Experimental Multi-objective Evaluation of Radial and Loop Distribution Network Configuration Using Distribution Network Equipment

Paper

Experimental Multi-objective Evaluation of Radial and Loop Distribution Network Configuration Using Distribution Network Equipment

Shigekazu Sakai*, student member, Yasuhiro Hayashi*, member, Shoji Kawasaki*, member, Junya Matsuki*, member, Yoshiaki Fuwa**, member, Kenjiro Mori**, member

In this paper, the authors propose an experimental multi-objective evaluation method based on use of distribution network equipment to evaluate distribution network configuration candidates with distributed generators such as photovoltaic generation system and wind power generation system by hourly changing states of sectionalizing switches satisfied with constraints of voltage and line current limit. In the proposed experimental multi-objective evaluation method, the optimal network configuration is determined by using multi-objective evaluation based on total distribution loss rate, maximum voltage total harmonic distortion, and maximum voltage imbalance rate in order to reduce distribution loss and keep power quality. The proposed method is applied to radial and loop distribution network configuration by using an experiment of scaled-down three-phase distribution network with one bank distribution transformer, 5 distribution lines, 5 sectionalizing switches, 12 single-phase loads and 5 DGs.

Keywords : Distribution network, Distributed generator, Sectionalizing switch, Distribution loss, Voltage total harmonic distortion, Voltage imbalance rate, Sending voltage

1. INTRODUCTION

Since a distribution system with many feeders has many sectionalizing switches, there are huge radial network configuration candidates by determining states (opened or closed) of sectionalizing switches. Recently, total number of distributed generators (DGs) such as photovoltaic generation system and wind power generation system connected to an actual distribution network increases drastically in Japan. The distribution network connected with many DGs must be operated while keeping reliability of power supply, power quality and loss reduction. Several methodologies to reliably operate distribution systems with DGs have been proposed, and these availabilities have been verified by computer simulation [1]-[17]. However, since computer modeling of the distribution system and DG can not recreate physical phenomenon such as harmonic accurately, the computer simulation can not correctly evaluate the power quality of the distribution network with DGs. Therefore, a novel experimental configuration evaluation method is needed, which is based on power quality data measured in a equipment of distribution network with DGs. So far, an experimental multi-objective evaluation method of the distribution network configuration with DGs has not been proposed from viewpoints of power quality, distribution loss, and reliability of power supply.

In this paper, the authors propose an experimental multi-objective evaluation method based on voltage and current data measured by a distribution network equipment in order to accurately evaluate distribution network configuration candidates with DGs such as photovoltaic generation system and wind power generation system. In the proposed experimental multi-objective evaluation method, the optimal network configuration is determined in order to reduce distribution loss and keep power quality by using multi-objective evaluation based on total distribution loss rate, maximum voltage total harmonic distortion, and maximum voltage imbalance rate. The proposed method is applied to an experiment of scaled-down three-phase distribution network with 4 photovoltaic generation systems and a wind power generation system in order to realize the multi-objective evaluation based on measured power quality data while recreating various network configuration candidates. The results obtained by the proposed experimental multi-objective evaluation for radial and loop distribution network configuration with DGs are shown and compared to the conventional evaluation.

2. OUTLINE OF DISTRIBUTION NETWORK EQUIPMENT

Distribution network equipment installed in University of Fukui in Japan is a three-phase 200V distribution network that 6.6kV distribution one is scaled down. The photograph and structure of the scaled-down three-phase distribution network equipment are shown in Fig.1 and Fig.2, respectively. This equipment has AVR, sending voltage equipment, 7 distribution lines with switch, 18 single-phase constant impedance loads, 5 inverters modeled as DGs, programmable control equipment and digital measuring instrument. Sectionalizing switches states (opened or closed), sending voltage profile (transformer’s tap position), single-phase load profile and output of DGs can be controlled by time-series data. Therefore, it is easy to apply the proposed multi-objective evaluation method based on the optimal radial configuration and sending voltage profile to the distribution network equipment. Outline of each equipment is shown in Table 1.

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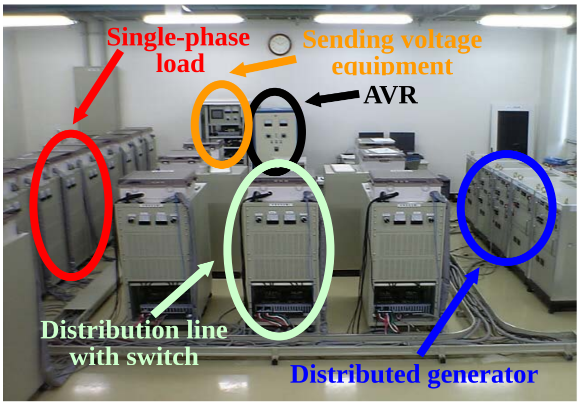


Fig.1. Picture of the scaled-down three-phase distribution network equipment.

