Adaptive Protection Method of Distribution Networks Using the Sensitivity Analysis for Changed Network Topologies Based on Base Network Topology

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ABSTRACT This paper proposes an adaptive protection method using sensitivity analysis that examines the effect of changed network topologies (CNTs) on the operation time of protective devices (PDs) for a base network topology (BNT) in a distribution network. In this study, BNT refers to the topological structure of the distribution network maintained over the long-term, whereas CNT is the changed structure maintained for a relatively short term for field workings, fault restoration, or real-time reconfiguration. The main purpose is to consider the PD’s operating speed and the number of controls for changing the settings and to calculate the optimal setting values for two terms while including the CNT in the BNT over a long duration. For this purpose, we used two approaches: First, a sensitivity index, defined as the increase in the operation time of the PD for the BNT when each CNT is included in the BNT, is used to determine the CNT’s inclusion priority. Second, an objective function (OF) is used to evaluate the maximum acceptable number of CNTs based on the priorities derived from the sensitivity analysis. This OF aims to minimize the weighted sum of the average operation time and the number of setting changes for the PDs. Case studies on the test systems were conducted, and the effectiveness of the proposed method was verified by comparing it with existing adaptive protection methods.

INDEX TERMS Adaptive protection, base network topology (BNT), changed network topology (CNT), distribution network, protection coordination.

I. INTRODUCTION

The interconnection of renewable energy-based distributed generations (DGs) with the distribution system is accelerating owing to environmental issues, such as global warming, fine dust, and policy changes in many countries. The increased use of DGs causes changes in the magnitude and direction of fault current. DGs also aggravate congestion in existing distribution operations by causing voltage and overload issues due to their intermittent behavior. In order to deal with the congestion problems, the concept of an active distribution network (ADN), which performs rapid coordination between the distribution operation system and the controller, has been employed in place of the existing networks that require excessive infrastructure investment [1]. This includes not only voltage control for increasing the hosting capacity of the power distribution system, but also infrastructure sharing through real-time network reconfiguration. Real-time network reconfiguration is a periodic control function that involves a conventional control to reduce power loss, balance loads, and restore unfaulted sections and a topological control to relieve network congestion according to an ADN operation [2]. The ADN operation is intended to mitigate voltage or current violations by temporarily sharing the neighboring feeders,
and it requires frequent topology changes to achieve these purposes. Therefore, a proper protection coordination method is required.

Adaptive protection is a way of changing the setting values to allow protective devices (PDs) to operate appropriately following changes in system state [3]. Previous studies on adaptive protection can be categorized into three groups. The first group involves changing the settings of PDs whenever the system topology changes. The second group involves using just one setting, for which no violation of protection coordination occurs for all expected system topology changes. The third group involves applying a corresponding stored setting to the system topology from multiple saved settings that are stored using the save function of PDs.

Regarding the first group, Abdelaziz et al. proposed a linear optimization method for obtaining the setting values by assuming that the multiples of the pick-up current are constant [3]. Shih et al. calculated the setting values using ant colony optimization, which is a metaheuristic technique, for the optimization problem expressed nonlinearly when the multiples of the pick-up are variables [4]. Furthermore, those authors defined the sensitivity of the PDs and compared the difference in sensitivity before and after adaptive protection [5]. Anang et al. also calculated the setting values using an adaptive modified firefly algorithm [6]. Manohar et al. proposed a method of storing the setting values that correspond to the dominant topology, and changing the setting values for the topology after judging the system state using fuzzy logic [7]. Shen et al. proposed an adaptive protection method that utilizes the results of fault analysis based on an estimation of Thevenin equivalent impedance [8]. Fani et al. proposed a setting method that considers additional photovoltaic (PV) disconnection caused by voltage fluctuations after a fault [9].

A voltage profile that would occur in case of a fault was calculated in advance, and a setting change was performed when the corresponding voltage profile occurred. Strezoski et al. proposed a setting change method by considering the fault ride-through (FRT) function of the inverter-based DG [10]. While comparing the FRT time due to the voltage drop and the operation time of the primary PDs in case of fault, the setting was changed in real-time according to the change of the fault current due to DG disconnection over time. These studies require frequent setting updates whenever the topology changes. In order to address this problem, Coffele et al. attempted to reduce the number of setting changes by adapting a difference of the average operation time as a threshold [11]. However, they did not provide a quantitative value for the difference in average operation time.

Regarding the second group, Noghabi et al. used a genetic algorithm (GA) to calculate pick-up current and linear programming (LP) for the time dial setting (TDS) to identify the setting that satisfies the protection coordination of all expected system topology changes [12]. Another study proposed a method that uses interval LP to calculate TDS [13]. Saleh et al. proposed a setting method that considers the isolated operation of the distribution network interconnected with the synchronous-based DG [14]. In addition to the changes in network topology caused by contingency conditions, the isolated operation of a whole feeder was considered as the expected topology. Huchel et al. proposed a method of considering topology change by the additional interconnection of DG [15] and used LP to calculate the setting values satisfying constant-interval increases of DG capacity. References [12]–[14] dealt with topology changes from the perspective of contingency analysis, such as line and generator disconnections. Reference [15] only considered additional capacity variations in DG, ignoring the topology change caused by the switching operation of the distribution networks. However, it may not be possible to calculate a single setting that ensures no violation of protection coordination in all topologies because the coordination pairs of PDs may be reversed when topological changes occur according to switching operation. Furthermore, all previous studies in this category had increased operation time because their objective was to obtain a setting that satisfied all the topology changes.

