Verification of Loss Reduction Effect on Loss Minimum Configuration of Distribution System by Zero-Suppressed Binary Decision Diagram for Large Penetration of Residential PV

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***Abstract*—This paper verifies, for distribution systems with residential photovoltaic generators (PV), the distribution loss reduction effect on the loss minimum configuration selected from all possible configurations. Methods that determine the loss minimum configuration of distribution systems have been developed. However, loss reduction effects and guidelines for future PV deployment to effectively reduce distribution loss have not been discussed extensively, because of difficulties in enumerating possible configurations and in comparing distribution losses for each. We have previously proposed a method for selecting loss minimum configurations from among all possible configurations. In this paper, we use the proposed method to verify the loss reduction effect on loss minimum configurations of a distribution system composed of 468 switches for three PV penetration patterns. We also evaluate the loss minimum configuration by comparing its distribution loss with that of other configurations and provide a guideline for future PV penetration position and system operation.**

***Index Terms*—distribution system, loss minimization, PV penetration, system reconfiguration, zero-suppressed binary decision diagram**

I. Introduction

As a method for reducing CO_2 emissions and distribution loss, Japan has set a target of developing 28 GW of capacity for penetrated photovoltaic (PV) generators by 2020, which is 20 times larger than the 2005 capacity [1]. To achieve this target, a large number of PV generators must be installed in residential distribution systems, significantly affecting power flow. Distribution systems should be operated in a loss minimum configuration. Therefore, optimizing PV penetration points and reconfiguration of distribution systems for significant PV penetration are necessary. Guidelines for PV generator deployment and system operations to effectively reduce distribution loss are scarce, because of difficulties in enumerating the huge number of possible configurations that satisfy system constraints, and in comparing distribution loss with other possible configurations.

Several proposed optimization methods provide loss minimum configurations, most relying on approximation techniques such as heuristics [2]–[5] and metaheuristics [6]–[9]. Although these methods scale well in large distribution systems, they provide only one solution of uncertain quality. Derived solutions can be arbitrarily worse than the optimal solution, so these approaches may fail to reduce the operating cost of managing the system. The brute force method presented in [10] guarantees optimality, but its scalability is limited to at most one hundred switches, while practical systems usually include several hundreds of switches [3], [8], [9]. We have previously proposed an optimization method to select a loss minimum configuration from all possible distribution system configurations enumerated using a zero-suppressed binary decision diagram (ZDD) [11]–[14]. However, loss reduction effects and changes in loss minimum configurations, including several PV patterns of the proposed method, have not been verified.

This paper verifies the loss reduction effect of loss minimum configurations for randomly selected distribution system configurations composed of 468 switches (2^{468} possible configurations) for three residential PV penetration patterns (at the feeder root, at the feeder end, and evenly distributed along feeders) using the proposed method.

Furthermore, to provide a guideline for future PV penetration position and system operation, we evaluate loss minimum configurations for three residential PV penetration patterns by comparing its distribution loss with that of other configurations.

II. Distribution Loss Minimization Problem

This paper defines the loss minimum configuration as the open or closed state of each switch when distribution loss is minimized under three constraints: (1) line current does not exceed line capacity, (2) voltage drop is within an acceptable range, and (3) the distribution system configuration is operated in radial and load-connect configurations. Figs. 1 and 2 show an example distribution system and an example configuration. As shown in Fig. 2, the configuration has two radial feeders at the root sections c_I and c_{II}. One feeder consists of sections c_I, c_3, and c_6, and the other includes sections c_{II}, c_4, c_5, c_7,c_8, and c_9. In addition, sections on the same feeder are separated into upstream sections and downstream sections. For example, section c_{II} on the same feeder is split into upstream $C_{\mathrm{II}}^{up} = \{\}$ and downstream $C_{II}^{down} = \{c_4, c_5, c_7, c_8, c_9\}$ sections. For section c_8 on the same feeder, sections are grouped into upstream $C_8^{up} = \{c_{II}, c_9\}$ and downstream $C_8^{down} = \{c_7\}$. This paper assumes that section loads are uniformly distributed on the section, and that the line current of section c_i is given by a backward sweep that calculates power flow in radial configurations [15]. Each section has impedance Z_i. The problem is formulated as follows:

$$Minimize \sum_{i=1}^{m} R_i J_i^2(\boldsymbol{x}) \quad (1)$$

where $R_i$is the resistance of section c_i, J_i is the line current at section c_i, and $\boldsymbol{x}$ represents a binary vector for a distribution system configuration with *n* open or closed switches ($\boldsymbol{x} \in \{0,1\}^n$; 0: opened; l: closed).