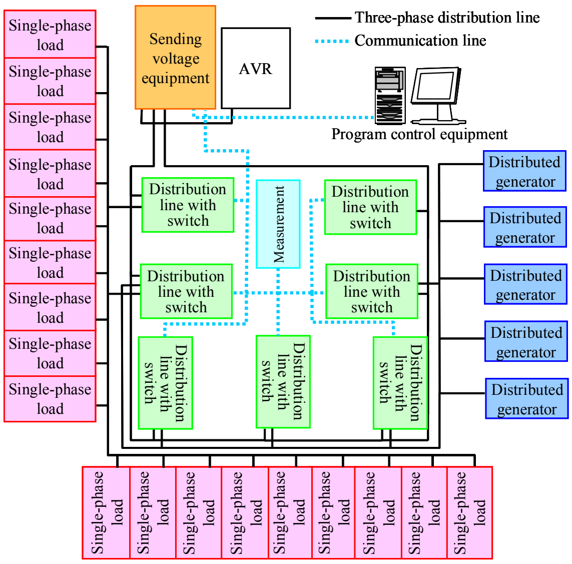


Fig.2. Structure of the scaled-down three-phase distribution network equipment.

3. EXPERIMENT OF MULTI-OBJECTIVE EVALUATION OF RADIAL AND LOOP DISTRIBUTION CONFIGURATION

In the proposed multi-objective evaluation method, the optimal network configuration is determined by using multi-objective evaluation based on total distribution loss rate, maximum voltage total harmonic distortion, and maximum voltage imbalance rate in order to reduce distribution loss and keep power quality. Radial network configuration candidate N and loop configuration are evaluated by multi-objective evaluation value E_N expressed by Eq.(1)-(4). The network configuration candidate with the minimum multi-evaluation value min{E_N} is determined as the optimal distribution network configuration.

(Total distribution loss rate)

$$LOSS_N=\left\{\sum_{t=1}^{24}\sum_{j=1}^{5}(I_{Atj}^2+I_{Btj}^2+I_{Ctj}^2)R_j\right\}\Big/(Total load)\times 100 \quad \text{.. (1)}$$

(Maximum voltage THD)

$$D_{\max N}=\max_{t,i,p}\left\{\frac{\sqrt{V_{5tip}^2+V_{7tip}^2}}{V_{1tip}}\times 100\right\} \quad \text{..... (2)}$$

Table 1. Outline of Distribution Network Equipment

AVR	・Range of voltage variation 200V±10%.
	・Accuracy 180V～220V±3V.
	・Rated capacity: 15kVA.
	・Response time: 1s.
Sending voltage equipment	・2V of 21 taps from 180V to 220V (correspond to 30V of 21 taps from 6300V to 6900V of 6.6kV distribution system).
	・Tap position can be controlled by digital signal from PC.
Distribution line with switch	・Aluminum wire 120mm2 (ALOE120) model.
	・State (opened or closed) of sectionalizing switch can be controlled by digital signal from PC.
	・Line impedance can be controlled from 0km to 1.5km.
	・Line capacity: 30A.
Single-phase load (constant impedance load)	・Rated current 2A, constant impedance load (correspond to 50A of 6.6kV distribution system).
	・Combination of R, L, and C (R:29, L: 9 and C: 8) can be controlled by digital signal from PC.
	・Heavy load and light load model (downtown, industrial , residence , and rural area) .
Distributed generator (constant power load)	・Pulse width modulation (PWM).
	・Switching frequency (chopper : 18kHz, inverter : 9kHz) .
	・Output current harmonic distortion (THD ≦5%, distortion of each harmonic order≦3%).
	・Output of active power, reactive power, and current can be controlled by digital signal from PC.
	・Distributed generator modeled by positive signal, constant power load modeled by negative signal.
	・Output range of active power: -9.2kW~9.2kW, Output range of reactive power: -9.2kvar~9.2kvar, and Output range of line current: 0A~26A.
Digital measuring instrument	・Measurement (measured data are saved as CSV files).
	Line voltage of primary transformer and secondary transformer (root-mean-square value).
	Phase voltage of secondary transformer (instantaneous value).
	Line current, Phase voltage of node (instantaneous value).
	Sampling time: 10μs～10s .
Program control equipment	・INPUT: range of input voltage ±5V or ±10V (32 A/D input channels).
	・OUTPUT: range of output voltage ±5V or ±10V (32 D/A output channels).

(Maximum voltage imbalance rate)

$$U_{\max N}=\max_{t,i}\left\{\frac{|\dot V_{Ati}+\dot a^2\dot V_{Bti}+\dot a\dot V_{Cti}|}{|\dot V_{Ati}+\dot a\dot V_{Bti}+\dot a^2\dot V_{Cti}|}\times 100\right\} \quad \text{..... (3)}$$

(Multi-objective evaluation value)

$$E_N=\sqrt{L_N{}^2+D_N{}^2+U_N{}^2} \quad \text{..... (4)}$$

where $LOSS_N$ [Wh] is total distribution loss rate of candidate N(=1~M); I_{Atj} , I_{Btj} , I_{Ctj} [A] are each phase line section j(=1~5) current at t(=1-24) [h]; R_j [Ω] is line resistance of line section j; D_{maxN} [%] is maximum value of voltage THD of candidate N; V_{1tip} , V_{5tip} , V_{7tip} [V] are p(=A,B,C) phase fundamental wave voltage, 5th harmonic voltage, and 7th harmonic voltage at node i at t [h], respectively; U_{maxN} [%] is maximum value of voltage imbalance rate of candidate N; $\dot V_{Ati}$, $\dot V_{Bti}$, $\dot V_{Cti}$ are A, B, C phase voltage vector at node i at t [h], respectively; $\dot a$ is vector operator ($\dot a=-1/2+j\sqrt{3}/2$), E_N is multi-objective evaluation value of candidate N; L_N is normalized total distribution loss rate of candidate N; D_N is normalized maximum value of THD of candidate N; and U_N is normalized maximum value of voltage imbalance rate of candidate N.

