Voltage-Sensitivity-Based Volt-VAR-Watt Settings of Smart Inverters for Mitigating Voltage Rise in Distribution Systems

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ABSTRACT Active and reactive power control using smart inverters (SI) is highly effective in mitigating voltage rise in distribution systems, which is caused by the high penetration of photovoltaic (PV) power generation. However, the voltage control performance depends on the SI settings. We propose a new approach that uniquely determines the parameter settings for volt-VAR-watt control based on the active and reactive power-voltage sensitivity matrix of SIs. Because the voltage sensitivity matrix is calculated based solely on the impedance of the distribution system and it does not vary with time or the number of SIs, the proposed method can determine the individual SI parameter settings theoretically and efficiently without the need for optimization problem formulation, power flow calculation, or communication between the SIs. To evaluate the proposed method, the voltage control performance in a real distribution system model with a large number of PV installations is compared with that of volt-VAR-watt control using default parameters and optimized parameters in case that the load demand and PV generation are given in advance. The results show that the proposed method achieves better control performance than other conventional methods in terms of all the evaluation indices; in particular, it realizes effective control in the case of voltage rise. Furthermore, the proposed method can also achieve the same level of voltage control performance as the optimization results, even though it uses only the voltage sensitivity matrix and SI rating capacities for parameters determination, and the accuracy of the proposed voltage control can be ensured.

INDEX TERMS Distribution system, smart inverter, voltage sensitivity, volt-VAR control, volt-watt control.

I. INTRODUCTION

DISTRIBUTED energy resources, such as photovoltaic (PV) power generation, are being increasingly adopted worldwide to reduce carbon dioxide emissions and realize a sustainable society. In Japan, the introduction of policies such as the feed-in tariff (FIT) for renewable energy has contributed to the rapid introduction of PV technology into distribution systems, and the number of PV installations is expected to continue increasing in the future [1]. However, distribution systems with high PV penetration involve voltage violation problems such as voltage rise and fluctuations caused by the increase in reverse power flow and weather-dependent fluctuations in the active power of

PV systems [2]. Voltage regulation in distribution systems plays an important role in maintaining the voltage quality for customers. Therefore, the advancement of voltage regulation technology in distribution systems is essential for the future expansion of PV installations. Traditionally, voltage regulation in distribution systems has been achieved by the tap operation of on-load tap changers (OLTCs) at distribution substations. However, because PV systems can be connected to all possible nodes of the distribution system, OLTCs, which comprehensively control the distribution system voltage, alone may not be able to handle local voltage violations at points of common coupling (PCCs) owing to changes in PV generation for each customer. In this context, several

studies have investigated volt-VAR optimization using reactive power control devices such as capacitor banks, static synchronous compensators, and PV inverters. Data-driven control approaches, for instance, control strategies with a machine learning [3] and artificial neural network [4], have been proposed to improve distribution system performance. Although its effectiveness can be verified, the learning and training process requires a large amount of data, such as historical datasets and optimized results, and there are challenges such as increased learning time when the number of SIs and reactive power control devices increases and risks using additional data which were not observed in the training dataset. On the other hand, in recent years, voltage management has been practically implemented using smart inverters (SIs) [5]. An SI is an advanced PV inverter equipped with various grid support and communication functions that allow voltage control based on locally measured voltages at PCCs, such as volt-VAR control and volt-watt control, thus providing effective voltage support for voltage violations that occur locally because of the introduction of PV systems [6], [7], and the usefulness of voltage management by smart inverters has been verified in actual distribution feeder in California [8], Hawaiian Electric Companies feeder [9]. Voltage control performance with and without SIs according to PV penetration levels have been analyzed in [10] and with SIs implementation, a PV hosting capacity in a distribution feeder has been significantly improved compared to the conventional inverters in [11]. However, because active and reactive power control by an SI is based on the characteristic curves, the voltage control performance depends on the parameter settings that define the characteristic curves. In other words, because the typical active and reactive power control characteristics are defined, it is possible to determine the parameter settings according to the requirements of the distribution system operator (DSO) while satisfying the constraints without adversely affecting the voltage regulation of the distribution system. Therefore, several studies have investigated control parameter determination of SIs. In [12], [13], all the candidate parameter settings were evaluated using time-series simulations, and the optimal parameters were selected according to the performance evaluation criteria with weight factors assigned to the objectives. However, it is difficult to clearly define the performance evaluation criteria in an actual power distribution system, and the selected parameters may vary with the assumed weight factors, etc. In addition, it is assumed that the power flow calculations and all the candidate parameter evaluations require a long computational time. Metaheuristic methods have been proposed to reduce the computational time required for parameter determination as well as to efficiently search for the control parameters. For example, particle swarm optimization (PSO) [14], [15] and a genetic algorithm (GA) [16], [17] have been used to derive appropriate parameters by solving multi-objective optimization problems. In [18], the authors combined different metaheuristic methods to determine the optimal control parameters. However, to solve the optimization problem,

power flow calculation requires detailed condition settings such as load demand and PV generation, but these are normally not available in advance. In addition, the optimal parameter settings must be updated by optimization calculations whenever the number of SIs connected to the distribution system changes. In addition, as the number of SIs increases, the complexity of the optimization scheme increases significantly, resulting in scalability issues and other problems for practical use. Some studies [12], [16], [19] have grouped a certain number of SIs for parameter settings; however, depending on the definition of the number of groups, etc., the parameter settings may not be appropriate. The voltage control capability can be maximized by setting different parameters for the individual SIs in the distribution system. In [20], the distribution loss minimization can be achieved by optimizing the volt-VAR control parameters according to grid information measured at regular minute-intervals, however, it requires a communication infrastructure and still has several issues in terms of practical use. Meanwhile, studies have investigated active power control schemes by considering the high R/X ratio of the distribution line impedance. Because active power control implies the loss of PV generation opportunities, the optimal volt-watt control parameters design of SIs to for evenly curtailing energy has been proposed in [21]. For the fair sharing of active power curtailment, an active power capping scheme [22] and an optimal power flow-based scheme [23] have been proposed, whereas the authors in [24] have discussed that the amount of active power curtailment in the entire distribution system may increase by using the equal sharing scheme. In addition, recent studies have investigated a technique for combining active and reactive power control, namely, volt-VAR-watt control, which combines volt-VAR and volt-watt control. The authors in [25] have confirmed the effectiveness of simple volt-VAR-watt control in mitigating voltage rise, and the methodology of droop settings for equal contribution to voltage management of all PV inverters have been presented in [26]. In [27], the authors have represented that a coordination of active and reactive power control improves a PV hosting capacity and voltage control performance in terms of voltage violation, distribution losses, transformer loading compared to the other control functions. However, in volt-VAR-watt control, it is necessary to perform active power control by considering the inverter rating and power factor constraint; few studies have clarified the implementation criteria for active power control when performing the parameter setting. Thus, there are considerable difficulties for proper use of many SIs in practical network operation although they have a large potential to increase PV hosting capacity.