Regarding the third group, Ojaghi et al. defined topology change as the disconnection of lines and generators. Whenever the topology changes, the average operation time of the PDs for the same TDS setting is calculated, and the final setting group (SG) is derived through clustering [16]. Chabanloo et al. dealt with topology change according to switching operation. They derived the number of SGs using GA and calculated the setting that did not violate the topology change corresponding to each SG using LP. In addition, they determined the setting values using an objective function (OF) to minimize the average operation time of each topology with respect to the number of SGs [17]. Samadi et al. defined the matrix of operation time for all SGs, and used it to calculate the optimal solution of TDS for each SG through particle swarm optimization (PSO) [18]. SG allocation of all expected topologies was performed using integer linear programming (ILP). However, most PDs do not have a multiple setting function, thus, the existing infrastructure must be upgraded to apply the algorithms proposed in this category. Furthermore, in this category, all expected topology changes are considered equally important. However, distribution networks are generally maintained according to a long-term plan and changed temporarily to deal with emergencies (such as fault restoration). Hence, a setting method that considers all topologies equally important can increase the frequency of controls. In order to prevent this, the effect of duration time on the topologies should be considered.

This paper deals with the PD setting method by considering two aspects of the actual operation of distribution networks. One is the aspect of protected equipment, which is the target of the protective devices. The PDs should be operated as soon as possible to minimize the impact of fault current on the equipment. The other is related to the tasks done to set the PDs. These tasks involve the calculation of setting value for PDs, the examination of calculated values, and the validation of transmitted setting values to the field devices [19]. The first task can be automated by the application program of
an operation system. However, the other tasks must still be done by human operators because the inputs used to calculate the setting values (especially topological information) may not always be accurate. Also, the control commends by the operation system may not always be accurately transmitted due to errors and problems with system functions, communication networks, and/or field devices. For these reasons, changing the setting values increases the burden on the operational staff’s tasks. Therefore, reducing the number of setting changes will alleviate the burden on the operators. For reasonable management of PDs in an ADN, a method of protection coordination is proposed that considers these two aspects. The proposed method considers topological change due to the switch operation and determines the optimal setting value through sensitivity analysis on the base network topology (BNT) operated for a relatively long-time. Sensitivity is defined as the change in the average operation time of the PDs on the BNT when including each changed network topology (CNT), and the OF is evaluated by accumulating them in ascending order of sensitivity. The OF is composed of the operation time and the number of controls for changing the setting values. The proposed algorithm improves the efficiency of adaptive protection by reducing the operation time of the PDs on the BNT and maximizing inclusion of the CNT to reduce unnecessary control actions.

The remainder of this paper is organized as follows. In Section II, existing adaptive protection methods are reviewed, and BNT and CNT are defined. Section III discusses the proposed adaptive protection method, which consists of extraction of CNTs, sensitivity analysis of PDs on BNT, and the definition of the OF. Simulation studies are presented in Section IV to validate the proposed method. Finally, Section V concludes the paper.

**II. EXISTING ADAPTIVE PROTECTION METHODS**

Protection of a conventional radial distribution system is based on overcurrent protection coordination by current measurement and differences in operation time between PDs. The PDs require selectivity to distinguish the area to be protected, speed to operate quickly, and sensitivity to sufficiently respond to the minimum fault current [20]. The roles of PDs are divided into primary and backup for protection coordination, and a coordination time interval (CTI) is set to distinguish these roles. Therefore, a PD should be set to operate as quickly as possible while ensuring the CTI. Network reconfiguration of a conventional distribution system is performed for the planning of distribution network and fault isolation, etc. However, introduction of an ADN to mitigate the impacts of DG interconnection involves real-time reconfiguration for several purposes. Therefore, network reconfiguration may be done relatively frequently compared to conventional distribution operations. Accordingly, the importance of the adaptive protection function is increasing and efficient methods that consider the CTI margin have been devised to reduce the number of setting changes according to the network reconfiguration.

Studies on adaptive protection can be divided into: i) studies that change setting values whenever topology changes, ii) studies that obtain one setting corresponding to all expected topology changes, and iii) studies that establish SGs to accommodate multiple topologies using the save function of the PDs.

Especially, group 3 considers the inclusion of CNTs, as illustrated in Fig. 1 [16]–[18].

Calculation of the setting values in these studies is divided into three steps. First, the expected topologies are extracted. These are considered contingencies (source and line disconnection) in [16], and on/off of DG and switching operations during the normal state in [17], [18]. Second, the topologies to be allocated to the SGs are determined by the clustering technique [16], GA [17], or ILP [18], and then the settings of each group that satisfy the protection coordination of the allocated topologies are calculated through LP [16], [17] or PSO [18]. Finally, the setting values are evaluated based on a specific purpose. The weighted sum of TDS in [16], average operation time in [17], and the total sum of operation time in [18] are used, respectively.