[Constraints on distribution system operation]

$$Configuration\ \boldsymbol{x}\ provies\ valid\ feeders \quad (2)$$

Constraint (2) describes topological constraint. Distribution systems in Japan must be operated in a tree-like radial structure with each feeder rooted at the root section. Topological constraints include network radiality and load connectivity. Radiality is satisfied if the distribution system has no loops. This implies that the distribution system forms a set of disjoint trees (a forest). Load connectivity is satisfied if the forest spans all sections and every tree is rooted at a root section. This paper refers to such a forest as a spanning rooted forest. The system configuration must be a spanning rooted forest to satisfy the topological constraints. The line capacity constraint is

$$J_i(\boldsymbol{x}) = \sum_{j \in C_i^{down}} I_j + I_i \ \ (i = 1,2, \dots, m) \quad (3)$$

$$J_i(\boldsymbol{x}) \le J^{max} \quad (4)$$

where I_j is downstream from section c_i , I_i is the load of section c_i, C_i^{down} is a set of downstream sections, and J^{max} is the line capacity of the distribution system. The voltage drop constraint is

$$V_i(\boldsymbol{x}) = \sum_{j \in C_i^{up}} Z_j \left[\frac{I_j}{2} + \sum_{k \in C_j^{down}} I_k \right] \ (i = 1,2, \dots, m) \quad (5)$$

$$V^{min} \le V_i(\boldsymbol{x}) \le V^{max} \quad (6)$$

where V^{min} and V^{max} are the lower and upper limits on voltage drop, respectively.

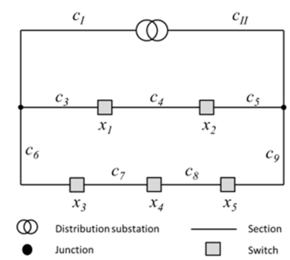


Figure 1. An example model of a distirbution system.

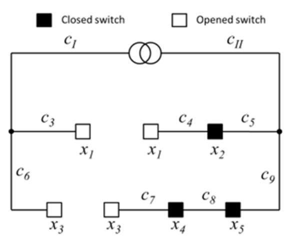


Figure 2. An example configuraion in the distribution system.

III. Loss Minimization with ZDD

A ZDD is a data structure that efficiently represents a family of sets [11]. In this paper, ZDD represents a family of closed-switch sets. ZDDs contain several algorithms. Intersection is one of the algorithms that constructs a ZDD containing all bit vectors satisfying all constraints of given multiple ZDDs. For example, as shown in Fig. 3, (d) is constructed by intersection of (a), (b), and (c). Thus, a ZDD satisfying the topological, line capacity and voltage drop constraints can be easily constructed. In this section, the construction process of each ZDD satisfying the constraints is described. Moreover, the determination process of the loss minimum configuration of distribution system by using the ZDD satisfying all constraints is described.

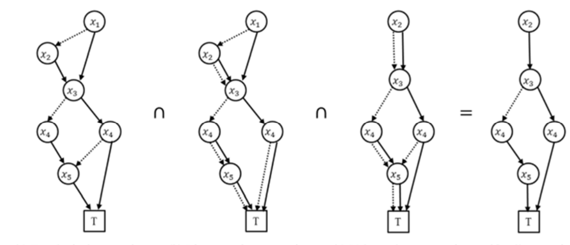


Figure 3. ZDD representing each constraint of Fig. 1.

A. ZDD for Topological Constraint

As a first step, all bit vectors satisfying the topological constraint are represented as a ZDD. Each of these configurations must be a spanning rooted forest, as described in Section II. In this paper, all such forests were found using the frontier-based method [14], an algorithm that finds all paths between a given pair of vertices on a graph and constructs a ZDD containing the paths and satisfying topological constraint (2).

