Multi Evaluation Method of Distribution Network with Distributed Generators

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Abstract **— In this paper, the authors propose a multi evaluation method to evaluate the distribution network configuration candidates satisfying constraints of voltage and line current limit from two viewpoints: distribution loss and voltage imbalance rate. In the proposed evaluation method, after several high-ranking candidates with small distribution loss are extracted by combinatorial optimization method, each candidate is evaluated with regard to two viewpoints using EMTP (Electro-Magnetic Transients Program). The standard analytical model of the distribution network based on the practical data is constructed to multilaterally evaluate the distribution network configuration candidates. The constructed model has 4 distribution substations, 72 feeders, 450 switches, 1,728 single-phase loads, and 54 distributed generators (DG). This model has 2^{450} configuration candidates. In order to examine the validity of the proposed evaluation method, the numerical simulations are carried out for the standard analytical distribution network model with DGs.**

Index Terms**— Distributed generator, distribution network, multi evaluation, distribution loss, voltage imbalance rate, EMTP**

I. INTRODUCTION

Since a distribution network with many feeders has many sectionalizing switches, there are huge radial network configuration candidates by changing states (opened or closed) of sectionalizing switches. Recently, total number of DGs such as photovoltaic generation system and wind power generation system connected to distribution network is drastically increased. The distribution network connected with many DGs must be operated keeping electric supply reliability and electric power quality. Therefore, the many configurations of the distribution network with DGs must be evaluated multilaterally from various viewpoints such as distribution loss, voltage imbalance rate and so on. So far, several researches to reliably operate distribution systems with DGs have been proposed [1-17]. However, the configuration has not been evaluated from several viewpoints (e.g. distribution loss and electric power quality).

In this paper, the authors propose a multi evaluation method to evaluate the distribution network configuration candidates satisfying constraints of voltage and line current limit from two viewpoints: distribution loss and voltage imbalance rate. In the proposed evaluation method, after several high-ranking candidates with small distribution loss are extracted by an efficient enumeration method for three cases of total capacity of DGs (0%, 15%, and 30% of total load), each candidate is evaluated from the two viewpoints using EMTP.

II. ANALYTICAL MODEL OF DISTRIBUTION NETWORK WITH DGS

A constructed standard analytical model of distribution network to evaluate the distribution loss and voltage imbalance rate is shown in Figure 1. This model has 4 distribution substations, 72 feeders, 450 switches, 1,728 single-phase loads, 54 DGs (photovoltaic generation systems), and 2^{450} distribution network configuration candidates. The standard analytical model data based on practical power utilities data is shown in Table 1.

The standard analytical model uses data of the sending current and power factor in the residential area, industrial area, and commercial area measured by the electric power company. The sending current of each load area is shown in Figure 2. Figure 3 shows the power factor of each load area. Output of three type of DGs is shown in Figure 4. By connecting the three imbalance single-phase loads to each feeder, the imbalance of each feeder load is modeled.

Each single-phase load is modeled as an impedance load which consists of a resistance load R, an inductive load L, and a capacitive load C as shown in Figure 1.

III. MULTI EVALUATION METHOD FOR DISTRIBUTION NETWORK CONFIGURATION CANDIDATES

The proposed multi evaluation method has three procedures in order to evaluate the distribution loss and voltage imbalance rate for many distribution network configuration candidates. These procedures are described