This paper deals with reconfiguration of a distribution network according to the switching operation in the normal state. Therefore, references [17] and [18] are more relevant for our purposes than reference [16] in regards to contingency. Also, [17] and [18] consider each changed topology to be of equal importance. However, when the changed topologies extracted by the switching operation are considered from a distribution system management perspective, there are important differences between them.

Fig. 2 illustrates the types of topology change with respect to the operation time of the distribution system. The topology changes can be divided into topologies for planning and operation. First, the topological changes for planning are long-term changes performed once or twice a year for load balancing or loss minimization of the feeder and securing a margin for fault restoration. On the other hand, the topological changes for operation are short-term changes, such as fault restoration, field working, and real-time reconfiguration to resolve a voltage violation or local overload of the feeder. Thus, the former and latter topologies are defined as BNT and CNT, respectively. Also, CNTs exist temporarily when the switching operation occur, and the topology is returned.
to the original BNT once the purpose of the operation is completed [21], [22].

The relative differences in importance of topologies exist because of the duration time of the related operations, as can be seen in Fig. 2. PDs will operate mostly in BNT since the duration of BNT is relatively long. Therefore, this study addresses a method of coordination of PDs in BNT considering the importance of topologies.

III. PROPOSED ADAPTIVE PROTECTION METHOD

The proposed adaptive protection method is consist of three steps. First, CNTs are extracted according to the switching operation. Each switching operation is assumed to include the closing of one normally opened (NO) switch and opening of one normally closed (NC) switch. Protection coordination pairs are extracted from the CNTs, and the maximum fault currents at each PD location are calculated. Second, “sensitivity analysis” is performed to evaluate the impact of each CNT on BNT operation time. The inclusion priorities of the CNTs are then determined by comparing the sensitivities. Finally, the OF is evaluated by accumulating the CNTs in ascending order of sensitivity. The setting value of the PDs are determined to minimize the OF, which is the weighted sum of the average operation time and the number of setting changes.

A. EXTRACTION OF CNTs

If the topology changes, the location of the coordination pairs and the interconnection of DGs can vary. Thus, the fault current measured by the PDs may also change. Fig. 3 shows an illustration of an example system. The change of only one pair of NO and NC switch are assumed when deriving each CNT. The basic requirements for the topological structure of the distribution network are also considered. At first, since the distribution network should maintain a radial structure, one of the switches (S1, S3, S4, and S6) needs to be opened when the N1 switch is closed. Similarly, when the N2 switch is closed, one of the switches (S1, S2, S4, and S5) needs to be opened. Furthermore, there should be no outage section due to the isolation of the feeder. Therefore, when N1 is closed, S2 and S5 should be closed. When N1 is closed, and S3 is opened in the BNT structure, the interconnected position of the DG moves from feeder 1 to feeder 2. This change can cause CTI violations between PDs due to a change in the fault current.

Fig. 4 shows the flowchart for CNT extraction. First, the closing of each NO switch and the opening of each NC switch is assumed in the initial switch state. If the topology is radial and does not have any isolated sections, it is included in the CNTs. Whether the topology is radial or not is examined using a method from [23]. The adjacency matrix is constructed by representing all power sources as a single root node, switches as a branch, and lines as a node. If the sum of row elements for the matrix is 1, it is deleted, and this process is repeated. Finally, it is determined that the topology is radial when the matrix is unity. Next, the protection coordination pairs for the corresponding CNT are extracted, the maximum fault current of each pair’s primary position is calculated, and these two results are saved and used to estimate the final setting values using sensitivity analysis and OF. A total of eight CNTs (CNT1 (N1 closed, S1 open) – CNT8 (N2 open, S5 closed)) were extracted from the two-feeder system.
time of the BNT when each CNT is included. The sensitivity can be used to determine the priority of CNTs that will be included when calculating the setting values for the BNT.

Fig. 5 shows the flowchart of the sensitivity analysis. First, to measure the effect of each CNT on the BNT, the setting values for BNT are calculated considering the status of CNT. For this, the protection coordination pairs and fault current calculated during CNT extraction are used, and the optimization problem formulated in (1) is solved by the LP method.

![Flowchart of sensitivity analysis for each CNT.](image)

where $N_t$ is the total number of topologies, $N_p$ is the total number of coordination pairs, $t_{ij}^p$ is the operation time of primary PDs for the near-fault about $i^{th}$ coordination pairs of $p$ th topologies, $t_{b}^i$ is the operation time of backup PDs, $CTI$ is the coordination time interval between coordination pairs, and $TDS_{min}$ and $TDS_{max}$ are the minimum and maximum limit values of the PD settings, respectively. In the sensitivity analysis, $N_t$ is 2 (BNT and each CNT). The operation time of the PDs is calculated using the time/current (T/C) characteristic in (2). In this study, the IEC very inverse curve is used [24].

$$t = \left( \frac{B}{(I_f/I_p)^A - C} \right) \times TDS$$

where $t$ is the operation time, $I_f$ is the fault current passing through the PDs, $I_p$ is the pick-up current, and $A$, $B$, and $C$ are the T/C characteristic parameters.