In addition, for the radial configuration candidates and loop configuration, determination of the optimal sending voltage profile is carried out in order to maintain node voltage within the secure voltage range. The optimal sending voltage profile is determined so as to minimize total number of tap position's changing per day E and maximize voltage margin H under the voltage and current limit constraints as formulated by Eq.(5)-(13).

[Objective function]

$$F = E + \alpha H \quad \rightarrow Minimize \qquad (5)$$

$$E = \sum_{i=1}^{M}\sum_{t=1}^{24} x_{i,t-1}(I_{LOAD}, I_{DG})\{x_{i,t-1}(I_{LOAD}, I_{DG}) - x_{it}(I_{LOAD}, I_{DG})\} \qquad (6)$$

$$H = \sum_{i=1}^{M}\sum_{t=1}^{24} (V_{TARGET\,t} - V_{it}x_{it}(I_{LOAD}, I_{DG}))^2 \qquad (7)$$

$$V_{TARGET\,t} = (V\max_t + V\min_t)/2 \qquad (8)$$

[Operational constraints]

(Tap position)

$$\sum_{i=1}^{M} x_{it}(I_{LOAD}, I_{DG}) = 1 \qquad (t = 1,2,...,24) \qquad (9)$$

(Sending voltage limit)

$$V\min_t \le V_{it}x_{it}(I_{LOAD}, I_{DG}) \le V\max_t$$

$$(i = 1,2,...,M,\ t = 1,2,...,24) \qquad (10)$$

$$V\min_t = \max\{V_{Amint}, V_{Bmint}, V_{Cmint}\} \qquad (t = 1,2,...,24) \qquad (11)$$

$$V\max_t = \min\{V_{Amaxt}, V_{Bmaxt}, V_{Cmaxt}\} \qquad (t = 1,2,...,24) \qquad (12)$$

(Each node voltage limit)

$$\underline{v_s} \le v_{sw}(V_{it}x_{it}(I_{LOAD}, I_{DG})) \le \overline{v_s}$$

$$(s \in S, w \in W_s, i = 1,2,...,M, t = 1,2,...,24) \qquad (13)$$

where, I_{LOAD} [A], I_{DG} [A] are profile of load current and DG output current; $x_{it}(I_{LOAD}, I_{DG})$ is 0-1 variable to determine tap position i at t(=1-24)[h] (if use 1, otherwise 0) ($x_{i,0}(I_{LOAD}, I_{DG})=x_{i,24}(I_{LOAD}, I_{DG})$); E is total number of tap position changes per day, H is total error for target voltage; V_{it} [V] is sending voltage at t[h] using tap position I; $V\min_t$ [V], $V\max_t$ [V] are lower and upper voltage limit at t[h]; $V_{TARGETt}$ [V] is target sending voltage at t[h]; S is set of pole transformer tap section number; W_s is set of feeder section number in pole transformer tap section s; v_{sw} ($V_{it}x_{it}(I_{LOAD}, I_{DG})$) is 6.6kV system voltage based on $V_{it}x_{it}(I_{LOAD}, I_{DG})$ for feeder section w in pole transformer tap section s at t[h]; $\underline{v_s}, \overline{v_s}$ are lower and upper limit of 6.6kV system voltage in pole transformer tap section s; M is total number of tap positions(=11); α is coefficient (=10^{-8})

The proposed method is applied to distribution network equipment. The experimental configuration has one bank distribution transformer, 5 distribution lines, 5 sectionalizing switches, 12 single-phase R-L-C constant impedance loads, one wind power generation system (WP) and 4 photovoltaic generation systems (PVs) as shown Fig.3. Daily active power and reactive power of single-phase load, WP output and PVs output are shown in Fig.4 and Fig.5, respectively. Power factor of PV and WP is set as 1 from viewpoint of the severest condition of voltage rise. Since the experiment configuration has five sectionalizing switches, there are 5 radial distribution network configuration candidates (candidate1-5) and one loop configuration closed all switches. 5 radial distribution network configuration candidates and loop configuration of the distribution network equipment are shown in Fig.6.

After three-phase node voltage and three-phase line current are measured for 5 configuration candidates and loop configuration of distribution network equipment, total distribution loss rate, maximum voltage THD, maximum voltage imbalance rate and multi-objective evaluation value E_N are calculated.