B. ZDDs for Electrical Constraints

All bit vectors satisfying the line capacity and voltage limit are represented as ZDDs. The electrical constraints with respect to a substation specify the limit on line current at the substation and voltage drop at the leaves of the corresponding feeder. The values of line current and voltage drop depend on only the corresponding feeder and are irrelevant to other feeders. Therefore, constructions of ZDDs representing each electrical constraint spend less time than the ZDD constructed in subsection A; these ZDDs include only a few variables and much smaller than that of the topological constraint. In constructing the ZDDs for a substation, edges are ordered in a breadth-first manner, starting from the corresponding substation node. We then start to construct an inclusion-exclusion tree. Given the tree up to the (i – 1)th level, candidates for new nodes are created. Any candidates violating an electrical constraint are removed at this point. Completing these processes generates the ZDDs that satisfy the line capacity and voltage drop constraints.

C. ZDD for All Distrubution Operation Constraints

Intersecting the ZDDs constructed in subsection A and B creates a ZDD that contains all bit vectors satisfying all constraints, which is in turn used to determine the loss minimum configuration of a distribution system.

D. Loss Minimization with ZDD

Since the distribution loss is a nonlinear function of the switch configuration $\boldsymbol{x}$, the ZDD satisfying all constraints must be transformed into the search space by aggregating the variables in a *component* of the distribution system. As shown in Fig. 4 (a), a distribution system is separated into independent components when the root section and first junctions are ignored. Switches 1, …, n are divided into q subsets M_1,...,M_q. Similarly, the configuration vector $\boldsymbol{x}$ is divided into subvectors $\boldsymbol{x_1}$, …, $\boldsymbol{x_q}$. Non-root sections of each component are represented as N_1, …, N_q, and the set of root sections is represented as U. Using this notation, the objective function (1) is rewritten as

$$\sum_{i\in U} R_i J_i^2\,(\boldsymbol{x}) + \sum_{k=1}^{q}\sum_{i\in N_k} R_i J_i^2(\boldsymbol{x_k}) \tag{7}$$

Minimizing (7) is extremely difficult due to global dependencies of J_i at root sections. However, the loss at a non-root node can be easily obtained by independently calculating the loss in each component; the line current is determined by only the conditions of switches at a section and it depends on only sections downstream from that section. Therefore, when root section are ignored, the global optimal solution $\boldsymbol{x}^*$ is determined by solving following function under the topology, line capacity, and voltage limit constraints.

$$\sum_{k=1}^{q}\sum_{i\in N_k} R_i J_i^2(\boldsymbol{x_k})\,, \tag{8}$$

The variable aggregation procedure determining the global optimal solution $\boldsymbol{x}^*$ is as follows. The aggregated categorical variable is defined for $\boldsymbol{x_k}$ as $v_k \in \{0, \ldots, 2^{|M_k|} - 1\}$. Although v_k might take $2^{|M_k|}$different values in the worst-case scenario, the domain is usually much smaller due to topological and electrical constraints. A component-level diagram is created as follows. First, the ZDD shown in Fig. 4 (b) is rearranged such that the variables in a component are aligned next to each other. The set of nodes at the top level in each component contains the boundary nodes. Second, only the boundary nodes are copied to the component-level diagram and edges between these nodes are then created by enumerating all ZDD paths between the boundary nodes. A ZDD path from component k to $k+1$ specifies a configuration of switches for v_k in the kth component. Finally, the total loss in the component is calculated corresponding to the ZDD path and the loss is assigned as the weight of the new edge in the component-level diagram. As shown in Fig. 4 (c), if there are multiple ZDD paths, the minimum loss is taken as the weight. Finally, the optimal solution minimizing (8) is obtained by routing the shortest path from the root node to the terminal in the component-level diagram.

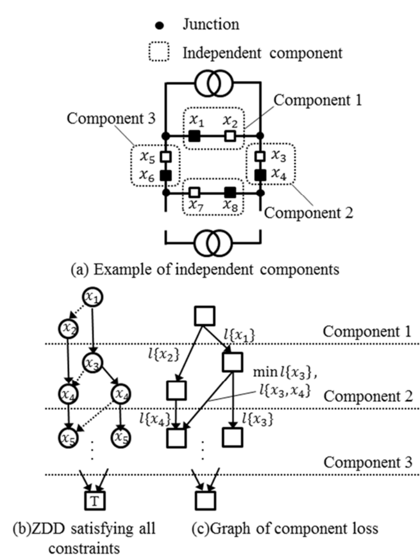


Figure 4. Process of seperation and connection of components.