The increased average operation time of the BNT can be calculated using (3) as follows:

$$\Delta t_{avg-k} = \frac{1}{N_{(p,b)}} \sum_{i=1}^{N_{(p,b)}} (t_{b}^i + t_{p}^i)_{CNT_k} - \frac{1}{N_{(p,b)}} \sum_{i=1}^{N_{(p,b)}} (t_{b}^i + t_{p}^i)_{BNT}$$

where $\Delta t_{avg-k}$ is the increase in the average operation time when the $k^{th}$ CNT is included in addition to the BNT. This value was defined as the sensitivity of the $k^{th}$ CNT, $N_{(p,b)}$ is the number of coordination pairs for the BNT, and $CNT_k$ indicates inclusion of the $k^{th}$ CNT. Furthermore, $t_{b}^i$ and $t_{p}^i$ are the operation times for the primary and backup PDs in case of a fault of the primary PD for the $i^{th}$ coordination pair. The operation time of backup PD $t_{b}^i$ is included in this equation because not only the operation of the primary PD, but also the operation of the backup PD is important when the primary PD does not operate in the event of a fault [25].

When the sensitivity analysis is performed, a feasible solution may not be obtained in the LP process. For example, among the CNTs derived in Fig. 3, the relationship of protection coordination between R2 and R3 for CNT5 (N2 closed, S1 open) is opposite to that of BNT. In this case, it may not be possible to obtain a setting value that satisfies these two topologies simultaneously [17], [26]. Therefore, these CNTs are excluded from the calculation of the setting values. When the sensitivities ($\Delta t_{avg-k}$) of all CNTs are calculated, the decrease in sensitivity can be evaluated. Then, the priority of CNT inclusion is determined by ascending order.

Fig. 6 shows the results of sensitivity analysis for the two-feeder system depicted in Fig. 3. The values of $\Delta t_{avg-k}$ are different for each CNT. This means that the effect of inclusion of each CNT on the BNT varies. For example, the values of CNT 1 - 8 are 0.018, 0.025, 0.001, 0.002, 0.060, 0.080, 0.042, and 0.075, respectively. Therefore, CNT 1 - 4 have a relatively low impact on the operation time of BNT. Accordingly, CNT 5 - 8 may not be included in the settings of the BNT from the evaluation through OF.

![Results of sensitivity analysis (\(\Delta t_{avg-k}\)) for each CNT.](image)

C. CALCULATION OF OPTIMAL SETTINGS THROUGH OBJECTIVE FUNCTION

In this paper, two operational factors were considered for PD settings in operation of an actual distribution network. One is to keep the operating speed of PDs as fast as possible, and the other is to reduce the number of controls as much as possible. The number of controls is inversely related to the operation time, i.e., as the number of included CNTs increases, the number of controls will decrease, but the operation time of BNT will increase. This relationship is formulated by the
OF of (4). To evaluate the OF, the left and right terms of (4) are calculated by accumulating CNTs according to priority.

The left term in (4) is related to the increase in the operation time. Here, selectivity is reflected through CTI, which is a component of (1). Speed is considered through TDSs, which are the setting values that minimize the operation time while maintaining the CTI. Sensitivity is considered through the minimum fault current ($I_p$) of the TIC characteristic curve in (2). Accordingly, these are applied to the left term of (4). The right term in (4) is related to the number of controls necessary to change the settings. $N_e$ is the number of CNTs that have been accumulated to calculate the operation time in BNT. $N_i$ is the total number of CNTs for which the LP can be performed. As $N_e$ increases, the left term increases and the right term decreases.

\[
\text{min} \left( \text{Operation time} + \text{Number of controls} \right) = \min \left( w_a \frac{\Delta t_{\text{avg} - e}}{\Delta t_{\text{avg} - \text{all}}} + w_b \frac{N_i - N_e}{N_i} \right) \tag{4}
\]

where $\Delta t_{\text{avg} - e}$ is the increase in the average operation time in BNT when CNTs are included up to $N_e$. $\Delta t_{\text{avg} - \text{all}}$ is the increase in the average operation time in BNT when CNTs are included up to the maximum. $w_a$ is the weight of the operation time and $w_b$ is the weight of the number of controls. $\Delta t_{\text{avg} - e}$ can be calculated by (5) as follows:

\[
\Delta t_{\text{avg} - e} = \frac{1}{N(p,b)} \sum_{i=1}^{N(p,b)} \left( t_{I_p}^{i} + t_{D_p}^{i} \right)^{\text{CNT}_{1,\ldots,N_e}} - \frac{1}{N(p,b)} \sum_{i=1}^{N(p,b)} \left( t_{I_p}^{i} + t_{D_p}^{i} \right)^{\text{BNT}} \tag{5}
\]

where CNT\(_{1,\ldots,N_e}\) indicates $N_e$ CNTs included by accumulating them in order of sensitivity. For example, when $N_e = 3$ is applied, the left term of (5) is the average operation time of BNT using the setting values calculated using (1) with the inclusion of 3 CNTs according to priority and BNT.

