I_{pickup-i}$ must be greater than the maximum load current and less than the minimum fault current seen by the ith relay. Selection of I_{pickup} incorporates a compromise between the dependability and security of the protection system.

Meanwhile, the second type of constraints is related to coordination between primary and backup relays. Once a fault occurs at the protection zone of the ith relay, the fault current can be detected by both the ith and jth relay as primary and backup protection, respectively. Hence, for preventing maloperation and miscoordination between primary and backup relays, the backup relay operating time (T_j) must be equal to or greater than the sum of the primary relay operating time (T_i) and coordination time interval (CTI). This constraint is formulated as follows:

$$T_j \geq T_i + CTI \tag{5}$$

In addition, CTI could vary from 0.2 to 0.5 in different conditions [12,13].

3. Simulation results

In this section of the paper, a 20-kV, 50-Hz primary test power distribution network connected to a 5-MVA subtransmission substation with short circuit level of 100 MVA is proposed in Figure 1. As shown in the figure, three 1-MW wind turbine generator DG units with short circuit level of 15 MVA are connected to a distribution feeder and 5 distribution lines ($R_1 = 0.01273\ \Omega$, $R_0 = 0.3864\ \Omega$, $X_1 = 0.2933\ \Omega$, $X_0 = 1.2963\ \Omega$) are supplying the residential and commercial consumers in secondary distribution systems, which are depicted as five 1000-kW, 500-kVAR loads. Furthermore, a resistive type SFCL is located in series with the high voltage (HV) grid due to its high short circuit level in comparison with DG units. In this regard, 4 case studies related to various conditions that possibly occur in a distribution grid will be considered and uncertainty analysis on connection status of SFCL and DG will be implemented. Additionally, optimal coordination of overcurrent relays has been performed in each condition considering connection status uncertainty of SFCL and DG. Moreover, numerical calculation results will be discussed and depicted in the figures. Meanwhile, due to installation of SFCL at the beginning of the feeder, results will be obtained for forward relays (R_{11}, R_{21}, R_{31}, R_{41}, and R_{51}) in the next case studies.

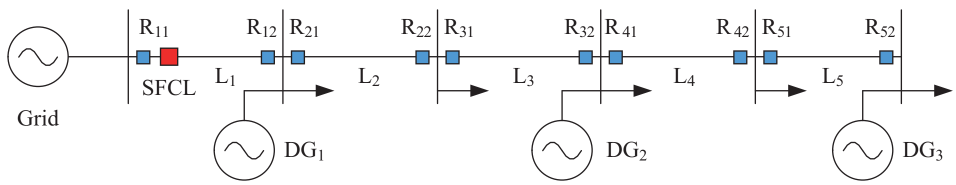

Figure 1. Test power distribution system with DG.

3.1. Case 1: Adding the SFCL in the presence of all DG units

In this case, the distribution system without SFCL in the presence of all DG units is considered. Therefore, the overcurrent relays are optimally coordinated in this condition by GA, as shown in Table 2. As depicted in Figure 2, the sum of operating times of 5 consecutive relays and the average of coordination time interval between the relays for 4 different types of overcurrent relays are shown as $\Delta T - a$ and ΔT-a, respectively, as initial state parameters. Afterwards, the SFCL is connected to the distribution grid, and the sum of operating times of relays and their average of coordination time intervals are shown in the figure as $\sum$T-b and $\Delta T - b$, respectively, as changed state parameters. As presented in the figure, after connecting the SFCL, the sum of operating times of relays and their coordination time intervals are increased for all relay types due to decreasing the fault currents. Furthermore, as illustrated in the figure, the normally inverse relay type with operating time of 1.9399 becomes the slowest protection in comparison with the other relay types after connecting the SFCL. It is clear that to obtain a fast and reliable protection and preventing of maloperation, recoordination of the relays is inevitable.

