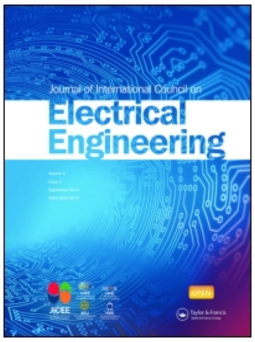

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Deployment of low-voltage regulator considering existing voltage control in medium-voltage distribution systems

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ABSTRACT
Many photovoltaic (PV) systems have been installed in distribution systems. This installation complicates the maintenance of all voltages within the appropriate range in all low-voltage distribution systems (LVDSs) because the trends in voltage fluctuation differ in each LVDS. The installation of a low-voltage regulator (LVR) that can accordingly control the voltage in each LVDS has been studied as a solution to this problem. Voltage control in a medium-voltage distribution system must be considered to study the deployment of LVRs. In this study, we installed LVRs in the LVDSs in which the existing voltage-control scheme cannot prevent voltage deviation and performed a numerical simulation by using a distribution system model with PV to evaluate the deployment of the LVRs.

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KEYWORDS
Distribution system; low-voltage regulator (LVR); voltage control; load-ratio control transformer (LRT); step voltage regulator (SVR)

1. Introduction

In distribution systems, the number of photovoltaic (PV) systems has rapidly increased because of environmental consideration. The installation of PVs causes reverse power flow and steep voltage fluctuation that complicates voltage maintenance within an appropriate range. Voltage-control methods using a load-ratio control transformer (LRT) and a step voltage regulator (SVR) have been studied to prevent voltage deviation caused by PVs.[1,2] LRT and SVR control the voltage in a relatively wide area, which includes many low-voltage (100/200 V) distribution systems (LVDSs). LRT and SVR face complications in maintaining the voltages in all LVDSs that have different voltage variations because of the PV installation. Therefore, a method to control the voltage in each LVDS is required. As a solution to this problem, voltage control using a low-voltage regulator (LVR), which is a pole transformer with an automatic tap changer and can control the voltage in each LVDS, has been studied.[3,4] The installation location of the LVRs should be determined to increase the distribution-system capacity considering the voltage-control effect by the LRT and SVR already installed in medium-voltage (6.6 kV) distribution systems (MVDSs). Additionally, each LVDS voltage that must be maintained by the LVR within an appropriate range fluctuates more than the MVDS voltage. The voltage-control performance needs to be evaluated with a sufficiently high time resolution that represents the characteristics of voltage fluctuation in the LVDS.

This paper presents an extension of a previous work.[5] The actual data of the PV and load and the distribution system model that includes the actual detailed characteristics of the LVDSs as well as the MVDS are used for the numerical simulation. We evaluate the deployment of the LVR to compare the existing voltage-control scheme using the LRT and SVR only and that using the LVR in terms of the number of houses whose voltages deviate from the appropriate range.

This paper is organized as follows: Section 2 explains the voltage control using the LRT, SVR, and LVR; Section 3 presents the evaluation of the voltage control using a distribution model with PV; and Section 4 concludes this paper.

2. Voltage control of a distribution system

Countermeasures must be provided in distribution systems where the existing systems cannot prevent problems such as voltage deviation. In this study, LVRs are installed as a countermeasure in the LVDSs in which the

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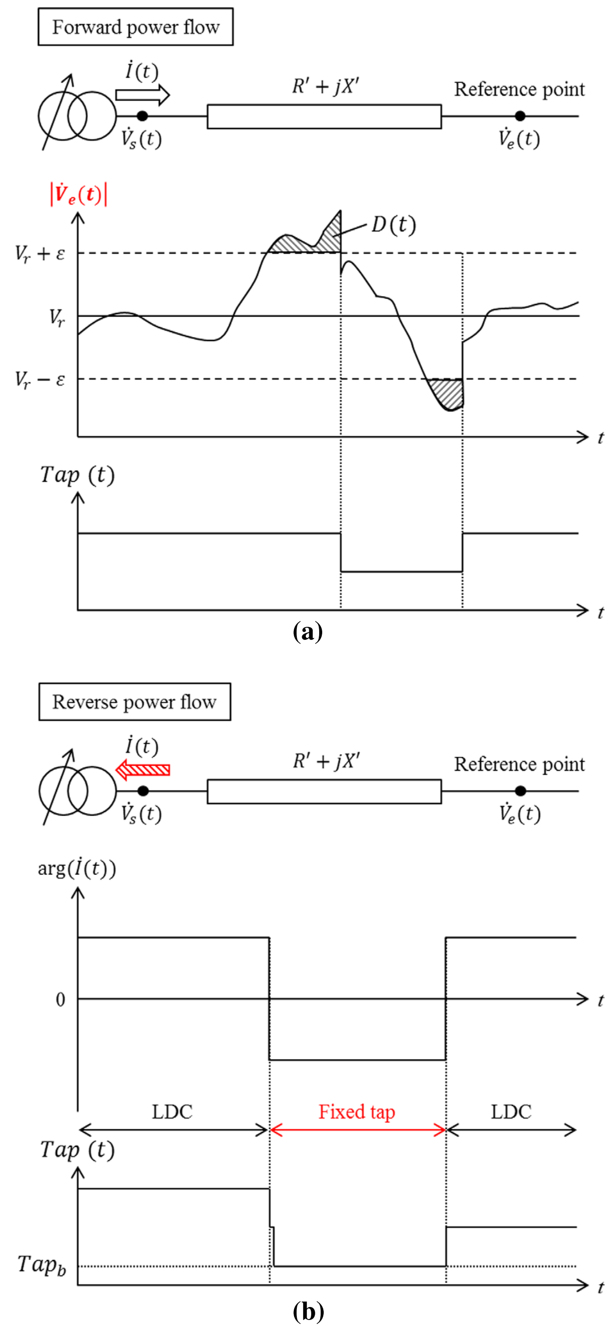