The left and right terms of the OF have a value between 0 and 1. The weight of the operation time ($w_a$) or number of controls ($w_b$) can be changed such that the total sum of the two weights is 1 from the perspective of the user that sets the PDs.

Fig. 7 shows the flowchart for obtaining the setting of PDs using the OF. The setting values are calculated using (1) by including the CNTs in priority order. As explained in Section 3.2, if there is no feasible solution for (1), the topology is excluded from the BNT and classified as a CNT to be controlled. Otherwise, $\Delta t_{\text{avg} - e}$ is calculated using (5), and an OF of (4) is evaluated. This is repeated for each $N_e$ until $N_i$. Finally, when the value of the OF is at a minimum, it is output as the optimal setting value.

**IV. CASE STUDY**

Case studies were conducted using two test systems. The performance of the proposed method was verified using the three-feeder test system in the first case study. For each procedure described in Section III, the results obtained by the proposed method were presented. Moreover, the derived setting values were compared with those of existing method 1 [3], which recalculates the setting values for each topological change; existing method 2 [12], which calculates one setting value that satisfies all topologies; and existing method 3 [16], which uses multiple SGs. We selected existing study 3 as a reference [16] because it can be compared with the proposed method as the average operation time is used. The second case study was performed on a five-feeder test system with two substations.

Some assumptions commonly applied to the case studies were as follows. The interconnection of PV was assumed because it mainly consists of a type of DG interconnected in the distribution system. The control method of PV inverter assumed to the BPSC (balanced positive sequence control) method that used commonly. Under some amount of solar radiation, this control method outputs a balanced current according to the PV terminal voltage when the inverter output current is below the maximum current. Otherwise, it is considered as a constant current source that outputs the maximum current. To reflect these control characteristics, a three-phase power flow method is used to calculate the fault current [27]. $\Delta$-Y (ground) was assumed as the wiring method of the interconnection transformer. A single line to ground fault is considered because the effect of DG in the PV-interconnected distribution system is greater than that of other types of faults. The criterion of CTI for protection coordination was based on the standard of Korea Electric Power Corporation (KEPCO). The PDs consisted of circuit breakers (relays) and reclosers (digital type). The CTI between reclosers was set to 0.083 seconds (5 cycles) and the time difference between fast and delay operation was set to 0.05 seconds (3 cycles); also, the CTI between relays and reclosers was set to 0.167 seconds (10 cycles) [19], [28]. Moreover, protection coordination was considered using the sequence coordination function for the fast and delayed operations between reclosers. When three reclosers are installed in one feeder, the sequences of 2F2D, 2F1D, and 2F are performed sequentially from the source side [19].
A. CASE STUDY 1: THREE-FEEDER TEST SYSTEM

Fig. 8 shows the 22.9 kV three-feeder system used for the test. The capacity of the main transformer is 45 MVA, while the capacity of each PV is 4 MW, and the cable type is ACSR 160/95 mm². The length of feeders 1, 2, and 3 are 10 km, 15 km, and 20 km, respectively.

Table 1 shows the coordination pairs on the BNT, the maximum fault current at each location, and the pick-up current. In that table, “d” and “f” refer to delay and fast operation of a recloser, respectively.

Table 2 lists the topologies derived from the switching operation of the test system. CNT₁ to CNT₁₈ are topologies that meet the conditions of a no-isolated and radial system. Also, coordination pairs and fault current data for some CNTs are shown in Table 10 of Appendix.

Table 3 outlines the results of sensitivity analysis for each CNT. The average operation time was 0.3348 seconds when only the BNT was considered. In the sensitivity analysis, it never occurred that a feasible solution was not obtained. Owing to this characteristic, CNTs with a very large impact on the increase in operation time may not be included in the setting of PDs on the BNT, whereas many CNTs with relatively small impacts on the operation time may be included. The operation time increased significantly compared to that of other topologies when the 16th topology was included, as shown in Fig. 9(a). The OF results in Fig. 9(b) showed the minimum value when CNTs were included up to the 15th priority.

Table 4 lists the TDS values with the minimum value of the OF.

Table 5 compares the average operation time and number of controls of the BNT for existing methods 1 and 2 and the proposed method. In existing method 1, the average

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**TABLE 1. Coordination pair of each feeder.**

| Coordination pair | Fault current (A) | Protective device | Pick-up current (A) |
|------------------|------------------|------------------|-------------------|
| Backup | Primary | Backup | Primary | R1 | 80 | R1 | 80 |
| R1 | RC1(d) | 1,181 | 2,932 | RC1 | 60 | RC1 | 60 |
| R1(c) | RC2(d) | 1,327 | 2,537 | RC2 | 60 | RC2 | 60 |
| R1(f) | RC1(f) | 1,327 | 2,537 | RC3 | 60 | RC3 | 60 |
| R2 | RC3(d) | 1,445 | 1,445 | R3 | 80 | R3 | 80 |
| R3 | RC4(d) | 474 | 2,018 | RC4 | 60 | RC4 | 60 |
| RC5(d) | RC6(d) | 348 | 975 | RC5 | 60 | RC5 | 60 |
| RC5(f) | RC6(f) | 348 | 975 | RC6 | 60 | RC6 | 60 |