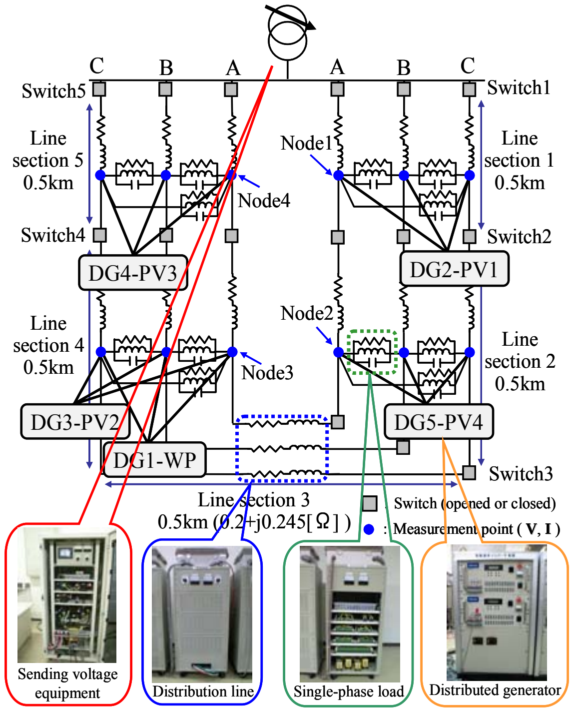
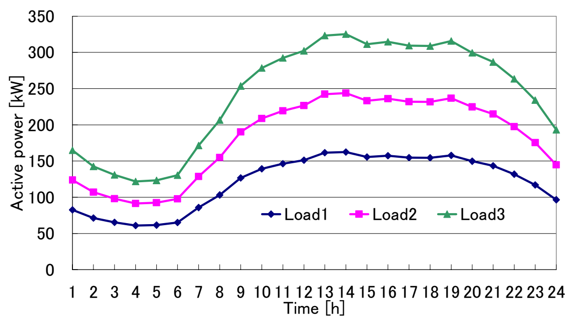
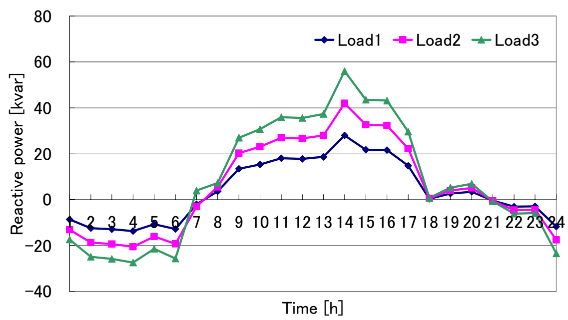


Fig.3. Experiment configuration.



(a) Active power



(b) Reactive power

Fig.4. Active power and reactive power of single-phase load.

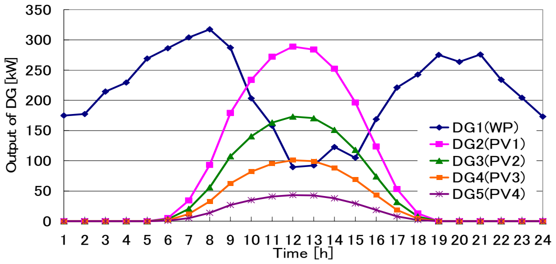


Fig.5. Output of DGs.

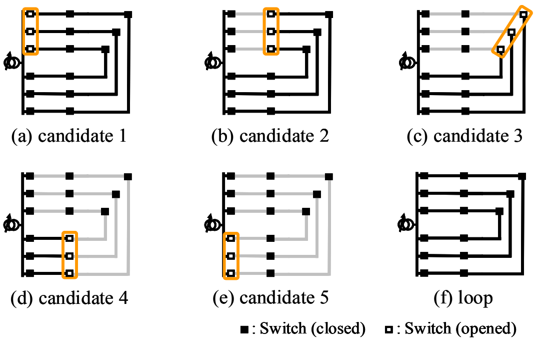


Fig.6. Radial distribution network configuration candidates and loop configuration.

4. EXPERIMENTAL RESULTS OF MULTI-OBJECTIVE EVALUATION OF RADAIAL AND LOOP DISTRIBUTION CONFIGURATION

Experimental results of total distribution loss rate, maximum voltage THD, maximum voltage imbalance rate, multi-objective evaluation value and optimal sending voltage profile for each configuration and loop configuration are shown in Fig.7-12, respectively. As shown in Fig.7, total distribution loss rate which is a conventional evaluation index decreases after DGs are connected. Fig. 8 and 9 shows that though maximum voltage THD and maximum voltage imbalance rate increase after connecting DGs, maximum voltage THD and maximum voltage imbalance rate are kept within the acceptable range (voltage THD $\leq$5% and voltage imbalance rate $\leq$3%). The optimal configuration obtained by using total distribution loss rate as the conventional index becomes the loop configuration when DG is connected or not. On the other hand, it is seen from Fig.10 that when the multi-objective evaluation value E_N as the proposed configuration evaluation index is used, the loop configuration becomes the optimal configuration without DG and configuration candidate 3 becomes the optimal configuration with DGs. Since the power qualities such as voltage THD and imbalance are evaluated by the proposed multi-objective evaluation, the optimal configuration with the minimum multi-objective evaluation value is changed before and after connecting DGs as shown in Fig.10. From Fig.11-12, it is seen that the sending voltage for each configuration and loop configuration can be controlled within the proper range by changing a few tap position.

In addition, in order to evaluate influence of DGs connection to distribution network, before and after connecting DGs, hourly distribution loss rate, hourly maximum voltage THD, and hourly maximum voltage imbalance rate for candidate 3 and loop configuration are shown in Fig.13-15. Furthermore, hourly node voltage THD and hourly node voltage imbalance rate for candidate 3 and loop configuration before and after connecting DGs are shown in Fig.16-19.