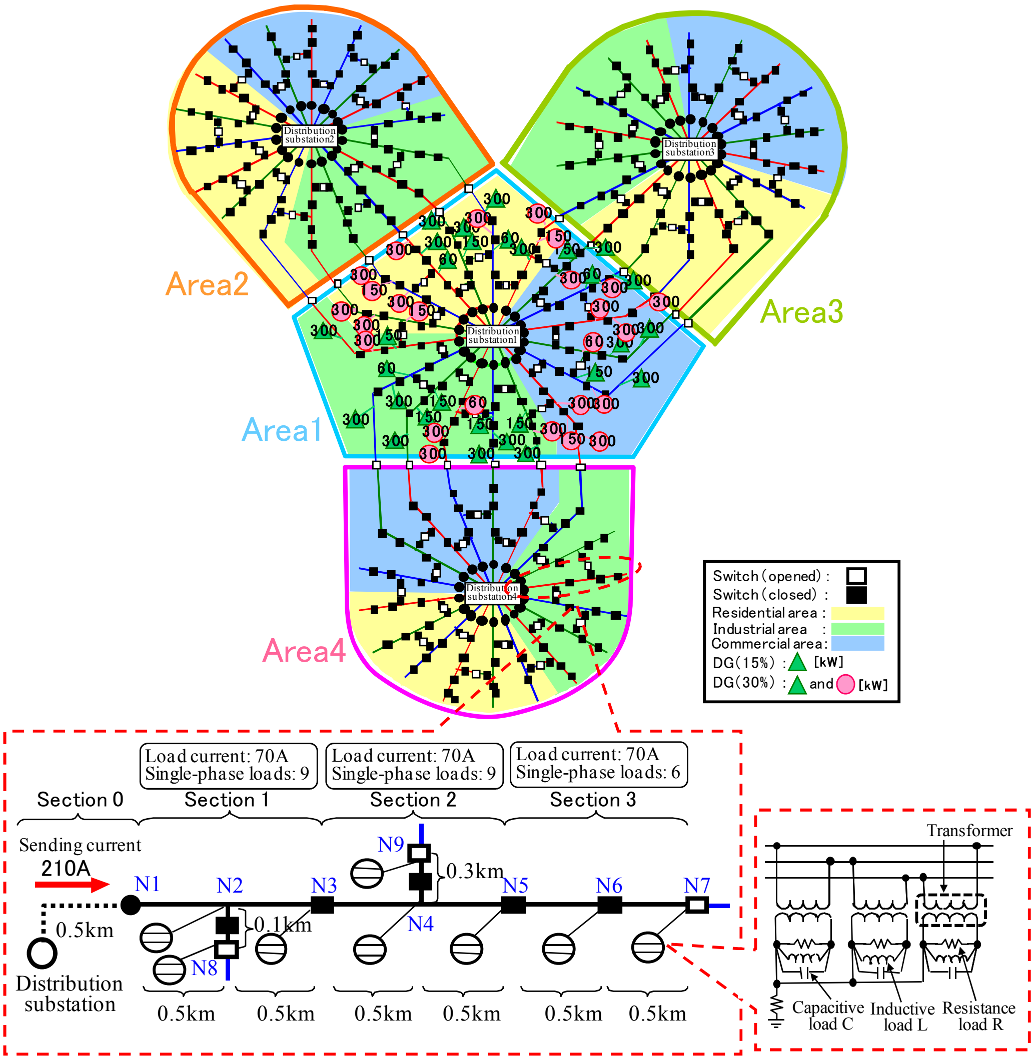

Figure 1: Standard analytical model of distribution network.

Number of distribution substations	4
Number of transformer banks	3/substation
Number of feeders	72
Number of switches	450
Number of distribution network configuration candidates	2^{450} (≈$2.9*10^{135}$)
Number of single-phase loads	1,728
Number of DG	Case1: 0 PV Case2: 29 PVs Case3: 54 PVs
Total load of system (24 hours)	2,805MWh
Number of load areas	Residential : 4 Industrial : 4 Commercial : 4
Sending line voltage	6,600V
Maximum sending current	210A/feeder
Feeder length	3.5km/feeder

Table 1: Standard analytical model data.

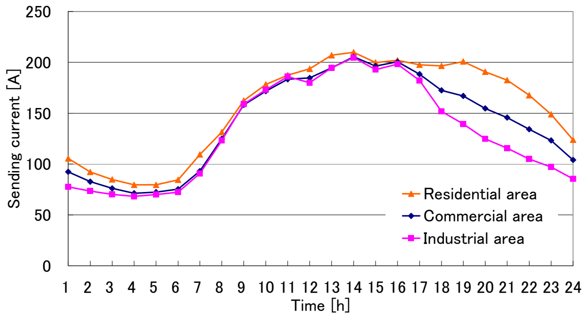

Figure 2: Sending current of each load area.