To overcome these issues, we propose an alternative parameter determination method for volt-VAR-watt control of an SI on the basis of the active and reactive power-voltage sensitivity matrix to make the most of this function in mitigating voltage problems associated with high PV penetration. The voltage sensitivity matrix is calculated for a real

distribution system model in Japan, and the volt-VAR-watt control parameters are uniquely determined by considering the mutual influence of active and reactive power control. Because the voltage sensitivity matrix defined in this study is calculated on the basis of the impedance of the distribution system, it neither changes with time nor depends on the number of SIs. Thus, the individual SI parameters can be determined in a straightforward manner without the need for optimization problem formulation, power flow calculation with the detailed load demand and PV output, or communication between the SIs. Finally, the voltage control performance using the proposed method is compared with the conventional volt-VAR-watt control with default parameters and optimized parameters in case that the load demand and PV generation are given in advance by considering all the significant factors such as the amount of voltage violation, reactive power, active power curtailment, distribution loss, and the number of tap operations. The results show that the proposed method can achieve better control performance than the other methods in terms of all the evaluation indices; in particular, it realizes effective voltage control in the case of voltage rise. Furthermore, the proposed method can also achieve the same level of voltage control performance as the optimization results, even though it uses only the voltage sensitivity matrix and SI rating capacities for parameters determination, and the accuracy of the proposed voltage control can be ensured.

The remainder of this paper is organized as follows. Section II defines the voltage sensitivity matrix employed in this study. Section III describes the details of the proposed method. Sections IV and V describe the numerical calculations performed to verify the effectiveness of the proposed method. Finally, Section VI concludes the paper.

II. VOLTAGE SENSITIVITY MATRIX OF SMART INVERTER

The voltage sensitivity matrix of an SI is a matrix that defines the relationship between the distribution line impedance, load demand, PV output, and voltage at the PCCs. Owing to its simplicity, it has been used in many studies [21], [26], [28]. In general, most voltage sensitivity matrices are obtained from the inverse of the Jacobian matrices [29]. However, in this study, the voltage sensitivity is directly calculated from the relationship between the voltage change at the PCC and the load demand and PV output change in a short time, on the basis of the impedance of the distribution system, in order to theoretically determine the control parameters of the SI.

Considering the simple distribution feeder model shown in Fig. 1, the voltage drop caused by the impedance of the distribution line can be approximated as

$$VD = V_s - V_r \cong IR\,cos\,\theta + IX\,sin\,\theta \qquad (1)$$

where V_s and V_r are the voltages at the sending and receiving ends, respectively, R and X are the sum of the line impedance from the sending end to the receiving end, I is the line current, and θ is the phase difference between the receiving-end voltage and the current. Using the p.u. method, (1) can be
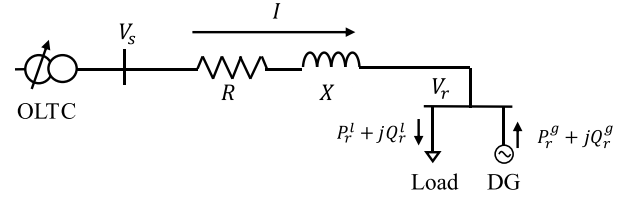

FIGURE 1. Simple distribution feeder with distributed generator (DG).

expressed as follows:

$$
\begin{aligned}
VD_{pu} &= \frac{IR\,cos\,\theta + IX\,sin\,\theta}{V_B} \\
&= \frac{R^{pu}P_r^{pu} + X^{pu}Q_r^{pu}}{V_r^{pu}}
\end{aligned} \qquad (2)
$$

where V_B is the base voltage. Assuming that the receiving end voltage V_r^{pu} is close to the reference voltage, the voltage drop equation can be approximated as

$$VD_{pu} \cong R^{pu}P_r^{pu} + X^{pu}Q_r^{pu} \qquad (3)$$

where P_r^{pu} and Q_r^{pu} are the net power at the receiving end, defined as

$$P_r^{pu} = P_r^g - P_r^l \qquad (4)$$
$$Q_r^{pu} = Q_r^g - Q_r^l \qquad (5)$$

Assuming that the sending-end voltage does not change significantly in a short period of time, the voltage change at the receiving end in a short period of time can be considered to be affected only by the temporal changes in the load demand and the PV system connected to the receiving end. In other words, the voltage change at node r in a short period of time can be expressed as the sum of the voltage changes due to the active and reactive power at node r. Consequently, it can be expressed as a function of the resistance and reactance values from the sending end to node r as follows:

$$\Delta V_r \cong R^{pu}\Delta P_r^{pu} + X^{pu}\Delta Q_r^{pu} \qquad (6)$$

where

$$\Delta P_r^{pu} = P_r^{pu}\,(t+1) - P_r^{pu}\,(t) \qquad (7)$$
$$\Delta Q_r^{pu} = Q_r^{pu}\,(t+1) - Q_r^{pu}\,(t) \qquad (8)$$

The voltage changes due to the active and reactive power are defined as voltage sensitivity matrices.

$$\alpha^p = \frac{\Delta V_r}{\Delta P_r^{pu}} = R^{pu} \qquad (9)$$

$$
= \begin{bmatrix}
R_{11} & R_{12} & \cdots & R_{1N} \\
R_{21} & R_{22} & \cdots & R_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
R_{N1} & R_{N2} & \cdots & R_{NN}
\end{bmatrix} \qquad (10)
$$

$$\alpha^q = \frac{\Delta V_r}{\Delta Q_r^{pu}} = X^{pu} \qquad (11)$$

$$= \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1N} \\ X_{21} & X_{22} & \cdots & X_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ X_{N1} & X_{N2} & \cdots & X_{NN} \end{bmatrix} \quad (12)$$

where N is the number of SIs. The voltage sensitivity matrices defined in (10) and (12) are $N \times N$ symmetric matrices, where R_{ii} and X_{ii} are the impedances from the sending end to node i, and R_{ij} and X_{ij} are the impedances between the nodes i and j. Although there will be errors in the expected voltage change when there is a large change in the power flow in a short time, the voltage sensitivity matrices are defined only by the impedances, are fixed unless the system configuration is changed, and do not change over time because they assume linearity of the voltage change.