Figure 1. Diagram of the LDC method with a fixed-tap type in reverse power flow. (a) Forward power flow and (b) Reverse power flow.

LRT and SVR cannot prevent voltage deviation. This section describes the voltage control methods implemented in LRT, SVR, and LVR, and the determination of the control parameters.

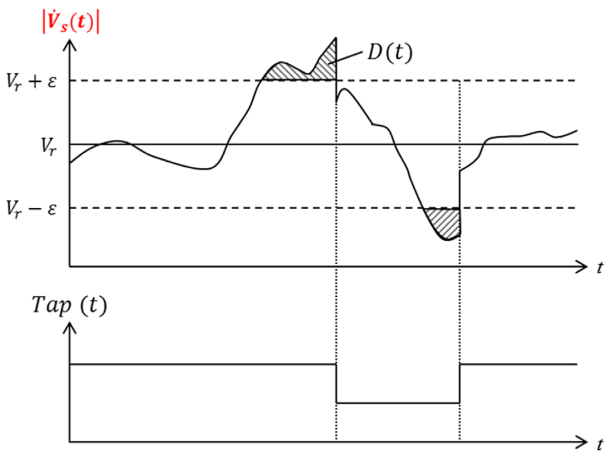


Figure 2. Diagram of the 90-relay method.

2.1. LRT and SVR control methods

A conventional line-drop compensator (LDC) method, which is typically used in existing distribution systems and fixes the tap in reverse power flow, is implemented in the LRT and SVR. Figure 1 shows a diagram of the LDC method. The LDC method automatically regulates the voltage to estimate the voltage drop between the LRT or SVR and a reference point on the basis of current $\dot{I}(t)$ and secondary voltage $\dot{V}_s(t)$ of the LRT or SVR at the forward power flow (Figure 1(a)). We let $\dot{Z} = \left(R^{'} + jX^{'}\right)L$ be the line impedance that changes with distance L between the LRT or SVR and a reference point. Estimated voltage $\dot{V}_e(t)$ is calculated as follows:

$$\dot{V}_e(t) = \dot{V}_s(t) - \sqrt{3}\dot{I}(t)\cdot\dot{Z}. \tag{1}$$

We let V_r be the reference voltage at the reference point, $D(t)$ be the integrated value of the difference between $|\dot{V}_e(t)|$ and V_r, and ε be the dead band. When $D(t)$ exceeds the deviation reference value D_r, tap position Tap(t) changes based on the following equations:

$$\Delta V(t) = |\dot{V}_e(t)| - V_r. \tag{2}$$

$$D(t) = \begin{cases} \int \mathrm{sgn}(\Delta V(t)) \times (|\Delta V(t)| - \varepsilon)\mathrm{d}t \\ \quad \text{if} \quad \Delta V(t) > \varepsilon \\ -\int \mathrm{sgn}\,(\Delta V(t)) \times (|\Delta V(t)| - \varepsilon)\mathrm{d}t \\ \quad \text{if} \quad \Delta V(t) \leq \varepsilon \text{ and } D(t) > 0 \end{cases} \tag{3}$$

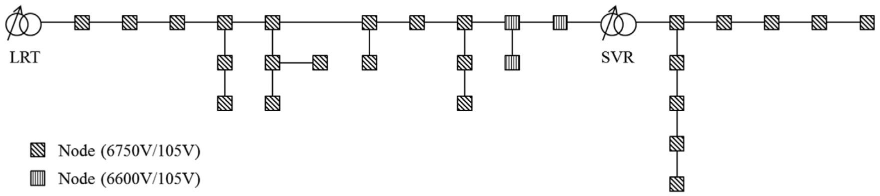


Figure 3. Distribution system model that includes MV and LV systems.