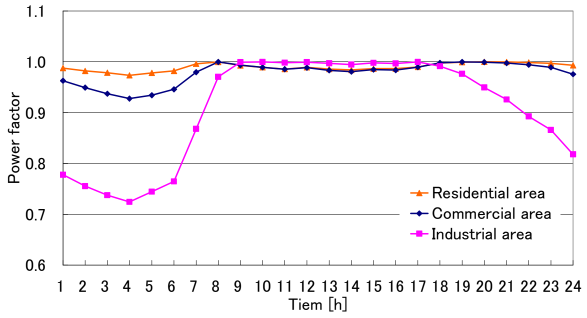

Figure 3: Power factor of each load area.

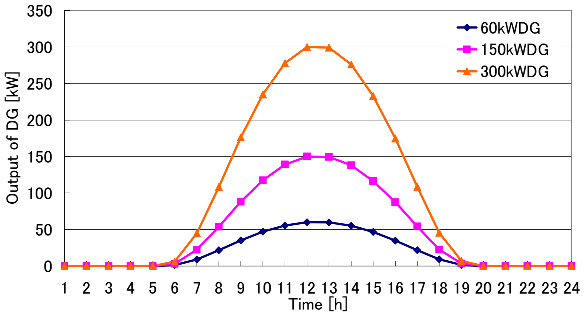

Figure 4: Output of DG.

below.

Procedure 1: Distribution network configuration candidates that are satisfying operation constraints (radial structure constraint, voltage drop constraint, and line capacity constraint) are selected. And then, several high-ranking candidates with small distribution loss at peak load are extracted from them by using ROBDD (Reduced Ordered Binary Decision Diagram) which is an efficient enumeration method [18][19] for assumed three cases of total capacity of DGs (0%, 15%, and 30% of total load).

Procedure 2: The selected distribution network configuration candidates are evaluated from viewpoints of total distribution loss and voltage imbalance rate. If the voltage imbalance rate of the distribution network configuration candidate exceeds the upper limit value (management target value), the candidate is removed from the preferable distribution network configuration candidate.

Procedure 3: The selected distribution network configuration candidates are evaluated from a viewpoint of total balance. The candidate with the minimum evaluated value of total balance is determined as the best distribution network configuration.

Figure 5 shows the flow of multi evaluation for distribution network configuration candidates. Each evaluation method of distribution loss, voltage imbalance rate, and total balance is explained below.

A. Evaluation of Distribution Loss

By calculating the distribution loss for several time periods in all feeders, the distribution network configuration candidates are evaluated from the viewpoint of the distribution loss. The evaluation formula is expressed by Eq. (1). The distribution network configuration candidate with the minimum value of Eq. (1) is evaluated as the best configuration from a viewpoint of the distribution loss.

$$LOSS_N = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{j=1}^{J}(I_{Utfj}^2 + I_{Vtfj}^2 + I_{Wtfj}^2)R_j \qquad (1)$$

where, $LOSS_N$ [Wh] is total distribution loss of distribution network configuration candidate $N(=1\sim M)$, I_{Utfj}, I_{Vtfj}, I_{Wtfj} [A] are each phase node section $j(=1\sim J)$ current in feeder $f(=1\sim F)$ at time period $t(=1\sim T)$[h], and R_j [Ω] is line resistance of between nodes section j.