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**TABLE 2. Topologies of three-feeder system.**

| Topology number | NC switch (Open) | NO switch (Close) | Topology number | NC switch (Open) | NO switch (Close) |
|-----------------|------------------|------------------|-----------------|------------------|------------------|
| BNT             | -                | -                | CNT₁₀           | S4               | N5               |
| CNT₁            | S1               | N1               | CNT₃            | S3               | N4               |
| CNT₂            | S3               | N1               | CNT₅            | S2               | N5               |
| CNT₃            | S1               | N2               | CNT₇            | S3               | N5               |
| CNT₄            | S2               | N2               | CNT₉            | S5               | N5               |
| CNT₅            | S3               | N2               | CNT₁₁           | S3               | N6               |
| CNT₆            | S4               | N2               | CNT₁₃           | S4               | N6               |
| CNT₇            | S1               | N3               | CNT₁₅           | S5               | N6               |
| CNT₈            | S2               | N3               | CNT₁₇           | S6               | N6               |

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**TABLE 3. Sensitivity analysis results for three-feeder system.**

| Topology inclusion | Δt_{avg−k} | Priority | Topology inclusion | Δt_{avg−k} | Priority |
|--------------------|------------|----------|--------------------|------------|----------|
| BNT+CNT₁           | 0.0234     | 13       | BNT+CNT₉           | 0.0105     | 7        |
| BNT+CNT₂           | 0.0130     | 8        | BNT+CNT₁₀          | 0.0233     | 12       |
| BNT+CNT₃           | 0.0029     | 4        | BNT+CNT₁₁          | 0.0241     | 14       |
| BNT+CNT₄           | 0.0089     | 5        | BNT+CNT₁₂          | 0.0807     | 16       |
| BNT+CNT₅           | 0.0926     | 17       | BNT+CNT₁₃          | 0.1172     | 18       |
| BNT+CNT₆           | 0.0196     | 9        | BNT+CNT₁₄          | 0.0000     | 2        |
| BNT+CNT₇           | 0.0652     | 15       | BNT+CNT₁₅          | 0.0209     | 10       |
| BNT+CNT₈           | 0.0220     | 11       | BNT+CNT₁₆          | 0.0000     | 3        |
| BNT+CNT₉           | 0.0000     | 1        | BNT+CNT₁₇          | 0.0094     | 6        |

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**TABLE 4. TDSs of protective devices for each feeder at minimum OF.**

| Feeder 1 | Feeder 2 | Feeder 3 |
|----------|----------|----------|
| R1       | 0.5152   | 0.4208   | 0.3350   |
| R1(c)    | 0.3760   | RC3(d)   | 0.1934   | RC5(d) | 0.1600 |
| R1(f)    | 0.2869   | RC3(f)   | 0.1473   | RC5(f) | 0.0856 |
| RC2(d)   | 0.4447   | RC4(d)   | 0.5071   | RC6(d) | 0.2013 |
| RC2(f)   | 0.2779   | RC4(f)   | 0.3373   | RC6(f) | 0.1259 |

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Table 5 compares the average operation time and number of controls of the BNT for existing methods 1 and 2 and the proposed method. In existing method 1, the average
operation time was the lowest. However, control must be performed for each CNT. In existing method 2, the setting values remained unchanged, but the average operation time was much increased. In the proposed method, the operation time was increased by approximately 42.98% compared to that of existing method 1 and decreased by approximately 57.01% compared to that of existing method 2. The number of controls for the proposed method decreased by approximately 83.3% compared to existing method 1 and increased by approximately 16.7% compared to existing method 2. Therefore, the proposed method had a relatively high reduction effect on operation time that coincided with a small increase in the number of controls. In addition, the OF value of the proposed method was calculated as a minimum of 0.2982.

The proposed method was also compared with existing method 3. In this study, the topologies were classified into included and not-included CNTs. Hence, two SGs were assumed for the comparison. After assigning the combinations of BNT and CNTs 1 to 18 to one group, the excluded CNTs were assigned to the other group. This was repeated for all CNT combinations, and the average operation time for each combination was calculated. The group with the minimum operation time was determined as the solution of existing method 3. Fig. 10 shows the average operation times for all cases with 19 topologies assigned to two SGs. A total of 262,143 cases were recorded, and the 258,135th case had the smallest average operation time. In this case, the minimum average operation time was 0.5215 seconds. Group 1, which included the BNT, contained 14 CNTs (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, and 16), and group 2 contained 4 CNTs (11, 14, 17, and 18).