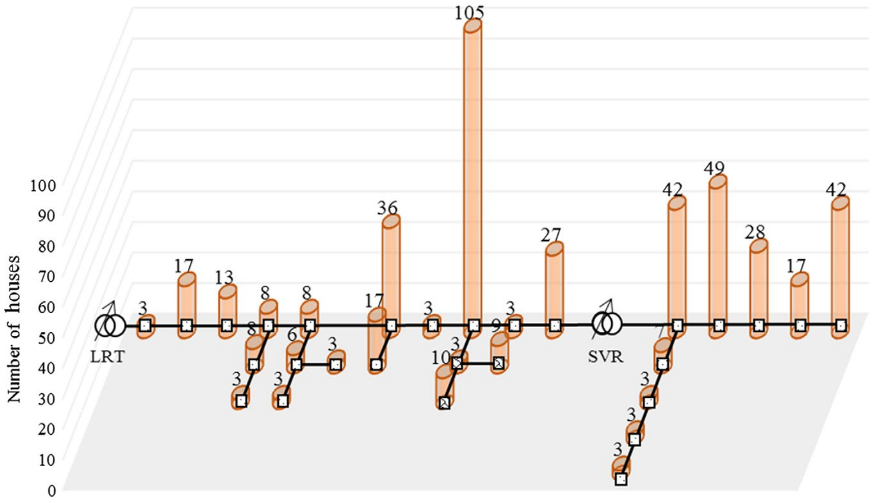


Figure 4. Total number of houses in each MV node.

$$\mathrm{Tap}(t) = \begin{cases} \mathrm{Tap}(t-1) - 1 & \text{if } D(t) > D_r \\ \mathrm{Tap}(t-1) + 1 & \text{if } D(t) < D_r \\ \mathrm{Tap}(t-1) & \text{otherwise} \end{cases} \tag{4}$$

On the other hand, $\mathrm{Tap}(t)$ is fixed at the specified tap position Tap_b in reverse power flow.

$$\mathrm{Tap}(t) = \mathrm{Tap}_b \text{if } \arg\left(\dot{I}(t)\right) < 0. \tag{5}$$

2.2. Determination of the control parameters of the LRT and SVR

To maximize the voltage-control performance of the LRT and SVR, the following LDC control parameters must be appropriately determined:

$$V_r = \left[V_{r(1)}, V_{r(2)}, \ldots, V_{r(N)}\right], \tag{6}$$

$$L = \left[L_{(1)}, L_{(2)}, \ldots, L_{(N)}\right] \tag{7}$$

where N is the total number of LRT and SVRs in the investigated distribution system.

The LDC control parameters are determined by considering the following problem that evaluates the distance from the central voltage V_{mid} and the total number of tap changes in the LRT and SVR:

$$\min F\left(V_r, L\right) = \min(\alpha_1 F_1\left(V_r, L\right) + \alpha_2 F_2\left(V_r, L\right)) \tag{8}$$

where α_1 and α_2 are the conversion factors. F_1 is the value that evaluates the distance from V_{mid} and the means, i.e.,

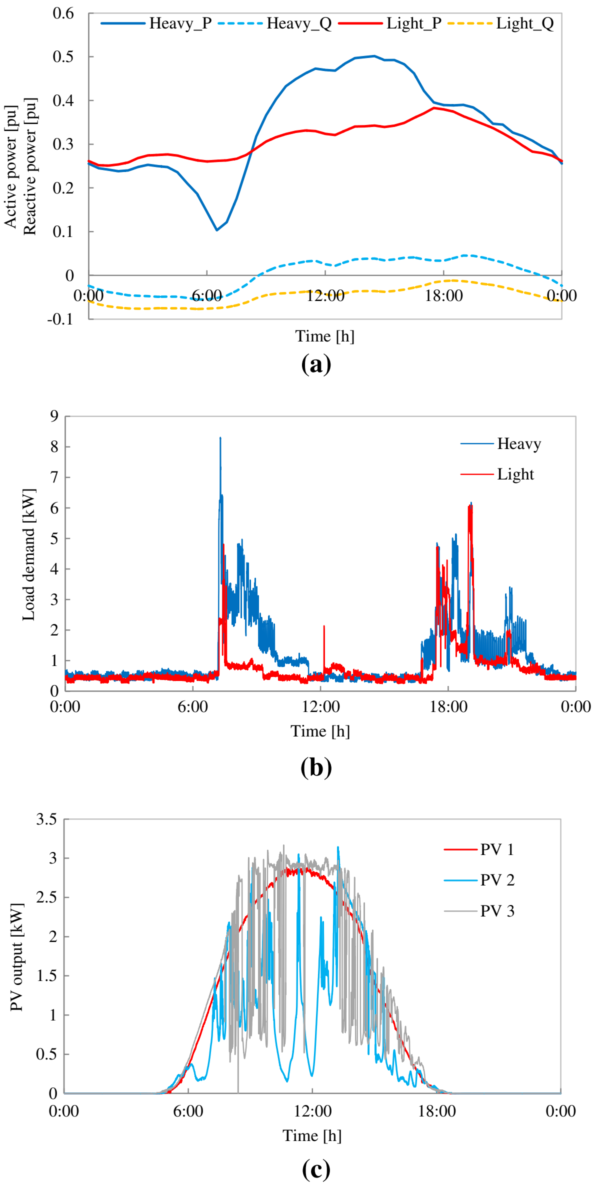
$$F_1\left(V_r, L\right) = \min_t \left(\min_{j \in \mathcal{J}} V_{HN}^j\left(t; V_r, L\right) - V_{\mathrm{mid}} \right), \tag{9}$$