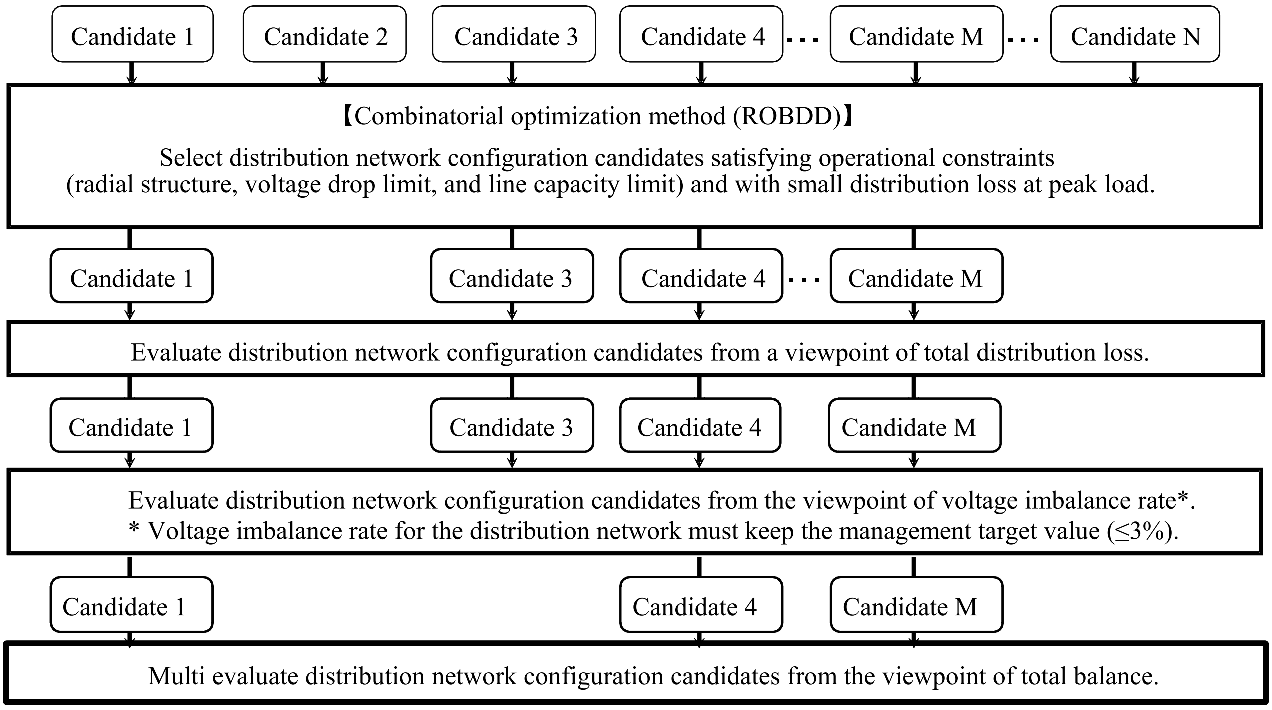

Figure 5: Flow of multi evaluation for distribution network configuration candidates.

B. Evaluation of Voltage Imbalance Rate

The distribution network configuration candidates are evaluated from the viewpoint of the voltage imbalance rate by calculating the maximum value of the voltage imbalance rate in all feeders, all nodes, and for several time periods. The evaluation formula is expressed by Eq. (2). The best distribution network configuration from the viewpoint of the voltage imbalance rate has the minimum value of Eq. (2).

$$U_{\max N} = \max_{t,f,i}\left\{\frac{|\dot{V}_{Utfi} + \dot{a}^2\dot{V}_{Vtfi} + \dot{a}\dot{V}_{Wtfi}|}{|\dot{V}_{Utfi} + \dot{a}\dot{V}_{Vtfi} + \dot{a}^2\dot{V}_{Wtfi}|}\times 100\right\} \qquad (2)$$

where, U_{maxN} [%] is maximum value of voltage imbalance rate of distribution network configuration candidate N, $\dot{V}_{Utfi}$, $\dot{V}_{Vtfi}$, $\dot{V}_{Wtfi}$ [V] are U, V, W phase voltage vector at node i of feeder f at time period t[h], and $\dot{a}$ is the vector operator ($\dot{a} = -1/2 + j\sqrt{3}/2$).