A simple comparison between the proposed method and method 3 is difficult. Thus, a different comparison method was required. Assuming that the topology returns to the BNT after one hour when each CNT occurs, the average of the operation times at different probabilities of BNT and CNTs, and the number of controls for setting change during 8,760 hours were calculated. For example, if there is a 90% probability of BNT and a 10% probability of CNTs in 8,760 hours, a total of 876 CNTs will be selected, and 18 CNTs have the same probability of occurrence. When the BNT or each CNT was selected, the operation time was calculated using the TDS in Table 4 for the proposed method. For existing method 3, the operation time was calculated using the final setting values of the above two groups. The probabilistic average operation time was calculated using (6) as follows:

$$t_{\text{weighted}} = \frac{t_0 \times t_{\text{avg}-0} + t_1 \times t_{\text{avg}-1} + \cdots + t_e \times t_{\text{avg}-e}}{8,760}$$  \hspace{1cm} (6)$$

where $t_{\text{weighted}}$ is the weighted average value of the operation time considering the duration weight in 8,760 hours for each topology, $t_0$ is the duration time assigned to the topologies and the total sum is 8,760, and $t_{\text{avg}-0}$ to $t_{\text{avg}-e}$ are the average operation time of each topology. Also, 0 denotes BNT and 1−e denotes CNTs.

Table 6 lists the operation time and number of controls based on the settings derived by existing method 3 and the proposed method, with the assumption that the ratio of time duration on the BNT decreased from 95% to 70% and that
on the CNTs increased from 5% to 30%. Existing method 3 showed little difference in the operation time as the ratio of CNT increased, but the operation time of the proposed method increased more. Since the existing method aims to minimize the total average operation time for BNT and CNT, the operation time for the entire topology remained almost unchanged as the CNT ratio increased. However, the proposed method set the operation time of BNT to be relatively small. Therefore, the operation time increased with the increase of the proportion of CNTs. Moreover, in all scenarios, the proportion of BNT was significantly larger than those of CNTs. Thus, the overall average operation time of the proposed method was less.

Regarding the number of controls, the overall ratio of existing method 3 and the proposed method was 4:3 because method 3 included four topologies in group 2, whereas the proposed method included three topologies. Therefore, from the operational viewpoint of returning from a CNT to the BNT when there is a topology change, the PD setting of the proposed method derived more appropriate results.

### B. CASE STUDY 2: TWO-SUBSTATION FIVE-FEEDER TEST SYSTEM

The test system consisted of two substations and five feeders designed using the standard model data of the distribution system in South Korea [29] for simulation in a realistic system environment. The assumptions for voltage and main transformer capacity were the same as in case study 1. The length of feeders 1, 2, and 5 were 24 km, respectively and feeders 3 and 4 were each 3 km long. The average number of switches based on the standard model was applied. Table 7 lists the capacities of the PVs and transformers in the test system.

The total number of CNTs in the system was 66. 5 CNTs (30 – 34) that had no feasible solution derived from the sensitivity analysis were excluded. A case with no feasible solution occurred when the OF was calculated at CNT number 29. The optimal solution was obtained when CNT number 52 was included according to the priority. Therefore, the number of CNTs to be excluded was 14 out of 66 CNTs (6 CNTs with no feasible solution, 8 CNTs excluded by OF evaluation), and 52 CNTs were included.

Table 8 presents the results of existing method 1 and 2 and the proposed method for the system in case study 2. The operation time of the proposed method increased by approximately 16.3% compared to that of existing method 1,
and decreased by approximately 83.7% compared to that of existing method 2. The number of controls for the proposed method decreased by 78.3% compared to existing method 1 and increased by 21.7% compared to existing method 2. Furthermore, the OF value of the proposed method was 0.1479. In summary, the performance of the proposed method has been demonstrated to be valid even when applied to a more realistic system.

Table 9 shows the results of the comparison with existing method 3 for case study 2. Sixty-seven topologies were derived from the system in case study 2, including the BNT. Approximately $7.3787 \times 10^{19}$ cases of topologies were assigned to two SGs through complete enumeration. Given that complete enumeration requires a great deal of time, the topologies were randomly assigned to SGs and the case with the smallest operation time among the number of iterations was selected for comparison. Six CNTs with no feasible solution were excluded from the analysis. Therefore, the values derived by the algorithm for 61 topologies (BNT and 60 CNTs) were compared. For each scenario, the average operation time of the proposed method was smaller than that of existing method 3. In existing method 3, 32 topologies were allocated to SG1 and 28 topologies were allocated to SG2. In the proposed method, 8 topologies were excluded and 52 topologies were allocated to the group with the BNT. In existing method 3, the topologies were allocated in a manner that minimized the operation time with equal importance. However, the proposed method allocated the CNTs to groups based on the BNT, considering both operation time and number of controls.

Consequently, the average operation time of the proposed method with a long duration of the BNT was inevitably shorter than that of existing method 3. Similarly, the number of controls for the proposed method is less than that of existing method 3 for the same reason, and the difference becomes larger in case study 2, which has a large number of CNTs. In conclusion, the proposed method yielded more appropriate results, even in the more complex and realistic system of case study 2.