where V_{HN}^j is the voltage at the MV node $j(\in \mathcal{J})$. Similarly, F_2 is the total number of tap changes in the LRT and SVRs, which is expressed as

$$F_2\left(V_r, L\right) = \sum_n^N \left(\sum_{t=2}^T \left|\mathrm{Tap}(t) - \mathrm{Tap}(t-1)\right| \right)_n. \tag{10}$$

2.3. LVR 90-relay method

A 90-relay method, which is a simpler control method compared to the LDC method, is implemented in the



(a)

(b)

(c)

Figure 5. PV output and load-demand profiles used in the numerical simulation. (a) MV load-demand profiles, (b) Low-voltage load-demand profile of one house, and (c) PV output profile of one house.

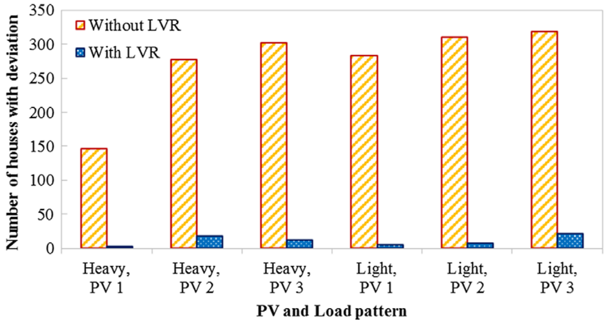


Figure 6. Total number of houses with voltage deviation in each PV and load pattern.

LVR. Figure 2 shows the diagram of the 90-relay method. The 90-relay method automatically regulates the voltage to maintain the LVR secondary voltage $\dot{V}_s(t)$ within an appropriate range. When $D(t)$ exceeds D_r, tap position $\mathrm{Tap}(t)$ changes to mitigate the deviation as follows:

$$\Delta V(t) = \left|\dot{V}_s(t)\right| - \dot{V}_r. \tag{11}$$

$$D(t) = \begin{cases} \int \mathrm{sgn}(\Delta V(t)) \times (|\Delta V(t)| - \varepsilon)\mathrm{d}t \\ \quad \text{if } \Delta V(t) > \varepsilon \\ -\int \mathrm{sgn}(\Delta V(t)) \times (|\Delta V(t)| - \varepsilon)\mathrm{d}t \\ \quad \text{if } \Delta V(t) \le \varepsilon \text{ and } D(t) > 0 \end{cases} \tag{12}$$

$$\mathrm{Tap}(t) = \begin{cases} \mathrm{Tap}(t-1) - 1 & \text{if } D(t) > D_r \\ \mathrm{Tap}(t-1) + 1 & \text{if } D(t) < D_r \\ \mathrm{Tap}(t-1) & \text{otherwise} \end{cases} \tag{13}$$

3. Numerical simulation

The voltage-control performance of the LRT and SVR is verified to evaluate the voltage in the LVDSs. Additionally,

Table 1. Simulation parameters.