III. VOLTAGE-SENSITIVITY-BASED VOLT-VAR-WATT SETTINGS

When applying volt-VAR or volt-watt control for voltage control of an SI, it is desirable to reduce the amount of reactive power injection/absorption, active power curtailment, and increase in the distribution loss owing to the application of these control schemes. Thus, the parameter determination problem for each control scheme is defined as an optimization problem that maximizes or minimizes the objective function of the DSO. However, because there are numerous SIs in a distribution system, the solution space becomes extremely large, which not only complicates the optimization problem but also requires a long computation time to obtain the global solution, and the control parameters vary with the weather conditions and other factors.

Therefore, we propose a method for determining the parameters of volt-VAR and volt-watt control of individual SIs on the basis of the active and reactive power-voltage sensitivity matrix described in Section II. Because the proposed method can calculate the SI parameters from the impedance of the distribution line and SI rating capacity, it does not require to solve complicated optimization problems; thus, the computational time can be reduced significantly and the control parameters of the numerous SIs in the distribution system can be obtained easily and uniquely. Fig 2 shows an overall flowchart of the proposed algorithm for Volt-VAR-watt settings.

A. VOLT-VAR SETTINGS

Volt-VAR control is a mechanism that mitigates voltage violations by reactive power injection/absorption according to the voltage at the PCC. The volt-VAR control curve is shown in Fig. 3.

In general, the reactive power capability of the SI is limited by the inverter capacity and PV output, and the instantaneous reactive power that can be output by the PV inverter is determined by the available capacity of the inverter. Thus, the active power output takes precedence over the reactive power output; therefore, most previous studies on volt-VAR control parameter determination were based on the available VAR
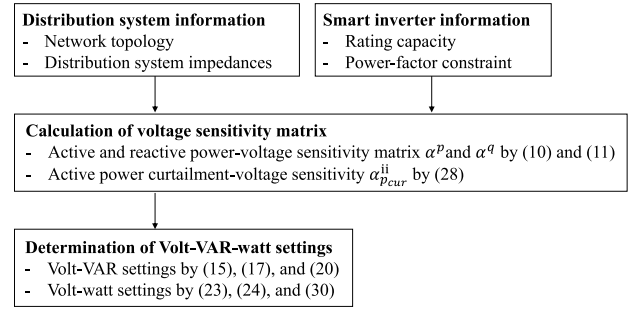

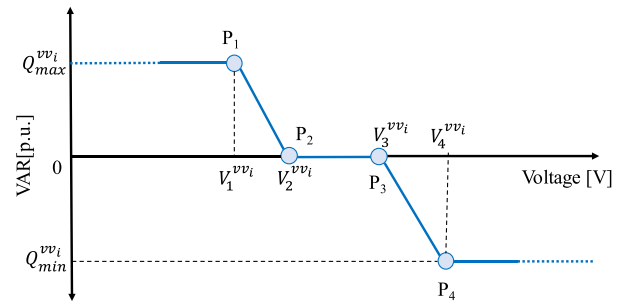**FIGURE 2. Flowchart of the proposed algorithm.**

FIGURE 3. Volt-VAR control curve.

capacity (%VAR avail.). However, the available capacity of the inverter changes over time, and the reactive power may not be output when the PV output is high. Therefore, in this study, the control parameters are determined on the basis of the rating capacity rather than the available capacity of the SIs in order to achieve effective reactive power control against voltage rise in distribution lines.

Assuming that the variation in load demand at the PCC is small, all the voltage changes at the PCC that occur in a short time may be considered to be caused only by the PV output fluctuation. Therefore, the amount of voltage fluctuation to be compensated by volt-VAR control is at most the amount of voltage fluctuation equivalent to the rated output of the inverter. Using SI_{cap}^i, which is the SI rating capacity of customer i, and the active power-voltage sensitivity from (9), the amount of voltage fluctuation to be compensated by volt-VAR control ΔV_p^i can be expressed as

$$\Delta V_p^i = \alpha_p^{ii} \cdot SI_{cap}^i + \sum_{j=1}^{N_i-1} \alpha_p^{ic} * w^i * SI_{cap}^j \quad (13)$$

$$\alpha_p^{ic} = \left(\alpha_p^{ii} \cap \alpha_p^{jj} \right), \quad j \neq i \quad (14)$$

where α_p^{ic} is the active power-voltage sensitivity common to customer i and j connecting to the same low-voltage system, w^i is the weighting factor to consider the influence from neighboring PVs ($= 0.25$), and N_i is the number of customers connecting to the same low-voltage system as customer i. In this paper, the weighting factor w^i for the neighboring PVs is calculated from the ratio of the average net power change of all consumers to the SI rating capacity when the maximum voltage change occurs, and the same value is used
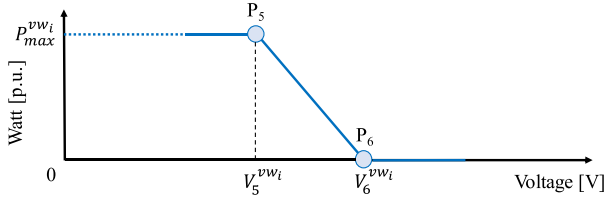
FIGURE 4. Volt-watt control curve.