C. Evaluation of Total Balance

From the above two viewpoints, the distribution network configuration candidates are evaluated by using 2-norm. The evaluation values obtained by Eq. (1) and Eq. (2) are normalized from 0.1 to 1 (minimum value is 0.1, maximum value is 1). The distribution network configuration candidates are evaluated according to the evaluation index of total balance shown in Eq. (3).

$$E_N = \sqrt{{L_N}^2 + {U_N}^2} \qquad (3)$$

where, L_N is normalized distribution loss of distribution network configuration candidate N, and U_N is normalized maximum value of voltage imbalance rate of distribution network configuration candidate N. From the viewpoint of the total balance, the distribution network configuration candidate with the minimum value of Eq. (3) is evaluated as the best configuration.

IV. NUMERICAL EXAMPLES

Examples of numerical calculation are carried out in order to check the validity of the proposed multi evaluation method using the analytical model shown in Figure 1. In the analytical model of the distribution network, the distribution network configuration candidates are evaluated from viewpoints of the distribution loss, the voltage imbalance rate, and the total balance based on the proposed method. This model has 2^{450} distribution network configuration candidates. In this paper, 50 high-ranking distribution network candidates with small distribution loss at peak load are extracted from among the huge candidates by using ROBDD. The evaluation results of the distribution network configuration candidates are shown in Figures 6 to 14.

The total distribution loss for each distribution network configuration in each case (total capacity of DGs is 0%, 15%, and 30% of total load) is shown in Figures 6 to 8, respectively. As shown in Figure 6, in case there is no DG, the best distribution network configuration obtained from the viewpoint of the distribution loss is candidate 5 ($LOSS_5$ =48,358kWh). When the total capacity of DGs are 15% and 30% of total load, the best distribution network configuration obtained from the viewpoint of the distribution loss are candidates 1 as shown in Figures 7 and 8 ($LOSS_1$=46,480kWh and 44,927kWh, respectively). From Figures 6 to 8, it is seen that total distribution loss is decreased by increasing total capacity of DGs.

Figures 9 to 11 show the maximum value of voltage imbalance rate in each distribution network configuration. When there is no DG, all the distribution network configuration candidates satisfy a constraint of the management target value (3%) as shown in Figure 9. Therefore, the best distribution network configuration obtained from the viewpoint of the voltage imbalance rate becomes candidate 9 (U_{max9}=2.86%). In case the total capacity of DGs is 15% of total load, since all the distribution network configuration candidates are less than the management target value as shown in Figure 10, the best distribution network configuration obtained from the viewpoint of the voltage imbalance rate is candidate 37 (U_{max37}=2.76%). In case the total capacity of DGs is 30% of total load, as shown in Figure 11, several distribution network configuration candidates which exceed the management target value are removed from the feasible distribution network configuration candidates. Furthermore, since a number of best distribution network configuration candidates with the same value of the voltage imbalance rate exist, the candidate with the smallest distribution loss is determined as the best distribution network configuration. Therefore, the best distribution network configuration obtained from the viewpoint of the voltage imbalance rate becomes candidate 1 (U_{max1}=2.95%).

The total evaluation value in each distribution network configuration is shown in Figures 12 to 14. From the viewpoint of the total balance, in case there is no DG, the best distribution network configuration is candidate 9 (E_9=0.21) as shown in Figure 12. When 15% and 30% of total load are total capacity of DGs, the best distribution network configurations are candidate 37 (E_{37} =0.63) and candidate 1 (E_1=0.14) as shown in Figure 13 and Figure 14, respectively.

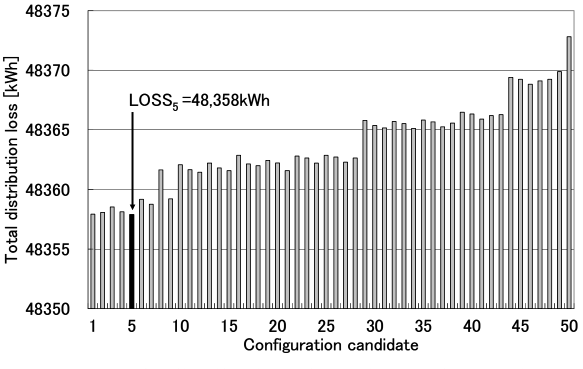

Figure 6: Total distribution loss in each configuration candidate in case there is no DG.