Object	Setting value
Tap position	LRT: {1, 2, …, 21} SVR: {1, 2, …, 9} LVR: {1, 2, …, 5}
LDC parameter search range	$\{V_r = 103, 104, \dots, 107[\mathrm{V}]\}, \left\{L = \begin{cases} 0, 500, \dots, 10500[\mathrm{m}] & (LRT) \\ 0, 500, \dots, 4500[\mathrm{m}] & (SVR) \end{cases}\right\}$
Dead band	$\varepsilon = \begin{cases} 1\% & (\mathrm{LRT}) \\ 1.5\% & (\mathrm{SVR, LVR}) \end{cases}$
Deviation reference value	$D_r = 30[\% \cdot s]$
Central voltage	$V_{\mathrm{mid}} = 105[\mathrm{V}]$
Reference voltage of LVR 90 relay method	$V_r = 101[\mathrm{V}]$
Conversion value	$\alpha_1 = 0.01$, $\alpha_2 = \begin{cases} 1 & (\text{No voltage deviation}) \\ 1000 & (\text{Otherwise}) \end{cases}$

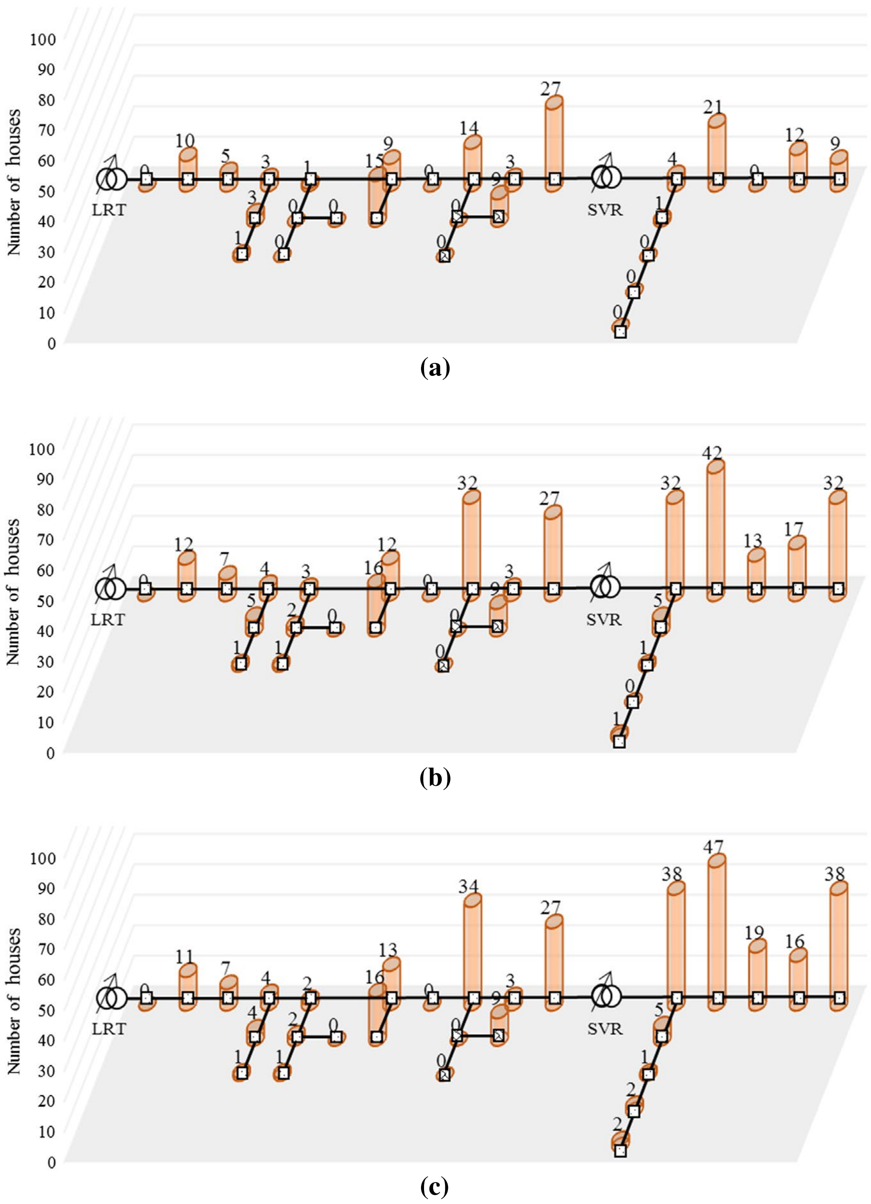
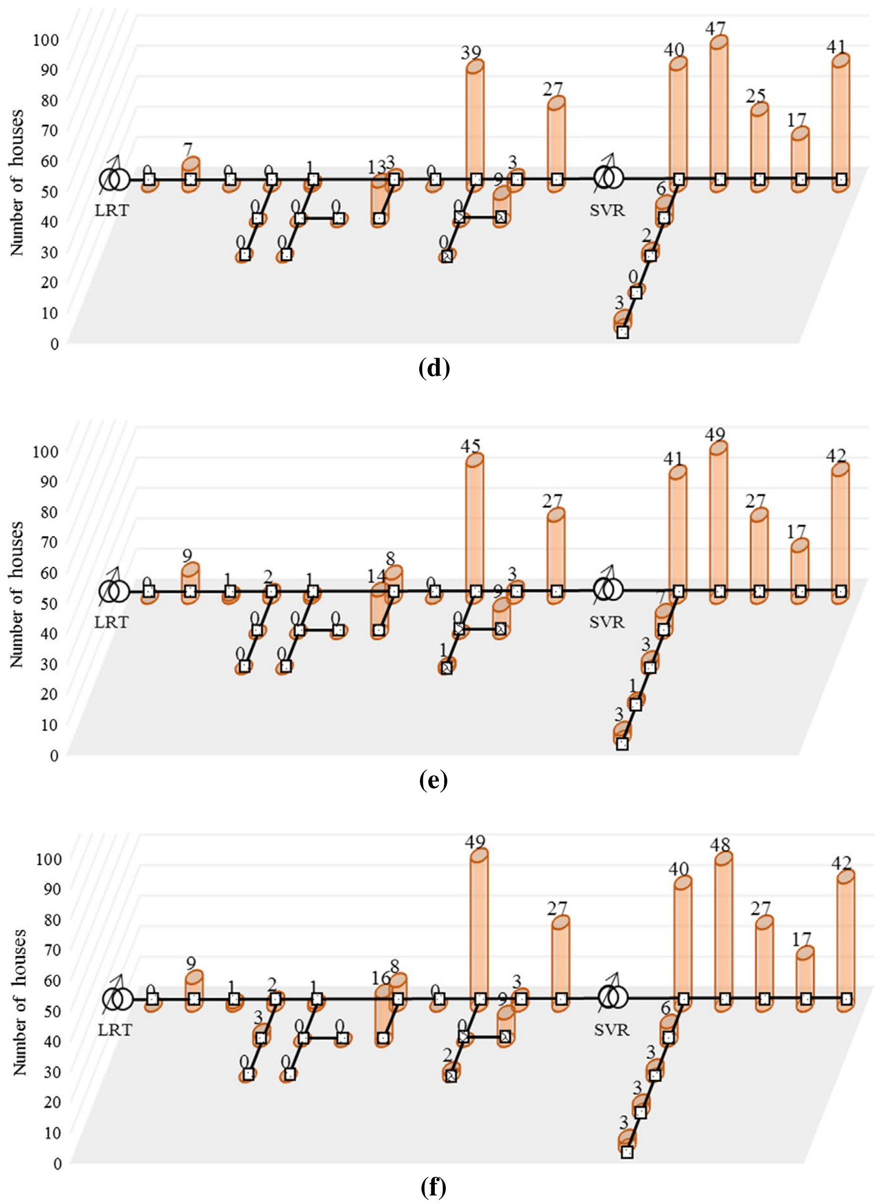