for all SIs for simplification. Therefore, in volt-VAR control for customer i, with the permissible voltage upper limit V_h, the voltage $V_3^{vv_i}$ at which the reactive power output is supplied to prevent voltage rise can be obtained as

$$V_3^{vv_i} = V_h - \Delta V_p^i \qquad (15)$$

Considering the power factor constraint for grid interconnection, the maximum active power P_{max}^i and maximum reactive power $Q_{min}^{vv_i}$ that the SI can output can be expressed as

$$P_{max}^i = SI_{cap}^i \cos \theta_{min} \qquad (16)$$
$$Q_{min}^{vv_i} = SI_{cap}^i \sqrt{1 - \cos^2 \theta_{min}} \qquad (17)$$

where $\cos \theta_{min}$ is the power-factor constraint. With the reactive power-voltage sensitivity, the voltage change for customer i owing to the reactive power output of $Q_{min}^{vv_i}$ can be expressed as

$$\Delta V_q^{vv_i} = \alpha_q^{ii} \left| Q_{min}^{vv_i} \right| + \sum_{j=1}^{N_i-1} w_i * \alpha_q^{i_c} * \left| Q_{min}^{vv_j} \right| \qquad (18)$$

$$\alpha_q^{i_c} = \left(\alpha_q^{ii} \cap \alpha_q^{jj} \right), \quad j \neq i \qquad (19)$$

where $\alpha_q^{i_c}$ is the reactive power-voltage sensitivity common to customer i and j connecting to the same low-voltage system. Thus, the voltage value at P_4 in Fig. 3 can be obtained as

$$V_4^{vv_i} = V_3^{vv_i} + \Delta V_q^{vv_i}, \quad s.t. V_4 \leq V_h \qquad (20)$$

Originally, as shown in Fig. 3, the volt-VAR control curve is defined by four points, and reactive power can be output to compensate for voltage rise as well as voltage drop. However, in Japan, the injection of reactive power to compensate for voltage drop is not allowed by the grid-interconnection code; therefore, in this study, the parameters are determined only for voltage rise, i.e., P_1 and P_2 for volt-VAR control are defined as

$$V_1^{vv_i} = V_2^{vv_i} = V_3^{vv_i} \qquad (21)$$
$$Q_{max}^{vv_i} = 0.0 \qquad (22)$$

B. VOLT-WATT SETTINGS

Volt-watt control is a mechanism that prevents voltage rise by curtailing the active power depending on the voltage, as shown in Fig. 4. Therefore, when applying the volt-watt control mechanism, it is desirable for low-voltage customers

to reduce not only the voltage violation amount but also the active power curtailment amount.

In volt-VAR-watt control, which combines volt-VAR and volt-watt control, to prevent voltage violation while reducing the active power curtailment amount to the maximum extent possible, active power curtailment by volt-watt control should be performed only in situations where voltage violation cannot be avoided by reactive power control of volt-VAR control alone. Therefore, the curtailment start voltage V_5^i for volt-watt control is determined as

$$V_5^{vw_i} = V_4^{vv_i} \qquad (23)$$

Meanwhile, when the active power is curtailed by volt-watt control, the reactive power output of volt-VAR control is also reduced owing to the power factor constraint on grid interconnection. Therefore, the voltage value at which the active power output is set to zero by volt-watt control (i.e., $V_6^{vw_i}$ in Fig. 4) must be determined by considering the amount of voltage change due to the reduction of active and reactive power. Under a certain power factor constraint, the maximum curtailed power $P_{max}^{vw_i}$ in volt-watt control is the maximum active power that the SI can output and is thus similar to the value given by (16):

$$P_{max}^{vw_i} = SI_{cap}^i \cos \theta_{min} \qquad (24)$$

The maximum voltage change caused by the active power curtailment of volt-watt control, $\Delta V_p^{vw_i}$, can be expressed using the active power-voltage sensitivity as

$$\Delta V_p^{vw_i} = \alpha_P^{ii} P_{max}^{vw_i} \qquad (25)$$

Using the reactive power-voltage sensitivity, the voltage change $\Delta V_q^{vw_i}$ due to the reactive power decrease caused by the active power curtailment given by (25) can be expressed as

$$\Delta V_q^{vw_i} = \alpha_Q^{ii} \times \left(P_{max}^{vw_i} \times \sqrt{\frac{1}{\cos^2 \theta_{min}} - 1} \right) \qquad (26)$$

Thus, the voltage change of customer i owing to the reduction of active and reactive power ΔV^{vw_i} is

$$\Delta V^{vw_i} = \Delta V_p^{vw_i} - \Delta V_q^{vw_i}$$
$$= P_{max}^{vw_i} \left(\alpha_p^{ii} - \alpha_q^{ii} \sqrt{\frac{1}{\cos^2 \theta_{min}} - 1} \right) \qquad (27)$$

When the amount of active power curtailment by volt-watt control is P_{cur}^i for customer i, from (27), the voltage change ΔV_{cur}^i caused by the active power curtailment can be expressed as

$$\alpha_{p_{cur}}^{ii} = \alpha_p^{ii} - \alpha_q^{ii} \sqrt{\frac{1}{\cos^2 \theta_{min}} - 1} \qquad (28)$$

$$\Delta V_{cur}^i = \alpha_{p_{cur}}^{ii} P_{cur}^i \qquad (29)$$

Note that $\alpha_{p_{cur}}^{ii}$ is the amount of active power curtailment-voltage sensitivity coefficient defined by the active

power-voltage sensitivity, reactive power-voltage sensitivity, and power factor constraint value, and the amount of voltage change is positive in the direction of voltage reduction. According to (29), if $\alpha_{p_{cur}}^{ii}$ is positive, the amount of voltage change will also be positive, which means that the voltage rise can be reduced by curtailing the active power even under power factor constraints. By contrast, if $\alpha_{p_{cur}}^{ii}$ is negative, the effect of mitigating the voltage rise by reactive power control is large, which means that curtailing the active power may cause a voltage rise. In other words, under the power factor constraints, whether or not to curtail the active power is determined by the sign of $\alpha_{p_{cur}}^{ii}$; volt-watt control must be applied only when $\alpha_{p_{cur}}^{ii}$ is positive, and its control parameters can be obtained as follows:

$$V_6^{vw_i} = V_5^{vw_i} + \Delta V^{vw_i}, \quad if \alpha_{p_{cur}}^{ii} \geq 0 \qquad (30)$$

The proposed method can easily determine the parameters of volt-VAR-watt control for each SI by using the active and reactive power-voltage sensitivity matrix. With the proposed method, the control parameters can be uniquely determined from the distribution system impedance for each SI and the rating capacity, and they neither change over time nor depend on the change in the number of SIs as long as the distribution system configuration is not changed.