From Fig.14, Fig.16 and Fig.17, it can be seen that hourly voltage THD at each node increases before and after connecting DGs, and those increasing rate THD are different by affection of DGs connection. The more it approaches the edge of feeder, the bigger the increasing rate is. As shown in Fig.15, Fig.18 and Fig.19, before and after connecting DGs, though hourly maximum voltage imbalance rate increases, tendency to increase and decrease of hourly node voltage imbalance rate is different in each node, since the hourly node voltage imbalance is depended on hourly load current imbalance.

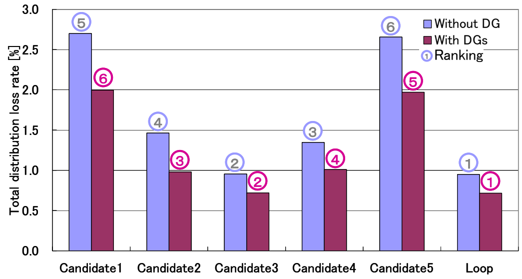


Fig.7. Total distribution loss rate for each candidate and loop configuration.

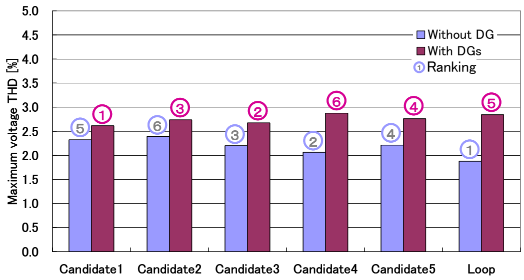


Fig.8. Maximum voltage THD for each candidate and loop configuration.

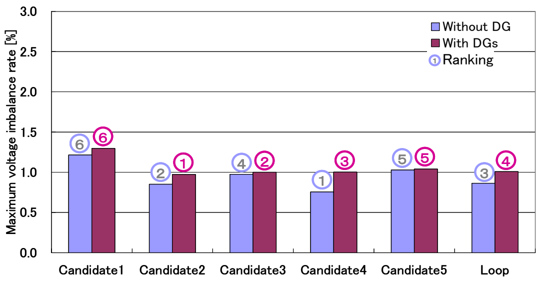


Fig.9. Maximum voltage imbalance rate for each candidate and loop configuration.

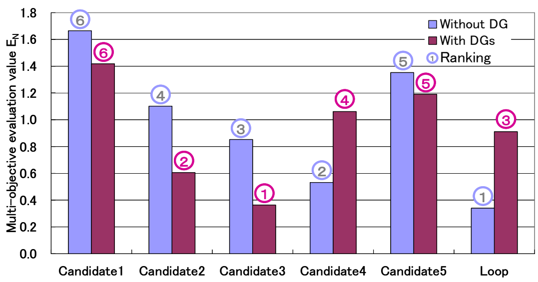
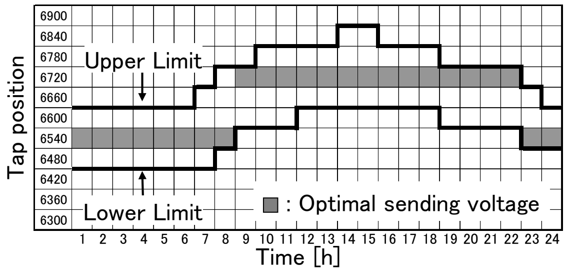
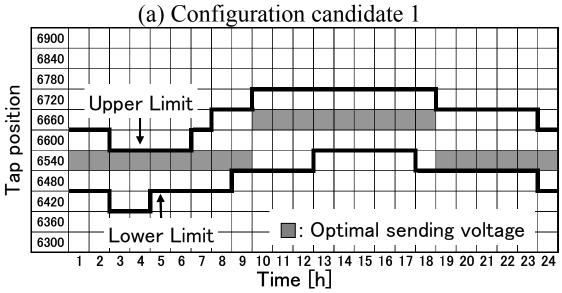


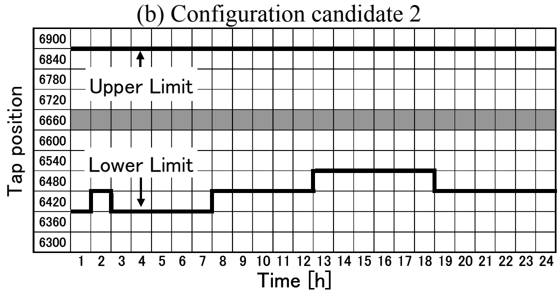
Fig.10. Multi-objective evaluation value for each candidate and loop configuration.