Figure 7. Total number of houses with voltage deviation at each MV node without LVR. (a) Heavy load and PV 1, (b) Heavy load and PV 2, (c) Heavy load and PV 3, (d) Light load and PV 1, (e) Light load and PV 2, and (f) Light load and PV 3.

the effect of the LVR location is verified to evaluate the location of the LVRs in the LVDSs in which the LRT and SVR cannot prevent voltage deviation.

3.1. Simulation conditions

The distribution system model that includes an MVDS and the LVDSs with actual detailed characteristic is used to evaluate the location of the LVRs. Figure 3 shows the configuration and the MV node of the simulation model. This model has 14 MV consumers and 479 LV consumers; all LV consumers have PVs. Figure 4 shows the total number of houses in each MV node. Two patterns of load profiles, namely, heavy- and light-load patterns, in each MV and LV consumers are used (Figure 5(a) and (b)). Three patterns of PV output profiles, namely, a day whose curve is smooth (PV 1), a day whose fluctuation per unit time is large (PV 2), and a day whose fluctuation is frequent (PV 3), are used (Figure 5(c)). The control method explained in Section 2.1 is implemented in the LRT and SVR, and that explained in Section 2.3 is implemented in the LVR. The LVRs are installed in the LVDSs where the LRT and SVR cannot prevent voltage deviation. The setting values related to the voltage-control methods and voltage regulators are listed in Table 1.