IV. CASE STUDY SETUP

A. SIMULATION SETTINGS

Numerical simulations were performed on the real distribution system model shown in Fig. 5, reflecting the load characteristics of heavy and light loads and PV characteristics such as sunny and cloudy weather, to verify the effectiveness of the proposed SI parameter determination method based on significant factors such as the amount of voltage violation, reactive power output, active power curtailment, and the number of tap operations. The distribution system model simulated six medium-voltage distribution lines originating from the distribution substation, and the low-voltage systems from the pole transformer to the low-voltage customers were also simulated in detail, as shown in Fig. 6 [30], [31]. The medium-voltage distribution lines were divided and controlled by a total of 55 sectionalized switches, and proper voltage was maintained by the tap operation of the OLTCs installed in the distribution substation. It was assumed that 112 medium-voltage customers and 6057 low-voltage customers are connected to the distribution system, and that a loop-top PV system is installed for all low-voltage customers. The SI capacity and PV panel capacity were set to 4.5 kVA and 5 kW, respectively, assuming oversizing where the PV panel capacity was larger than the inverter capacity. The load demand data for the medium-voltage and low-voltage users were based on the Energy Management System Open DATA by the Sustainable open Innovation Initiative (SII) [32] and the actual measurement data from the project "Demonstrative research on Grid-interconnection of Clustered Photovoltaic Power Generation Systems (FY2002-FY2007) [33]" supported by the New Energy and Industrial Technology Development
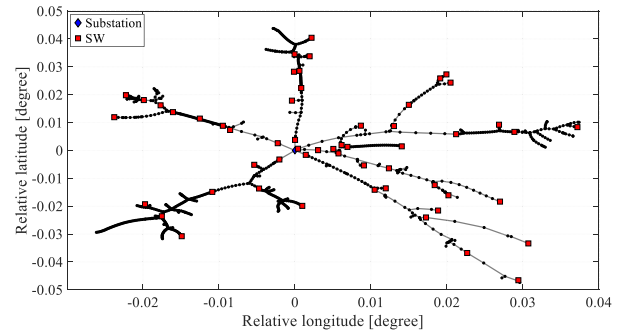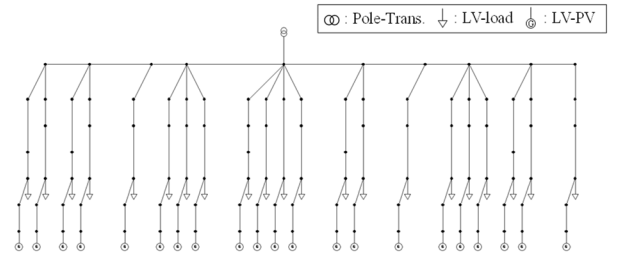

FIGURE 5. Medium-voltage distribution system.

FIGURE 6. Example of low-voltage distribution system.

TABLE 1. Conditions for case study.

Case	SI control scheme	Parameters
Case 1	w/o control	$cos\,\theta = 1.00$
Case 2	Fixed-PF	$cos\,\theta = 0.95$, lagging
Case 3	Volt-VAR	$V_3^{vv} = 1.002[\%], V_4^{vv} = 1.031\,[\%]$ $Q_{min}^{vv} = -0.44\,[pu]$
Case 4	Volt-Watt	$V_5^{vw} = 1.031\,[\%], V_6^{vw} = 1.07\,[\%]$ $P_{max}^{vw} = 1.0\,[p.\,u.\,]$
Case 5	Volt-VAR-Watt	$V_3^{vv} = 1.012\,[\%], V_4^{vv} = 1.041\,[\%],$ $V_5^{vw} = 1.041\,[\%], V_6^{vw} = 1.07\,[\%]$ $P_{max}^{vw} = 1.0\,[p.\,u.\,] Q_{min}^{vv} = -0.44\,[p.\,u.\,]$
Case 6	Volt-VAR-Watt	$V_3^{vv} = 1.05[\%], V_4^{vv} = 1.059\,[\%],$ $V_5^{vw} = 1.059\,[\%], V_6^{vw} = 1.07\,[\%],$ $P_{max}^{vw} = 1.0\,[p.\,u.\,], Q_{min}^{vv} = -0.44[p.\,u.\,]$
Case 7	Volt-VAR-Watt	Eqs. (15), (16), (20), (22), (23), and (30)

Organization, respectively. Based on previous studies [34], the measured PV values were classified into five weather categories, and the measured values for a total of 20 days, i.e., two days randomly selected from each category in each of the light load and heavy load periods, were used for the numerical calculations.

To evaluate the voltage control performance of the SI, we compared the voltage control performance when volt-VAR control and volt-watt control were applied, in addition to the fixed power factor (fixed-PF) control currently used in Japan, and we verified their effectiveness in terms of the amount of voltage violation, reactive power output, active power curtailment, and the number of tap operations (see Table 1). For all the SI controls, the power factor constraint on the reactive power was set to 0.9. The SI control

parameters for the compared methods (Case 3 – Case 5) were based on the default values given in Hawaiian Electric's Source Requirement Document (SRD) v1.1 [35], and they were converted into the permissible voltage range for Japan. For Case 6, the SI control parameters were determined with the multi-objective optimization [16], [17] to improve distribution system performance in case that the load demand and PV output for a are given in advance, for more details in Appendix. Meanwhile, the distribution system voltage depends not only on the voltage control function of the SI but also on the tap operation of the OLTC. Line drop compensation (LDC) control, which is widely used worldwide, is an autonomous control method in which the tap control depends on the passing current of the OLTC and is strongly affected when the power flow changes owing to the active and reactive power control of SIs. Therefore, it is difficult to directly compare the voltage control performance of SIs when LDC control is used because the appropriate control parameters of OLTCs are expected to vary with the PV installation rate and the control parameters of the SIs. Hence, in this study, the centralized voltage control scheme was adopted as the tap operation of the OLTC, and the voltage control performance with different parameter settings of the SIs was evaluated under the assumption that appropriate tap control was applied according to the change in the grid voltage over time. The details of the centralized voltage control scheme are described in the next section.

B. VOLTAGE REGULATION OF OLTC

In the centralized voltage control scheme, the tap position is switched so that the distribution line voltage approaches the nominal value while minimizing the amount of voltage violation in the entire distribution system on the basis of the measured voltage values obtained from the switches with built-in voltage sensors installed in the medium-voltage distribution system and the SIs in the low-voltage distribution system.