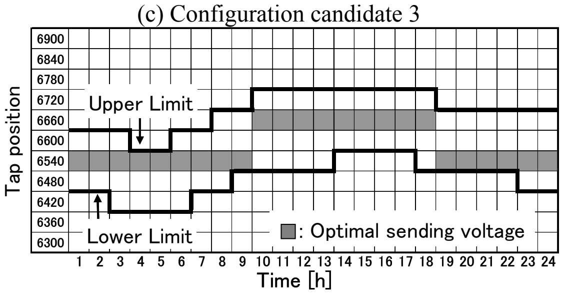
(a) Configuration candidate 1



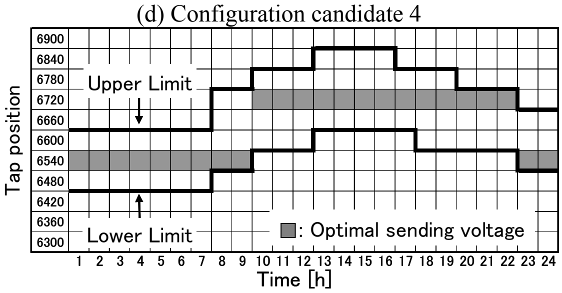
(b) Configuration candidate 2



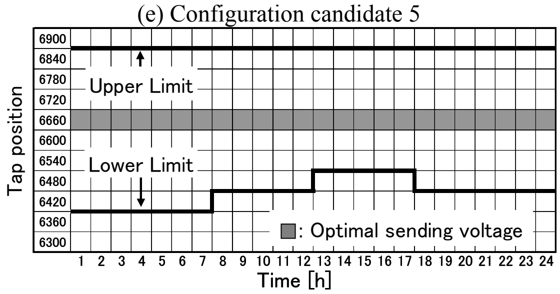
(c) Configuration candidate 3



(d) Configuration candidate 4

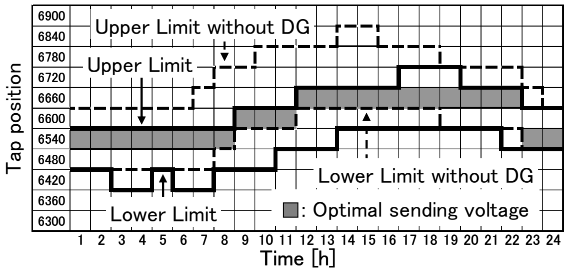


(e) Configuration candidate 5

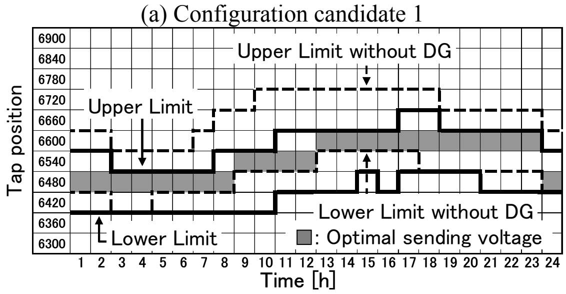


(f) Loop configuration

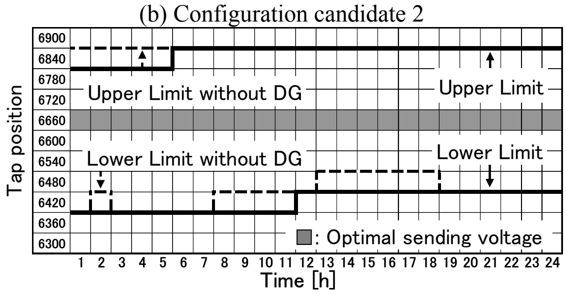
Fig.11. Optimal sending voltage profile for each candidate and loop configuration without DG.