3.2. Case 2: Removing the SFCL in the presence of all DG units

Regarding the previous case and slow protection owing to connecting the SFCL, the relays are recoordinated considering the presence of the SFCL and all DG units by GA, and considered as initial state. In such a condition, the SFCL may require maintenance and being disconnected from the distribution network. In this case, the influence of removing the SFCL from the grid is investigated. Hence, this state is considered as changed state. As depicted in Figure 3, the sum of operating time of the relays and the average of coordination time

Table 2. Results of optimal coordination of the relays for all types in initial status of Case 1.

Long T Inv.	R_{11}	R_{21}	R_{31}	R_{41}	R_{51}
TDS	0.1093	0.0970	0.1043	0.0696	0.0511
I_{pickup}	643.49	629.28	338.05	362.05	35.62
T_{op}	0.4017	0.3744	0.3342	0.2290	0.1028
T_{total}	1.4421				
Normal Inv.	R_{11}	R_{21}	R_{31}	R_{41}	R_{51}
TDS	0.1724	0.1269	0.1013	0.0752	0.0552
I_{pickup}	578.27	664.25	495.71	380.99	42.46
T_{op}	0.5010	0.4027	0.2840	0.1251	0.0945
T_{total}	1.4073				
Very Inv.	R_{11}	R_{21}	R_{31}	R_{41}	R_{51}
TDS	0.1077	0.1065	0.1046	0.0611	0.0580
I_{pickup}	629.06	489.59	257.85	248.81	40.31
T_{op}	0.3253	0.3040	0.2510	0.1380	0.0148
T_{total}	1.0331				
Extremely Inv.	R_{11}	R_{21}	R_{31}	R_{41}	R_{51}
TDS	0.1078	0.1077	0.1046	0.0611	0.2673
I_{pickup}	136.12	112.06	74.12	74.00	26.00
T_{op}	0.2326	0.2167	0.1901	0.1329	0.0030
T_{total}	0.7753				

intervals ($\sum T - b$ and $\Delta T - b$) are decreased in comparison to the initial state ($\Delta T - a$ and $\Delta T - a$) by increasing the fault currents after removing the SFCL. As shown in the figure, the extremely inverse relay type with operating time of 0.5759 s becomes the fastest and the most unreliable protection after disconnecting the SFCL from the power distribution grid. It is obvious that recoordination of the relays is inevitable to have a reliable and secure protection system.

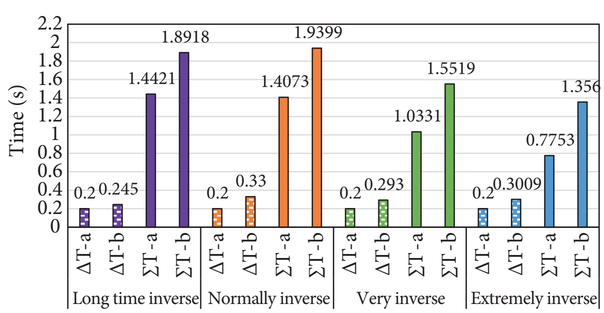

Figure 2. Impacts of adding the SFCL in 4 different overcurrent protection systems.

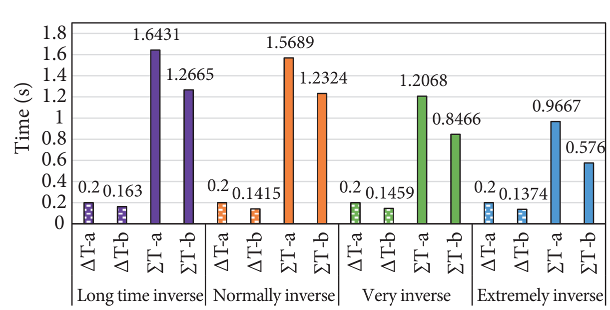

Figure 3. Impacts of removing the SFCL in 4 different overcurrent protection systems.