When the tap operation in one section is limited to one (raise, lower, and maintain), the tap operation of the OLTC can be formulated as follows:

$$Tap\,(\tau + 1) = Tap\,(\tau) + \Delta Tap\,(\tau) \tag{31}$$

$$\Delta Tap\,(\tau) = \underset{\Delta Tap(\tau) \in \{1, 0, -1\}}{\arg\min} \, F_\tau \tag{32}$$

$$F_\tau = \sum_{p=1}^{3} \sum_{j=1}^{M} \left\{ \left(V_\tau^{j,p} - 1.0 \right)^2 + w \cdot Vio_\tau^{j,p} \right\} \tag{33}$$

$$Vio_\tau = \begin{cases} V_\tau^{j,p} - \varepsilon_h, & if\ V_\tau^{j,p} > \varepsilon_h \\ V_\tau^{j,p} - \varepsilon_l, & if\ V_\tau^{j,p} < \varepsilon_l \\ 0, & otherwise \end{cases} \tag{34}$$

where $Tap\,(\tau)$ is the tap position at time τ, $\Delta Tap\,(\tau)$ is the tap switching candidate, $V_\tau^{j,p}$ is the 10-min average of the measured voltages at node j and phase p, ε_h and ε_l are the upper and lower voltage limit thresholds, respectively, w is
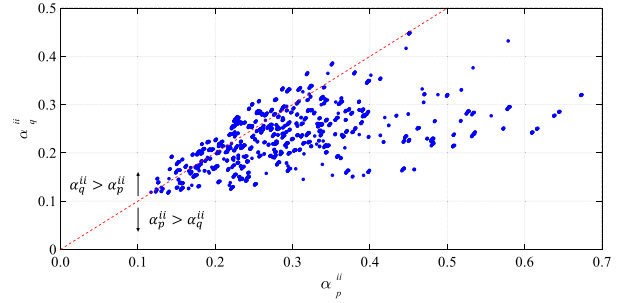

**FIGURE 7.** Relationship between P-voltage and Q-voltage sensitivity.

the violation penalty factor $(= 10^{10})$, and M is the number of measured locations. In this study, the tap operation period of the OLTC was set to 10 min.

V. RESULTS AND DISCUSSION
A. VOLTAGE SENSITIVITY ANALYSIS

To evaluate the necessity of volt-VAR-watt control for SIs, we conducted voltage sensitivity analysis using the voltage sensitivity matrix described in Section II for each SI in the distribution system. Because volt-VAR control and volt-watt control are based on the local voltage, only the diagonal components of the voltage sensitivity matrix were used to analyze the active power-voltage sensitivity and reactive power-voltage sensitivity of SI i.

Fig. 7 shows the relationship between the active power-voltage sensitivity and the reactive power-voltage sensitivity for each SI. The red line in the figure represents the SIs for which the active power sensitivity and reactive power sensitivity are equal, meaning that the SIs located above the red line have high sensitivity to reactive power control owing to the distribution system impedance; conversely, the SIs located below the red line have high sensitivity to active power control. In this distribution system model, there are 6057 low-voltage customers, 1577 of which have high reactive power-voltage sensitivity and the remaining 4480 have high active power-voltage sensitivity, indicating that volt-watt control is effective against voltage rise in many of the SIs. This is also evident from the fact that the resistance value of the distribution line impedance is larger than the reactance value. However, because active power control results in the loss of generation opportunities for the customers, it is desirable to perform active power control after mitigating voltage rise by reactive power control, as in volt-VAR-watt control. Meanwhile, Fig. 8 shows the active power curtailment-voltage sensitivity coefficient under the power factor constraint given by (28). As shown in Fig. 8, $\alpha_{p_{cur}}^{ii}$ is positive for all the SIs in the distribution system, and active power curtailment is effective in mitigating further voltage rise whereas reactive power control is performed considering the power factor constraint. In other words, volt-VAR-watt control, as expected in this study, is highly effective in preventing voltage rise.
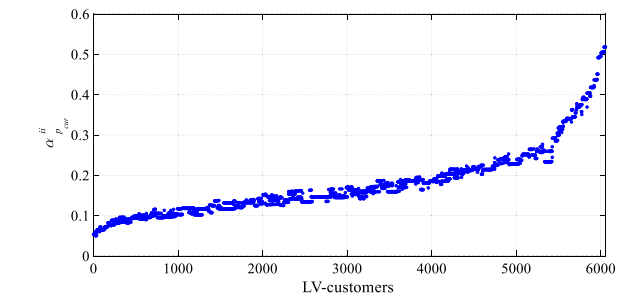
FIGURE 8. PV curtailment-voltage sensitivity under power factor limit.

TABLE 2. Estimated voltage fluctuation amount and error.

	Case1 (w/o control)	Case 7 (Estimated by (13))	Demand only
Average [V]	2.670	1.994	0.489
Standard deviation [V]	0.746	0.522	0.202
RMSE [V]	-	0.987	-

TABLE 3. Determined SI control parameters by proposed method.

Volt-VAR-Watt control parameters (Average)				
V_3^{vv} [%]	$V_4^{vv} = V_5^{vw}$ [%]	V_6^{vw} [%]	P_{max}^{vw} [p. u.]	Q_{min}^{vv} [p. u.]
1.05	1.06	1.07	1.0	-0.44

B. ACCURACY OF PROPOSED CONTROL PARAMETERS

Table 3 shows the amount of voltage fluctuation due to load demand variation, in Case 1, and in the proposed method. Note that voltage fluctuation amount in the proposed method is an estimated value by (13), and voltage fluctuation due to load demand variation occurs mainly in the morning and evening when PV power generation is small. From the results, it can be seen that PV output fluctuation is the dominant factor of voltage fluctuation in a short time and causes much larger voltage fluctuation compared to load demand variation. Meanwhile, the estimation error of the proposed method is small at the average value of all low voltage customers, and the root mean square error (RMSE) is also kept small. Therefore, it can be said that the proposed method is able to estimate the voltage fluctuation amount with relatively high accuracy. As shown in Table 3, the control parameters determined by the proposed method are similar to those determined by the multi-objective optimization shown in Table 2 as Case 6, which confirms the validity of the proposed parameter determination using the active power-voltage sensitivity.