(d)

(e)

(f)

Figure 7. *(Continued)*

3.2. Simulation results

Figure 6 shows the total number of houses that cannot prevent voltage deviation. The left bars show the number of houses with voltage deviation with no LVR. The right bars show those with LVRs. These results suggest that the deployment of LVR in the LVDSs where the LRT and SVR cannot prevent voltage deviation is effective because the number of houses with voltage deviation is significantly reduced. The number of houses with voltage deviation in the light load is larger than that in the heavy load. Voltage control with PV and light load is supposed to be difficult because smaller PV-generated power is consumed by the load and larger reverse power flow increases voltage. The number of houses with voltage deviation with PV large fluctuation (PV 2) and frequent PV fluctuation (PV 3) is larger than that with smooth-curve PV (PV 1). This result indicates that voltage control using the LRT and SVR only is insufficient during large and frequent PV fluctuation.

The total number of houses with voltage deviation with no LVR voltage control in each MV node is shown in Figure 7. Figure 7 shows that the proportion of the number of houses with voltage deviation to the total number of houses is high at the nodes in the SVR primary side where the end of the node is controlled using LRT only

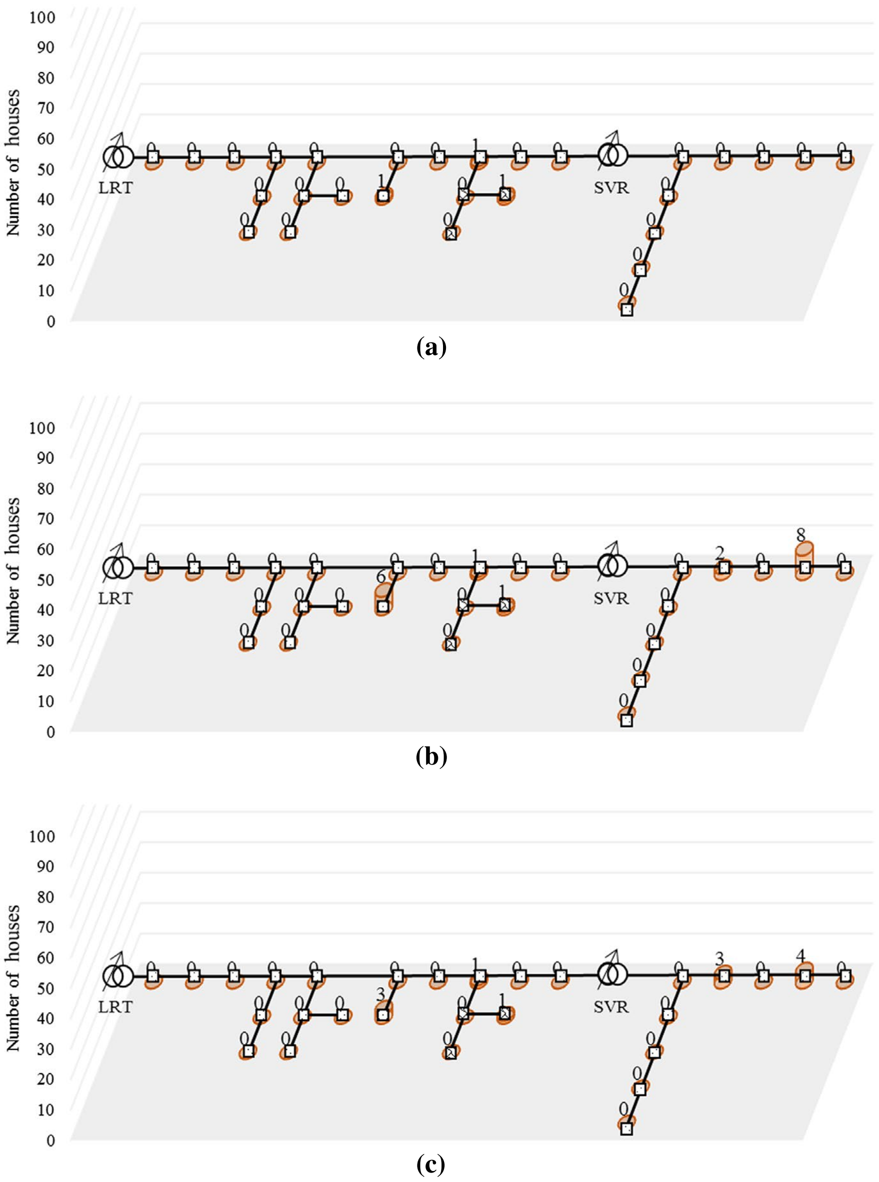


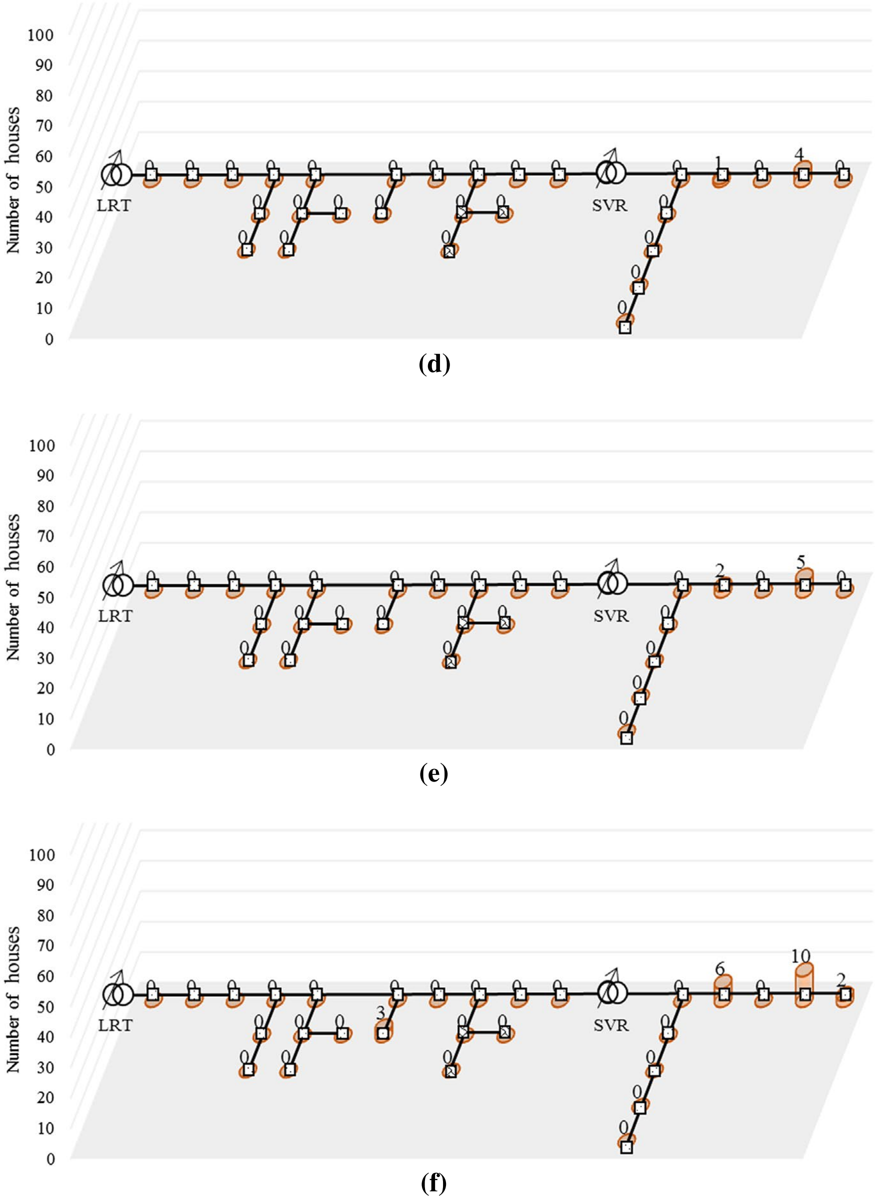
Figure 8. Total number of houses with voltage deviation in each MV node with LVR. (a) Heavy load and PV 1, (b) Heavy load and PV 2, (c) Heavy load and PV 3, (d) Light load and PV 1, (e) Light load and PV 2, and (f) Light load and PV 3.