V. CONCLUSION

This study proposed an adaptive protection method for efficient management of an ADN considering the duration time of the topologies. The proposed method derived the optimal solution by analyzing the effect of CNTs based on the BNT. CNT extraction and sensitivity analysis of the operation time of the BNT were proposed. We presented an OF consisting of the weighted sum of the increase in the average operation time for the PDs and the number of controls for setting changes based on the priorities derived from the sensitivity analysis.

To verify the proposed method, case studies of two test systems were performed. The case studies compared the proposed method with three existing methods. The results obtained from the two case studies can be summarized as follows:

1) When compared with existing methods 1 and 2, the proposed method showed a slight increase in the average operation time compared to that of existing method 1, but the number of controls for setting changes decreased dramatically. In addition, the proposed method showed a substantial decrease in the average operation time compared to existing method 2, but the number of controls for setting changes increased slightly. Regarding the OF, the proposed method showed more optimal values than the two existing methods. When topological changes of the system operation increased owing to the introduction of the ADN, the increase in the number of controls may significantly increase the burden on the system or the operator. Therefore, the proposed method is useful in this regard.
In comparison to existing method 3, the proposed method yields a shorter operation time and a smaller number of controls. This suggests that the proposed method, which performs analyses based on the BNT, is more effective.

3) The standards of protection coordination provided by the utility are only the CTI and the sequence settings for PDs. They do not provide practical criteria, such as the actual degree of margin and topological changes to be accommodated. The proposed method provides a setting method that obtains a practical margin of PDs. In addition, the proposed method is based on the operating guidelines of the utility company regarding the operation of a general distribution system, and most utilities worldwide operate with similar instructions. Therefore, the BNT-based adaptive protection method proposed in this study is very useful for the operation of actual distribution systems.

In this study, an effective method of setting PDs for an actual distribution system was presented, and its justification was demonstrated through offline simulation. However, to apply the proposed method in a real network, further study should be performed, including real-time simulation or field demonstration of a series of processes like periodic monitoring of system status, determination of whether to change settings, calculation of setting values, and command transmission to change the calculated values.

APPENDIX

The fault currents for some coordination pairs of CNTs and the TDS values for sensitivity analysis in case study 1 of Section IV are presented in Tables 10 and 11.

| TABLE 10. Coordination Pairs and Fault Currents for CNTs. |
|---------------------------------------------------------|
| **Coordination pair** | **Fault current (A)** | **Coordination pair** | **Fault current (A)** |
| Backup | Primary | Backup | Primary | Backup | Primary | Backup | Primary |
| CNT1 | CNT2 | CNT1 | CNT2 |
| R2 | RC1(d) | 704 | 2,156 | R1 | RC1(d) | 1,570 | 3,182 |
| R1(d) | RC2(d) | 1,084 | 2,136 | R1(c) | RC2(d) | 1,405 | 2,577 |
| R1(f) | RC2(f) | 1,084 | 2,136 | R2 | RC3(d) | 832 | 1,624 |
| R2(c) | RC3(d) | 1,020 | 1,950 | R1 | RC3(d) | 832 | 1,624 |
| R1(f) | RC4(d) | 601 | 2,051 | R3 | RC5(d) | 1,243 | 1,245 |
| R3 | RC5(d) | 1,237 | 1,237 | RC5(d) | RC6(d) | 347 | 974 |
| RC5(d) | RC6(d) | 345 | 973 | RC5(f) | RC6(f) | 347 | 974 |

| **TABLE 11. TDSs of BNT for sensitivity analysis with each CNT.** |
|---------------------------------------------------------------|
| **Protective devices** | **BNT** | **CNT1** | **CNT2** | **CNT3** | **CNT4** |
| R1 | 0.4373 | 0.4373 | 0.4471 | 0.4373 | 0.4373 |
| R1(d) | 0.3389 | 0.3389 | 0.3598 | 0.3389 | 0.3389 |
| R1(f) | 0.2607 | 0.2607 | 0.2767 | 0.2607 | 0.2607 |
| R2 | 0.4077 | 0.4077 | 0.4143 | 0.4077 | 0.4077 |
| R2(c) | 0.2548 | 0.2548 | 0.2590 | 0.2548 | 0.2548 |
| R3 | 0.3159 | 0.3592 | 0.3294 | 0.3160 | 0.3368 |
| R3(d) | 0.1424 | 0.1924 | 0.1607 | 0.1425 | 0.1707 |
| R3(f) | 0.0851 | 0.1113 | 0.0962 | 0.0852 | 0.1006 |
| R4(d) | 0.3223 | 0.3277 | 0.3223 | 0.3223 | 0.3254 |
| R4(f) | 0.2014 | 0.2048 | 0.2014 | 0.2014 | 0.2034 |
| R3 | 0.2706 | 0.2706 | 0.2706 | 0.2984 | 0.2836 |
| R3(d) | 0.1123 | 0.1223 | 0.1223 | 0.1601 | 0.1399 |
| RC5(f) | 0.0592 | 0.0659 | 0.0659 | 0.0749 | 0.0671 |
| RC6(f) | 0.1506 | 0.1506 | 0.1506 | 0.1565 | 0.1516 |
| RC6(f) | 0.0941 | 0.0941 | 0.0941 | 0.0978 | 0.0948 |

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