## C. VOLTAGE CONTROL PERFORMANCE

The voltage control performance was compared on the basis of six evaluation indices: maximum voltage, total voltage violation amount, total reactive power output, total active power curtailment, total distribution loss, and number of tap

operations. As an example of the voltage control results for one day, the voltage control results of the proposed volt-VAR-watt control were compared with those of fixed-PF control (Case 2) and the conventional volt-VAR-watt control that uses the same control parameters for all the SIs (Case 5), as shown in Fig. 9. These results are obtained when the maximum voltage is recorded in Case 5. Although fixed-PF control outputs reactive power proportional to the active power and thus provides sufficient voltage rise mitigation, the reactive power obtained from all the SIs results in excessive reactive power for the entire distribution system, causing voltage drop in the morning (e.g., 6:00-10:00) as shown in Fig. 9 (a) and (d). This phenomenon also occurs in the conventional volt-VAR-watt control; consequently, the tap positions of the OLTCs in both methods are maintained higher than those in the proposed method. Therefore, the conventional volt-VAR-watt control cannot avoid the voltage violation even though the same amount of reactive power as that in the proposed method can be output during the voltage violation. In addition, in the conventional volt-VAR-watt control results, the fluctuation of the active power output by volt-watt control is larger (see Fig. 9 (c) and (e)), and it is believed that the steep voltage violation caused by such active power change is accumulated and the voltage violation amount becomes much larger than that in fixed-PF control. Such control causes unnecessary tap operations of the OLTCs and voltage violations due to insufficient prevention of voltage rise; thus, the mutual influence of the voltage control of the SIs and the tap operation of the OLTC should be considered.

Meanwhile, in the proposed method, because the control parameters are determined by the voltage sensitivity, the reactive power is absorbed only by the SIs with a high possibility of voltage violation, and the reactive power is not absorbed in the morning when the PV output is small (see Fig. 9 (d)). Consequently, even in the case of sudden changes in the PV output, a margin from the upper voltage limit can be maintained, and sufficient voltage rise mitigation can be achieved by active and reactive power control. Table 2 lists the voltage control results for 20 days. It can be seen that the proposed method completely avoids the voltage violations that cannot be prevented solely by the centralized voltage control in Case 1, and the good results compared to other methods in all evaluation indices by the appropriate active and reactive power control are confirmed.

In addition to the proposed method, fixed-PF control volt-watt control (Case 4), and volt-VAR-watt control (Case6) were found to reduce the voltage violation. Fixed-PF control absorbs the reactive power proportional to the active power, which has a large impact on the centralized voltage control scheme that controls the taps on the basis of the measured voltage in real time; however, it can reduce the voltage violation because a constant reactive power can be obtained from the SIs regardless of the tap control results of the OLTCs. To further reduce the voltage violation amount,
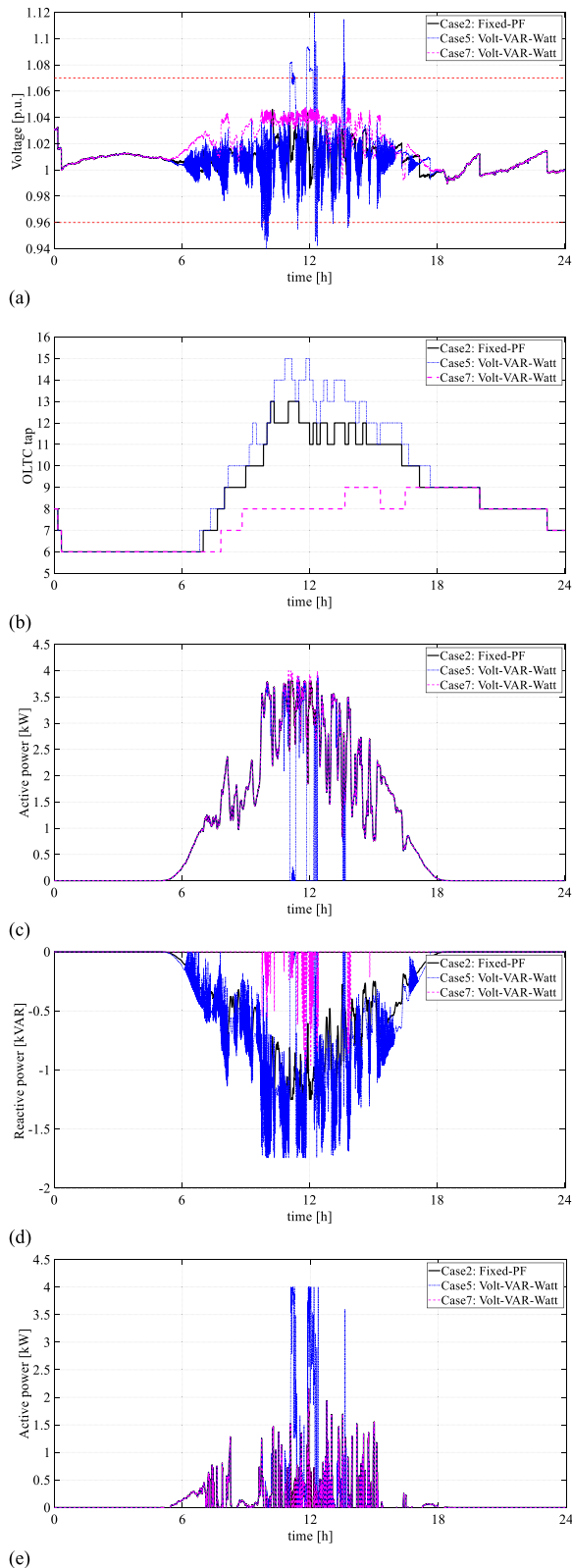
FIGURE 9. Voltage control results: (a) voltage profiles, (b) OLTC tap position, (c) active power, (d) reactive power, and (e) active power curtailment for Case 2, Case 5, an s".

it is necessary to change the power factor setting; however, the decision should be made in consideration of the effect

on the tap operation of the OLTCs and distribution losses. As shown in Fig. 7, because there are many SIs with high active power-voltage sensitivity in this distribution system, volt-watt control was effective in reducing the voltage violation, and this result also verified the validity of the system evaluation based on voltage sensitivity. The volt-VAR-watt control in Case 6, where the control parameters determined by the multi-objective optimization are used, shows better voltage control performance compared with other cases. However, these parameters can be obtained in the case that the detailed time-varying data of load demand and PV output of all customers connected to the distribution system for an evaluation period of 20 days are given in advance for power flow calculation, which are normally not available. On the other hand, even though the proposed method uses only active and reactive power-voltage sensitivity and SI rating capacities for parameters determination, it can be said that the control parameters can be selected similar to the optimized ones, and the proposed method can achieve sufficiently better voltage control performance than the other control methods.