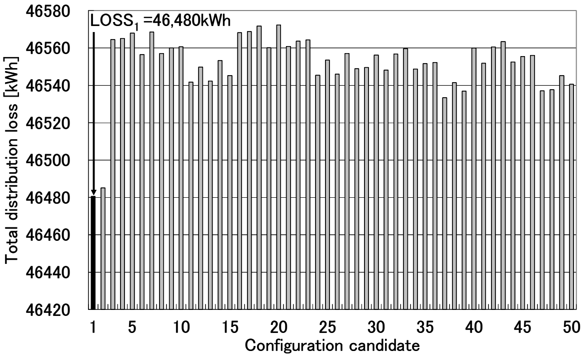

Figure 7: Total distribution loss in each configuration candidate when total capacity of DGs is 15% of total load.

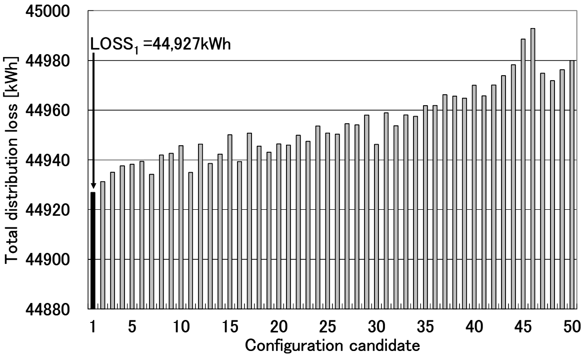

Figure 8: Total distribution loss in each configuration candidate when total capacity of DGs is 30% of total load.

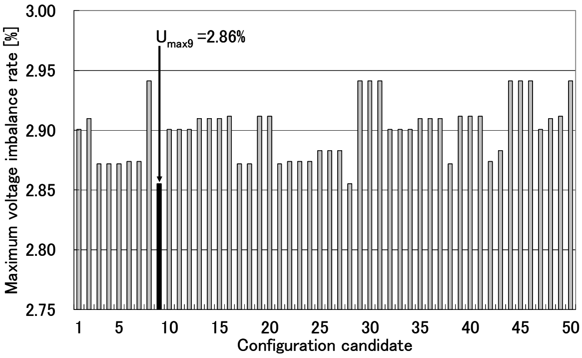

Figure 9: Maximum value of voltage imbalance rate in each configuration candidate in case there is no DG.

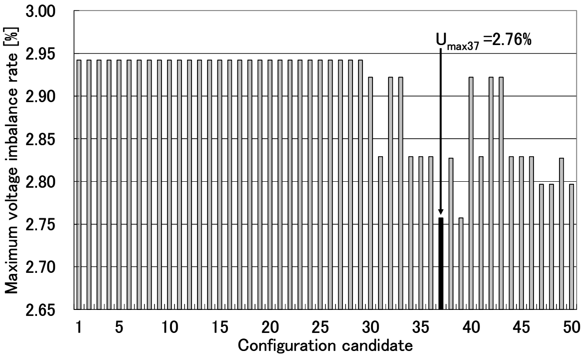

Figure 10: Maximum value of voltage imbalance rate in each configuration candidate when total capacity of DGs is 15% of total load.

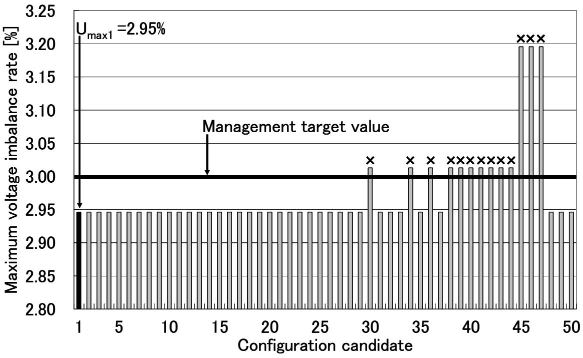

Figure 11: Maximum value of voltage imbalance rate in each configuration candidate when total capacity of DGs is 30% of total load.