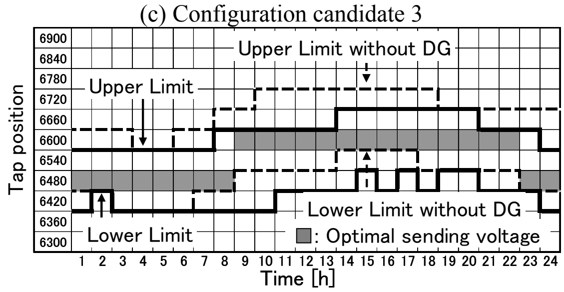
(a) Configuration candidate 1



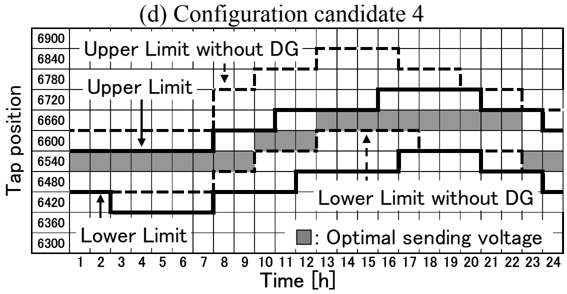
(b) Configuration candidate 2



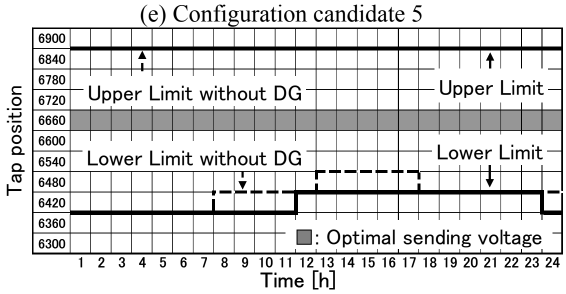
(c) Configuration candidate 3



(d) Configuration candidate 4

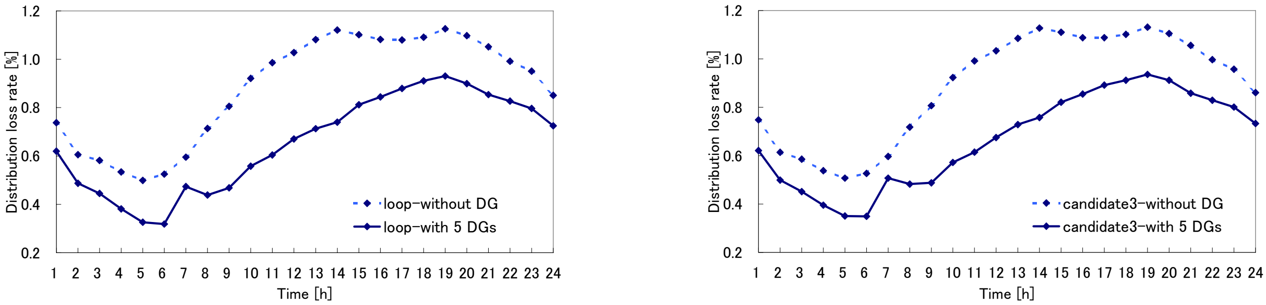


(e) Configuration candidate 5



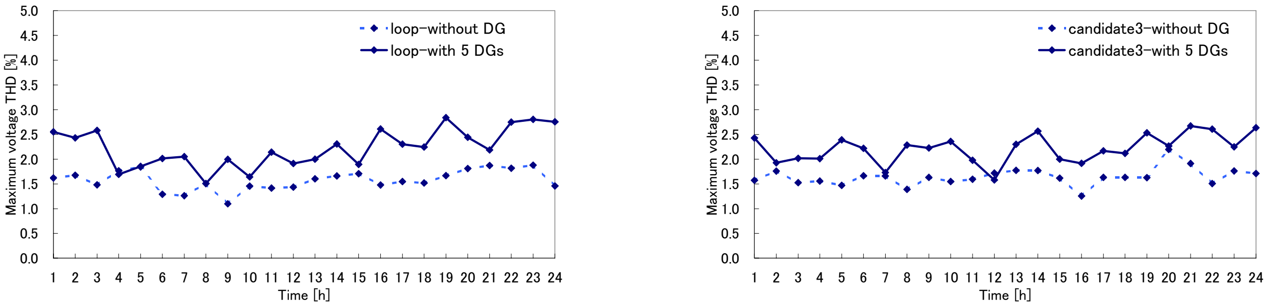
(f) Loop configuration

Fig.12. Optimal sending voltage profile for each candidate and loop configuration with DGs.



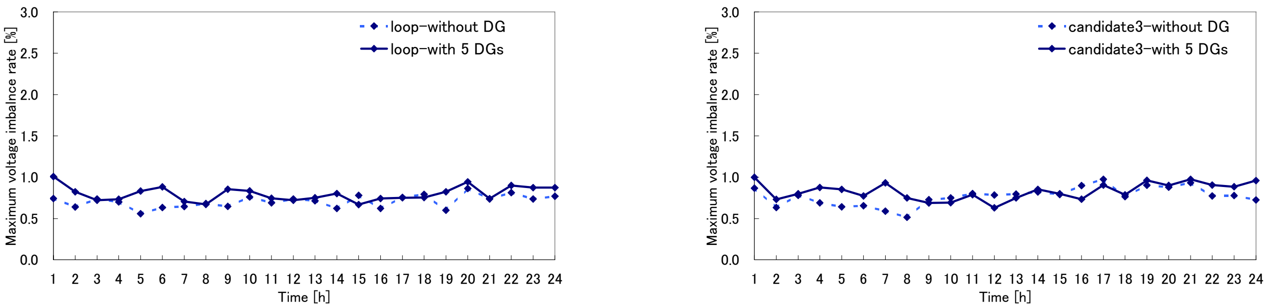
(a) Loop configuration (b) Radial configuration candidate 3

Fig.13. Hourly distribution loss rate before and after connecting DGs.



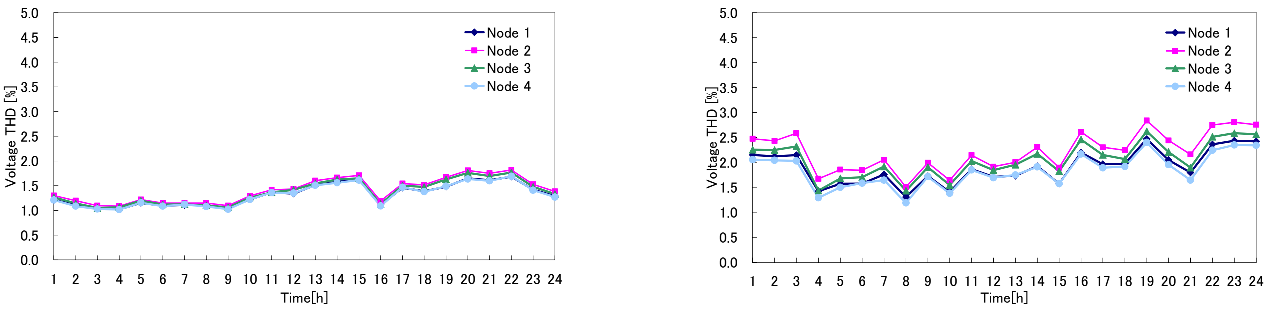
(a) Loop configuration (b) Radial configuration candidate 3

Fig.14. Hourly maximum voltage THD before and after connecting DGs.