3.3. Case 3: Removing DG_1 in the presence of the SFCL

In this case, the distribution network with all DG units in the presence of the SFCL is assumed. Hence, the relays are optimally coordinated in this circumstance by GA. Afterwards, DG_1, which is a wind turbine generator, is disconnected from the grid due to low wind speed. As presented in Figure 4, sum of the operating times of the relays is increased due to decreasing the fault currents. However, the averages of ΔT for all relay types have not impressively changed due to intensive decreasing in coordination time interval between relays R_{21} and R_{11}. As depicted in Figure 1, DG_1 is located between relays R_{11} and R_{21}. Therefore, after disconnecting the DG unit the fault current levels are decreased for relays R_{21}, R_{31}, R_{41}, and R_{51}. However, fault current of relay R_{11} is constant. Hence, operating time of R_{11} is not changed, while operating times of the other relays increase. Therefore, as depicted in Figure 5, ΔT-11-21, which is the coordination time interval between relays R_{21} and R_{11}, decreases and miscoordination occurs in this case. Nevertheless, in long-time inverse relay case R_{21} keeps better interval from R_{11}. It is self-evident that recoordination of the overcurrent protection is required for obtaining a reliable protection.

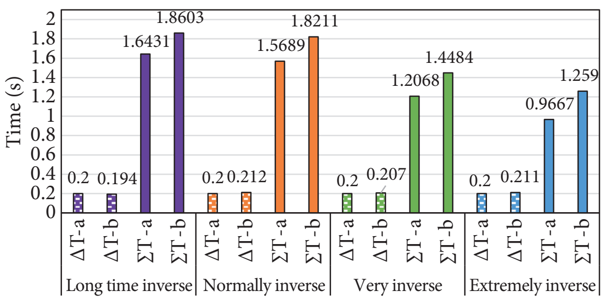

Figure 4. Impacts of removing DG_1 in 4 different overcurrent protection systems.

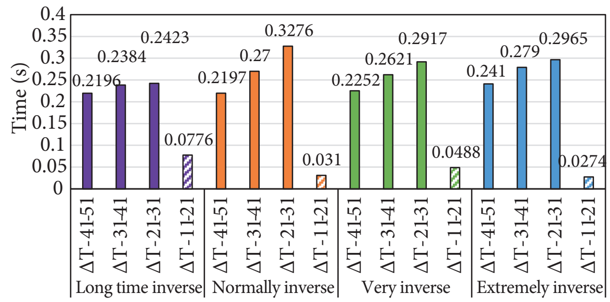

Figure 5. Comparison of ΔT of 4 different overcurrent protection systems.

3.4. Case 4: Removing the SFCL and DG_1

Considering the previous case, the distribution grid in the presence of DG_2, DG_3, and SFCL is assumed. Thereafter, the relays are optimally coordinated by GA. Afterwards, the SFCL is disconnected from the distribution feeder for maintenance. In this circumstance the impacts of disconnecting the SFCL from the feeder while DG_1 is not connected to the feeder is evaluated. As presented in Figure 6, the sum of the operating times of the relays and their coordination time intervals are decreased. Increasing fault currents due to disconnecting the SFCL is the reason for this phenomenon. It is clear from the figure that extremely inverse relay type with 0.0649 s decrease in $\Delta T-b$ in comparison with $\Delta T-a$ is the most uncoordinated and unreliable protection. Moreover, the fault currents seen by the relays for all case studies, i.e. with SFCL or without the SFCL (NSFCL) and with DG_1 or without DG_1 (NDG), are presented in Figure 7.

Considering the simulation results subsections and Figure 8, which is achieved by $|(\sum T-b)-(\sum T-a)|$ in all events and for all relay types, connecting the SFCL to a distribution network with an existing and coordinated overcurrent protection is the most important event in terms of the protection system. Furthermore, as shown in the figure, disconnecting DG_1 from the grid is the least important and effective event on the distribution network. In addition, extremely inverse overcurrent relay is the most sensitive and normal inverse and long-time inverse relays are the least sensitive relay types in confronting different events in the power distribution system. Furthermore, the percentage of positive (increasing) and negative (decreasing) change of operating times of the relays in all conditions are shown in the figure with plus (+) and minus (–) signs, respectively.