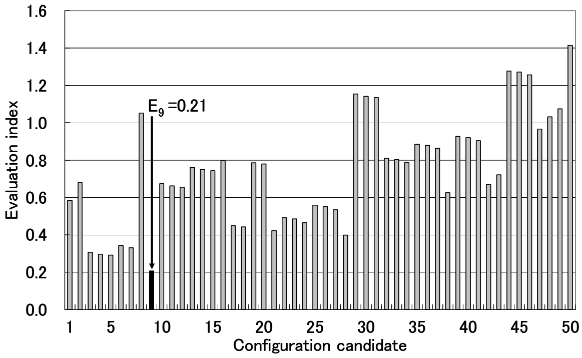

Figure 12: Total evaluation value in each configuration candidate in case there is no DG.

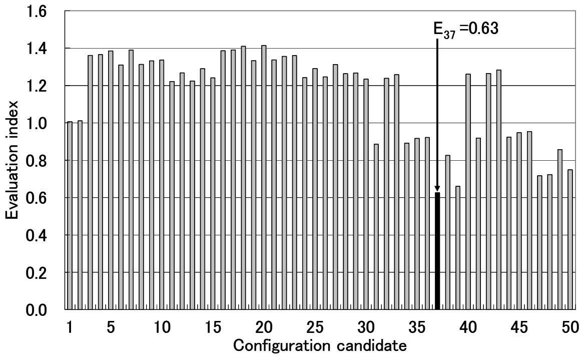

Figure 13: Total evaluation value in each configuration candidate when total capacity of DGs is 15% of total load.

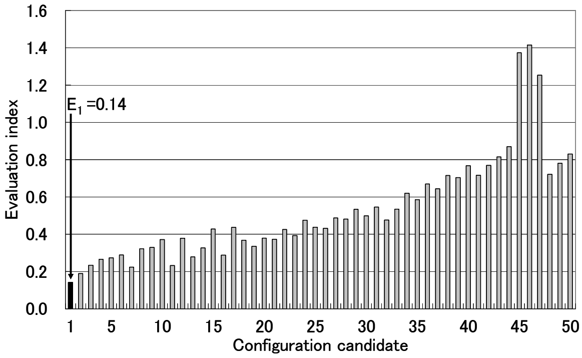

Figure 14: Total evaluation value in each configuration candidate when total capacity of DGs is 30% of total load.

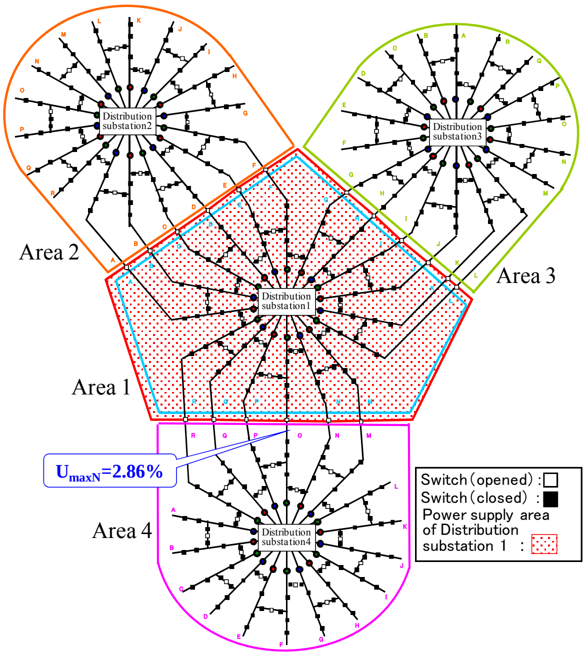

Figure 15: The best configuration in case there is no DG.