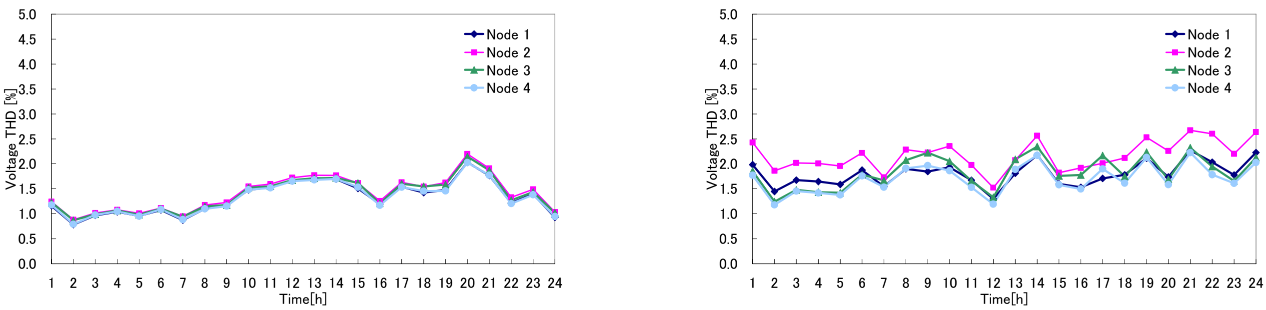
(a) Loop configuration (b) Radial configuration candidate 3

Fig.15. Hourly Maximum voltage imbalance rate before and after connecting DGs.



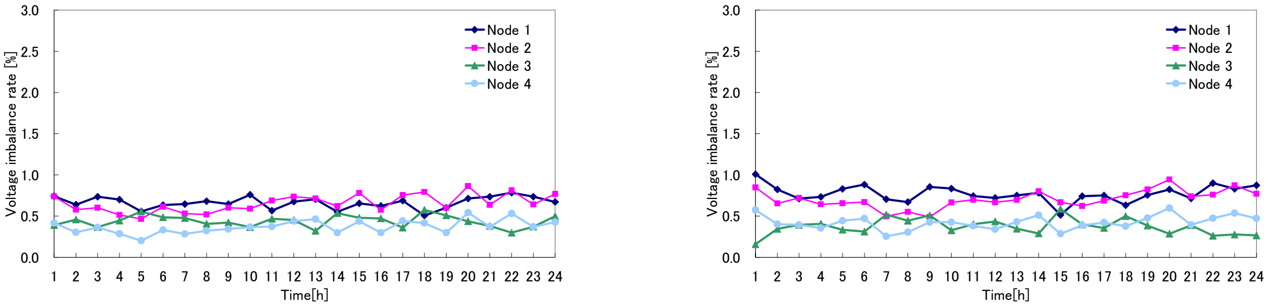
(a) Without DG (b) With DGs

Fig.16. Hourly node voltage THD in phase B before and after connecting DGs for loop configuration.



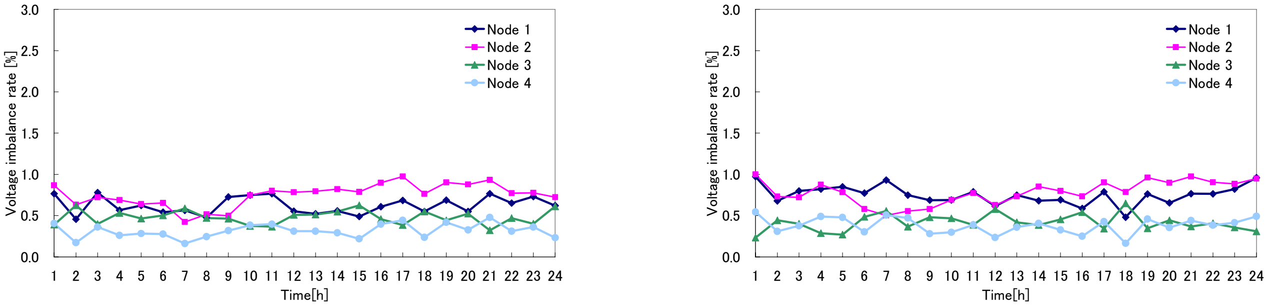
(a) Without DG (b) With DGs

Fig.17. Hourly node voltage THD in phase B before and after connecting DGs for radial configuration candidate 3.



(a) Without DG (b) With DGs

Fig.18. Hourly node voltage imbalance rate in phase B before and after connecting DGs for loop configuration.



(a) Without DG (b) With DGs

Fig.19. Hourly node voltage imbalance rate in phase B before and after connecting DGs for radial configuration candidate 3.

5. CONCLUSION

In this paper, an experimental multi-objective evaluation method of distribution network configuration candidates with distributed generators by using distribution network equipment was proposed. The optimal network configuration candidate can be determined by using multi-objective evaluation based on total distribution loss rate, maximum voltage total harmonic distortion and maximum voltage imbalance rate in order to reduce distribution loss and keep power quality. The proposed method is applied to an experiment of scaled-down three-phase distribution network with 4 photovoltaic generation systems and a wind power generation system. As the experimental results, it was shown that the total distribution loss rate of configuration decreases and the maximum voltage THD increases of configuration before and after connecting DGs. Since the power qualities such as voltage THD and imbalance are evaluated in the proposed multi-objective evaluation method, it was seen that the optimal configuration obtained by the proposed multi-objective evaluation is changed before and after connecting DGs.

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