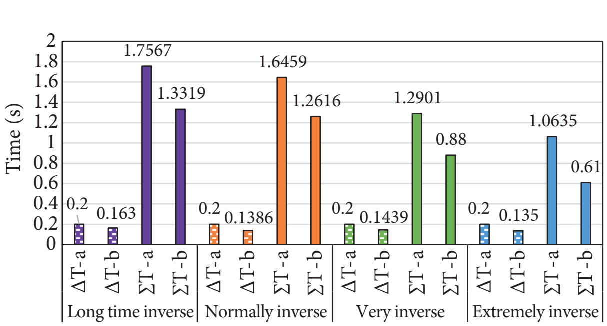

Figure 6. Impacts of removing DG_1 and SFCL in four different overcurrent protection systems.

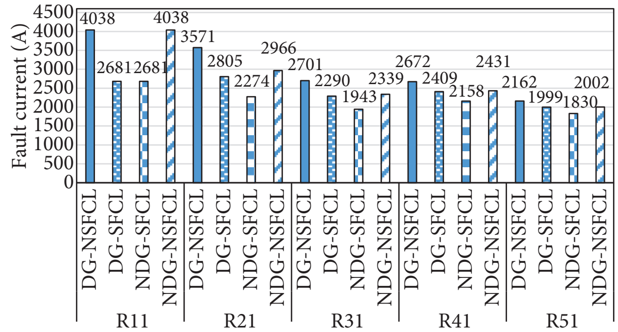

Figure 7. Fault currents for all case studies.

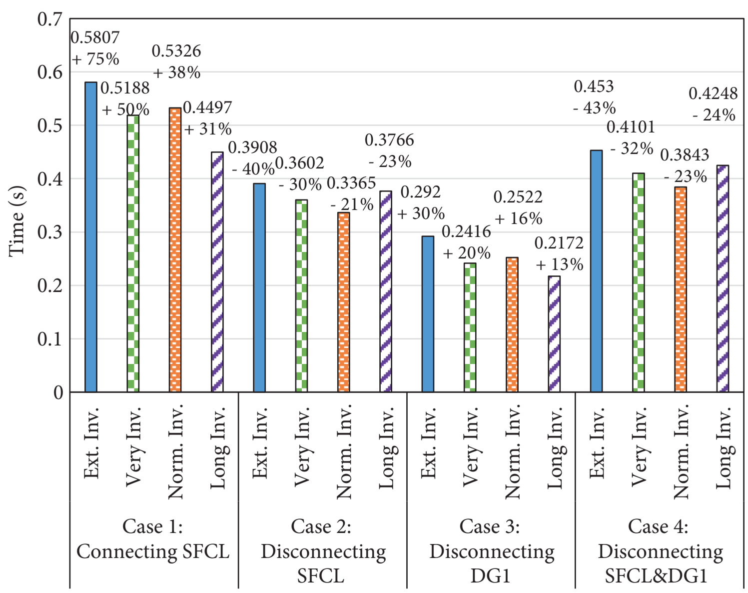

Figure 8. Impacts of 4 events on 4 overcurrent protection systems $|(\sum T-b)-(\sum T-a)|$.

4. Discussion

Owing to uncertainty in conditions of power distribution grids such as connection status of DGs and SFCL, the nature of distribution networks is fundamentally changing and uncertain. Therefore, in this research paper, a detailed analysis on impacts of uncertainty of equipment connection status on overcurrent protection coordination has been innovatively performed to obtain a reliable protection system. Furthermore, due to achieving an appropriate protection system and, additionally, minimizing operating times of protective relays in the presence of SFCL and DGs, the authors have utilized GA optimization. Thus, the best and optimal values of I_{pickup} and TDS have been obtained by GA for all overcurrent relays to achieve a fast protection system. Stages of performing the research can be classified as follows:

- Uncertainty analysis on connection status of SFCL in the presence of all DGs in an existing coordinated overcurrent protection system.