IV. Numerical Results

We performed numerical simulations to verify the loss reduction effect for a loss minimum configuration of a distribution system with PV penetration by using the method described in Section III. We evaluated the loss minimum configuration by comparing its distribution loss with that of other configurations.

A. *Distribution System Model*

Figure 5 shows the distribution system model used in the numerical simulation. The distribution system model was developed based on an actual distribution system and load profiles provided by a large utility [16]. The data are publicly available online [17]. As shown in Fig. 5, the distribution system consists of 72 feeders, 468 sectionalizing switches, and four distribution substations. Table I summarizes the simulation settings. For the simulation load profile, we used hourly load profiles on a summer day. Table II lists the PV scenarios and Fig. 6 shows the PV allocation of each. In the numerical simulation, PV was introduced to the residential areas, and we performed numerical simulation without PV and with three residential PV penetration patterns; the PV penetration was (1) at the root side of each feeder, (2) at the end side of each feeder, and (3) at all the residential sections in each feeder. The PV penetration amount for one feeder was equivalent to 10%, 20%, and 30% of the total residential load power in a single feeder. Fig. 7 shows hourly total load profiles and 30% PV outputs.

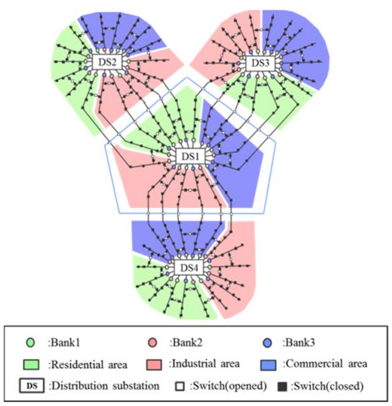
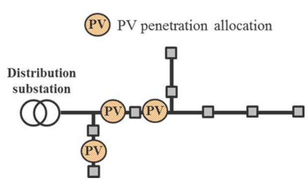
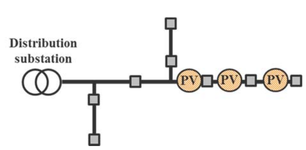


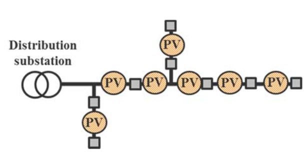
Figure 5. Distribution system model.



(a) Root side PV penetration pattern



(b) End side PV penetartion pattern



(c) Even PV distribution pattern

Figure 6. PV penetration allocations of each residential area feeder.

TABLE I. SIMULATION SETTING OF DISTRIBUTION SYSTEM

Total number of distribution substations	4 substations
Total number of banks	12 banks
Total number of feeders	72 feeders
Total number of switches	468 switches
Total number of sections	648 sections
Total number of load areas	4 residential areas
	4 industrial areas
	4 commercial areas
Sending line voltage (V_0)	6600V
Upper voltage limit ($V_0 - V^{min}$)	6900V
Lower voltage limit ($V_0 - V^{max}$)	6300V
Line capacity (J^{max})	300A

TABLE II. PV PENETRATION SCENARIOS

Residential PV penetration scenario	PV penetration amount
No PV penetration	0%
Root side penetration on the feeders	10%, 20%, 30%
End side penetration on the feeders	10%, 20%, 30%
Even distribution on the feeders	10%, 20%, 30%

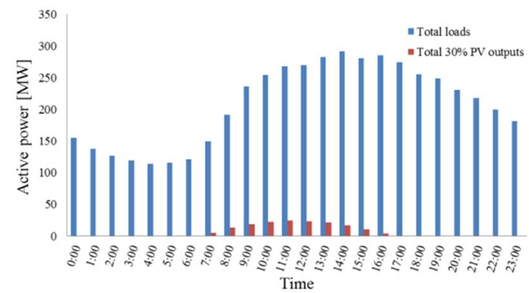


Figure 7. Hourly total load and PVoutput profiles.

B. *Loss Reduction Effect by System Reconfigration*

Figures 8 and 9 show the cumulative probability density function of distribution loss for each PV penetration pattern. These distributions are based on 10,000 randomly sampled configurations from among all possible configurations. As shown in Fig. 8, more than 85% of all the possible distribution configurations produce over 20% more electrical power loss than loss minimum configuration in the case of no PV penetration. In addition, Fig. 9 shows that loss minimum configuration effectively reduces distribution loss for each PV penetration pattern respectively. This verifies that distribution system reconfiguration from a conventional configuration to a loss minimum configuration reduces distribution loss.