and at the nodes from the secondary side of the SVR to the terminal of the feeder. This result indicates that the LRT and SVR control method should be improved because voltage deviation in a wide area should be prevented using the LRT and SVR.

Figure 8 shows the total number of houses with voltage deviation using the LVR voltage control at each MV node. Most houses with voltage deviation shown in Figure 7 are prevented from experiencing voltage deviation. This result suggests that the LVR voltage control significantly reduces the number of houses with voltage deviation. However, an improved LVR voltage-control method is necessary in some LVDSs because not all the houses can avoid voltage deviation.

4. Conclusion

In this work, we studied the location of the LVR in terms of voltage control in the MVDS. To evaluate the voltage-control results in the LVDSs with LVRs, a simulation model that includes both MVDS and LVDS was used. The simulation results showed that the installation of LVRs was effective in preventing voltage deviation that cannot be prevented using the LRT and SVR only. However, LVRs should not be necessarily installed in all LVDSs with voltage deviation because LRT and SVR are more efficient to avoid voltage deviation that occurs over a wide area in terms of the capital cost. In addition, some voltage



(d)

(e)

(f)

Figure 8. *(Continued)*

deviation remained even after installation of the LVRs. Therefore, improvement in the control methods for the LRT, SVR, and LVR is necessary. For our future work, we will examine the deployment of the LVR considering an improved voltage-control method for the LRT and SVR.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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