  In this regard, authors have illustrated the impacts of connecting and disconnecting SFCL on the overcurrent protection system. As depicted in Figure 2, connecting SFCL to a distribution network equipped with coordinated overcurrent protection causes irrecoverable delay in the protection system, because fault current is reduced by installing a SFCL in distribution systems. In addition, as shown in Figure 3, disconnecting SFCL from the distribution grid, whose overcurrent protection has been coordinated with SFCL, causes miscoordination between all relays and, consequently, all CTIs decrease from minimum possible CTI level, which is defined as 0.2 s. This phenomenon occurs because the fault current is increased due to removing the SFCL, and it causes decreasing the operating time of the relays considering Eq. (2).

- Uncertainty analysis on connection status of DG_1 in the presence of a SFCL in an existing coordinated overcurrent protection system.

  In this case, the authors have illustrated the influence of disconnecting DG_1 on the overcurrent protection system. As depicted in Figure 4, disconnecting DG_1 from the distribution network, whose protection system was coordinated in the presence of DG_1, causes considerable delay in the operating time of relays located after DG_1. The reason for this delay is the reduction of fault current due to disconnecting DG_1. On the other hand, as shown in Figure 5, disconnection of DG_1 causes miscoordination between consecutive relays at both sides of the DG (i.e. R_{11} and R_{21}). Because R_{11} is not affected by DG_1, however, R_{21} is affected and delayed.

- Optimal coordination of overcurrent relays in the presence of SFCL and DGs.

  In this regard, coordination of overcurrent relays after occurrence of each event (i.e. connecting or disconnecting SFCL or DGs) has been evaluated and then recoordination has been performed using GA.

- Study on impacts of different events on different overcurrent protection systems.

  As shown in Figure 8, which is obtained by $|(\sum \text{T-b}) - (\sum \text{T-a})|$ in all conditions and for 4 relay types, connecting a SFCL to distribution grid is the most effective event on coordination of overcurrent protection system. In addition, disconnecting DG_1 is the least effective event on coordination of overcurrent protection.

5. Conclusion

This paper presents a study on overcurrent protection coordination problems in confronting with connecting and disconnecting SFCL and DG in a distribution network. Furthermore, GA is utilized to optimize coordination of protective relays considering uncertainty in connection status of SFCL and DGs. In addition, to obtain comprehensive results, 4 types of overcurrent relays have been used and simulated in a test power distribution system. As illustrated in the paper, any change in the distribution system configuration leads to miscoordination between overcurrent relays. As a result, connecting a SFCL to the distribution grid mostly affects coordination of overcurrent protection, and the extremely inverse type overcurrent relay is the most sensitive relay in comparison with the other relay types in facing system reconfiguration. However, the widespread use of extremely inverse type relay in distribution grids due to its suitable characteristics for short lines is the bottleneck of this protection system. Therefore, using communication technology to achieve an adaptive and unit protection system seems to be essential for future protection systems. The main points of the paper are as follows:

- Normally inverse time overcurrent relay is the slowest relay in the case of connecting a SFCL.

- Extremely inverse time overcurrent relay is the fastest and the most unreliable protective relay in the case of disconnecting the SFCL.

- Disconnecting a DG unit leads to miscoordination between consecutive relays. However, long-time inverse relay keeps the highest CTI.
- Connecting SFCL and disconnecting a DG unit are the most important and unimportant events for the protection system, respectively.
- In the cases of 2 and 4 that are related to disconnecting SFCL and severe increasing the fault current, normally inverse time relay has the minimum operating time change.

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