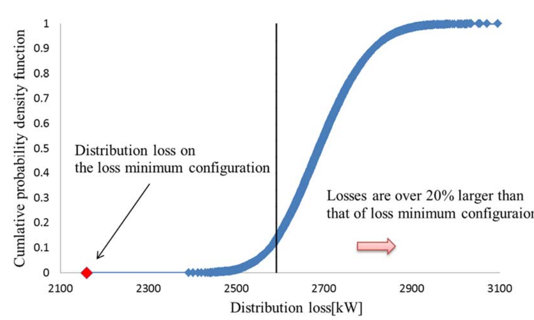


Figure 8. Cumulative probability denstity function of distribution loss without PV penetration at 11:00.

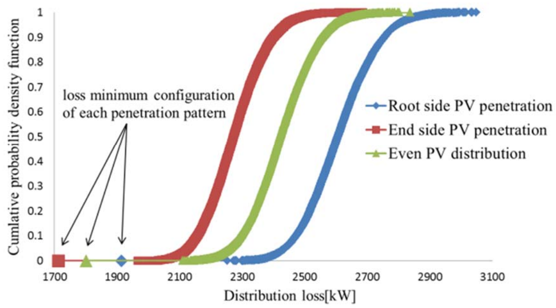
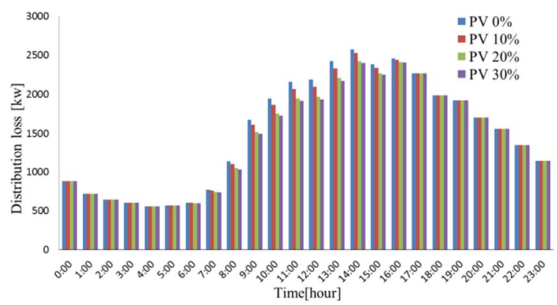


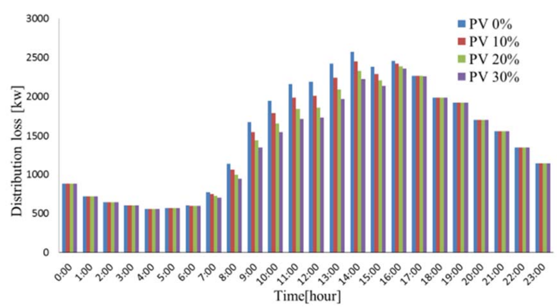
Figure 9. Cumulative probability denstity function of distribution loss with 30% PV penetrations at 11:00.

C. *Comparison of Loss Reduction Effect under Various PV Penetration Patterns*

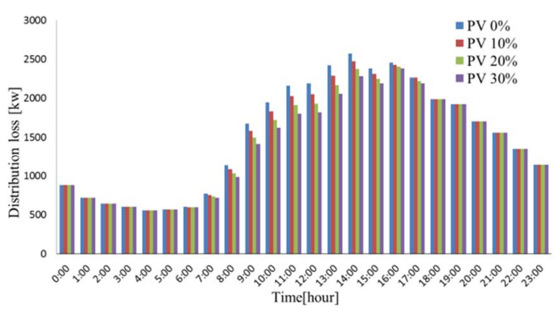
We verified hourly distribution losses and loss reduction effects on the loss minimum configuration for the PV penetration scenarios listed in Table II. Figs. 10 and 11 present distribution loss and loss reduction effects on distribution loss minimum configurations. End side PV penetration is the most effective to reduce distribution losses. The maximum loss reduction effect is about 20.7% at the peak time (11:00) of PV output. On the other hand, the loss reduction effect of root side penetration is about 11.4% and is relatively ineffective at reducing distribution losses. Even in the PV distribution case, the maximum loss reduction effect is about 16.7%, the second largest of the three PV penetration patterns. Thus, the appropriate PV allocation that increases loss reduction is the end side of feeders. Table III lists the hourly total number of changed switches from the loss minimum configuration without PV penetration pattern to the loss minimum configuration with each PV penetration pattern. As listed in Table III, the loss minimum configurations are largely changed from over 20% PV penetration in each penetration pattern. For end side PV penetration in particular, the number of state-changed switches for reconfiguration into loss minimum configuration is significantly larger than the other PV penetration patterns. This result shows that end-side PV penetration strongly affects the power flow of distribution systems. Therefore, reconfiguring the distribution system is valid for alleviating distribution loss.