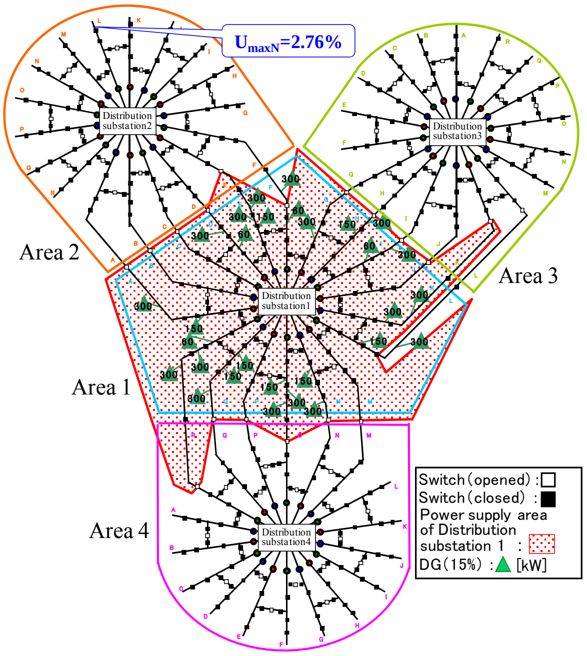

Figure 16: The best configuration when total capacity of DGs is 15% of total load.

The best distribution network configurations obtained from a viewpoint of the total balance is shown in Figure 15-17. From these figures, it is seen that the best distribution network configuration changes with differences in the total capacity of DGs, and the electric power supply area of substation 1 is expanded with the increase of total capacity of connected DGs.

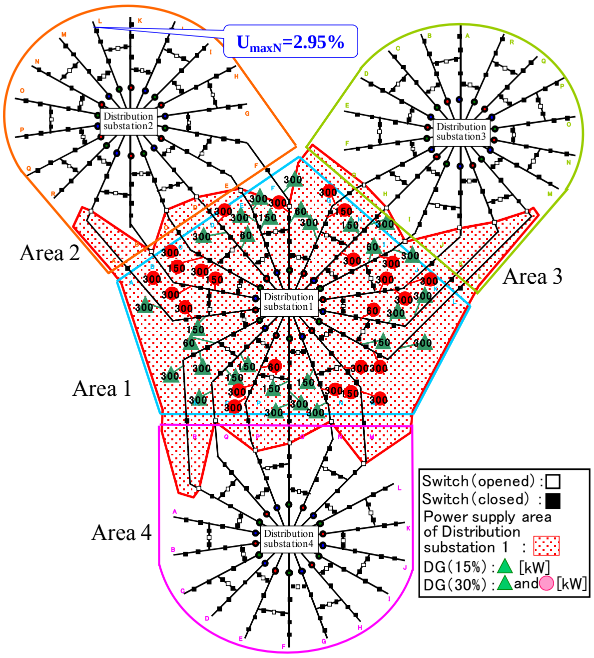

Figure 17: The best configuration when total capacity of DGs is 30% of total load.

V. CONCLUSION

In this paper, the authors proposed an evaluation method to evaluate the distribution network configuration candidates from two viewpoints of distribution loss and voltage imbalance rate. In order to examine the validity of the proposed method, the numerical simulations were carried out using EMTP for the constructed standard analytical distribution network model with 2^{450} distribution network configuration candidates based on the practical data. In the numerical simulations, after 50 high-ranking distribution network configuration candidates with small distribution loss at peak load were extracted from the huge configuration candidates for three cases of total capacity of DGs (0%, 15%, and 30% of total load), extracted candidates were evaluated from the two viewpoints and the best distribution network configurations were obtained. As the numerical results, it was shown that the best distribution network configuration changes with differences in the total capacity of DGs, and the electric power supply area with DGs is expanded with the increase of total capacity of connected DGs. It became clear that reevaluation of distribution network configuration candidates with the increase of total number of connected DGs is needed in order to keep reliability of power supply and minimize distribution loss of the distribution network with DGs.

VI. REFERENCES

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