(a) Root-side PV penetration pattern

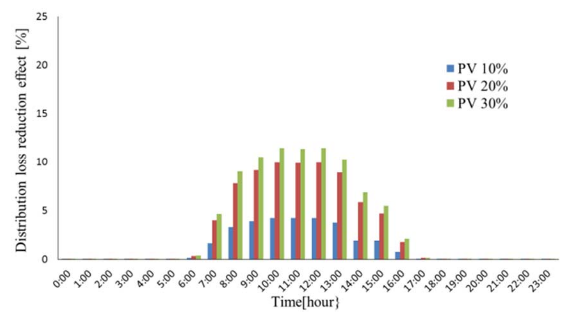


(b) End-side PV penetration pattern

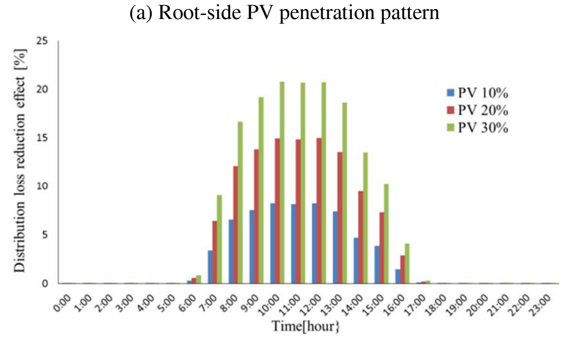


(c) Even PV distribution pattern

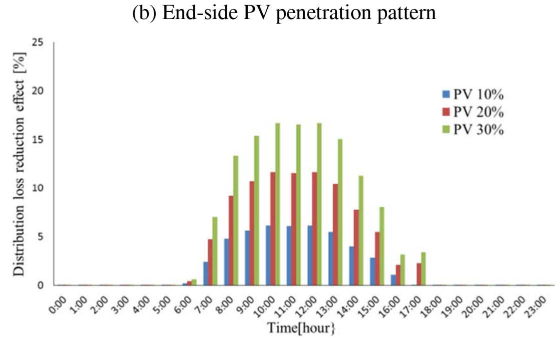
Figure 10 Hourly distribution losses on loss minimum configuration.



(a) Root-side PV penetration pattern



(b) End-side PV penetration pattern



(c) Even PV distribution pattern

Figure 11 Hourly loss reduction effects on loss minimum configuration.

TABLE III. TOTAL NUMBER OF STATE-CHANGED SWITCHES

	Root side penetration			End side penetration			Even distribution		
time	10%	20%	30%	10%	20%	30%	10%	20%	30%
0:00	0	0	0	0	0	0	0	0	0
1:00	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0
7:00	0	**3**	**3**	**3**	**6**	**6**	**4**	**4**	**5**
8:00	0	0	0	0	**4**	**12**	0	**2**	**4**
9:00	0	**3**	**4**	0	**10**	**14**	0	**3**	**6**
10:00	0	**3**	**4**	0	**10**	**17**	0	**3**	**7**
11:00	0	**3**	**4**	0	**11**	**16**	0	**4**	**7**
12:00	0	**3**	**4**	**1**	**10**	**14**	0	**3**	**6**
13:00	0	0	0	**1**	**4**	**12**	0	0	**4**
14:00	0	0	0	0	**3**	**3**	0	0	**3**
15:00	0	0	0	0	0	**4**	0	0	0
16:00	0	0	0	0	0	0	0	0	0
17:00	0	**1**	**1**	0	**1**	**1**	0	**1**	**1**
18:00	0	0	0	0	0	0	0	0	0
19:00	0	0	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0

V. CONCLUSION

This paper verified the loss reduction effect on the loss minimum configuration of distribution system selected from all enumerated configurations. Results of numerical simulation clearly show that the loss minimum configuration significantly reduces distribution loss in comparison with other configurations. The results also show that proper placement of PV penetration was effective to increase the loss reduction effect. In particular, end side PV penetration of feeders obtained significantly more loss reduction effect than did root side or even PV distribution. As a guideline for energy conservation and low-carbon operation, we conclude that distribution systems should be managed with loss minimum configurations and PV should be allocated at the end side of feeders. Acknowledgement

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