Fig. 10 shows the total reactive power output of the SIs in the conventional and proposed volt-VAR-watt control. In the figure, the SIs are aggregated for each pole transformer, and the total reactive power output of each aggregated group is plotted on the distribution system diagram. In the conventional volt-VAR-watt control, a large amount of reactive power is output at every node of the distribution system, whereas in the proposed method, there is no node where the reactive power is output frequently. The active power curtailment required by the proposed method is as small as 0.642 MWh over a period of 20 days, which indicates that the tap operation of the OLTCs and volt-VAR control of the SIs provide sufficient voltage rise mitigation. Moreover, the amount of reactive power output is extremely small compared to the other methods, and the number of tap operations of the OLTCs is also minimized. The control parameters appropriate for each SI can be set to reduce excessive reactive power output and unnecessary active power curtailment; thus, they act as a voltage support function for the centralized voltage control and reduce the impact on the OLTC tap operation.

On the other hand, by using the proposed method, the amount of reactive power becomes larger the closer it is to the end of the distribution feeder and the inability to ensure the fairness of control contributions among inverters can be an issue. However, the unfairness is not limited to the proposed method and is a common issue for the voltage-dependent active and reactive power control. Furthermore, it can be seen from the simulation results that excessive reactive power is obtained, and the voltage violation cannot be avoided in the case of a fixed-PF control scheme that can ensure fairness among inverters. The proposed method can mitigate the active power curtailment amount and distribution losses compared to the fairness method, thus, it can be said that the proposed method is very useful for improving PV hosting capacity in the entire distribution system.

TABLE 4. **Voltage control performance for 20 days.**

Case	Max. voltage [V]	Cumulative voltage violation [V·s]	Cumulative reactive power [MVARh]	Cumulative active power curtailment [MWh]	Distribution loss [MWh]	Tap operations (total/average)
Case 1	110.5	1.26×10^5	0.00	0.00	62.3	285 14.3
Case 2	107.8	345	570	1.60	68.5	331/16.6
Case 3	110.5	1.10×10^6	796	3.85	74.5	439/22.0
Case 4	108.8	4.19×10^4	0.00	30.9	59.1	229/11.5
Case 5	116.1	1.58×10^8	751	92.2	70.6	453/22.7
Case 6	106.8	0.00	9.00	0.211	62.1	209/10.5
Case 7	106.2	0.00	28.5	0.642	62.1	153/7.65
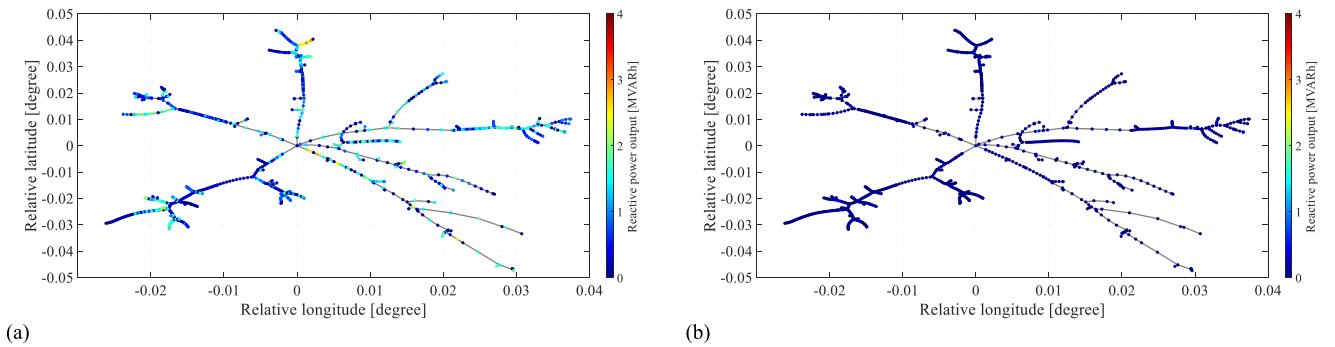
FIGURE 10. **Cumulative reactive power amount for (a) Case 5 and (b) Case 7.**

VI. CONCLUSION

To solve the voltage violation problem in a distribution system comprising a large number of PV installations, we focused on a voltage control using SIs and proposed a method to determine the control parameters of the individual SIs on the basis of the active and reactive power-voltage sensitivity matrix. The voltage sensitivity matrix is determined solely by the distribution system impedance; it does not change over time unless the distribution system configuration changes and it does not depend on the number of SIs. Therefore, the proposed method can uniquely and easily determine the control parameters for each SI without solving any optimization problem.

Numerical simulations reflecting the load characteristics of heavy and light loads as well as PV characteristics, such as sunny and cloudy weather, were performed on a large-scale distribution system model with PV systems to evaluate the effectiveness of the proposed method. In addition to the voltage violation, the voltage control performance of the proposed method was compared with that of fixed-PF control and conventional and optimized volt-VAR-watt control in terms of the amount of reactive power output, active power curtailment, distribution losses, and number of OLTS tap operations. It was clearly shown that the proposed method achieves good results in terms of all the evaluation indices compared to the conventional methods, thus realizing effective voltage control. Furthermore, the proposed method can also achieve the same level of voltage control performance as the optimization results, even though it uses only the voltage sensitivity matrix and SI rating capacities for parameters determination, and the accuracy of the proposed voltage control can be ensured throughout case studies.

The proposed method is reasonable, and the control parameters of each SI can be easily obtained from the voltage sensitivity that the DSO can identify. Because the parameters for voltage drop, which are not covered in this study, can be determined in a similar manner and the implementation is easy, the proposed method has high utility and can be fully applied to the real applications.

APPENDIX

In order to improve the performance of distribution systems using smart inverters, it is desired to be able to mitigate the amount of reactive power, active power curtailment, and distribution losses while avoiding voltage violations; therefore, the parameter determination problem for the volt-VAR-watt control can be formulated as a multi-objective optimization. The optimal control parameter set, $\psi^* = \left\{ V_3^{yv}, V_4^{yv}, V_5^{yw}, V_6^{yw} \right\}$, is given in the followings.

$$\psi^* = \arg\min_{\psi} F(\psi) \tag{A1}$$

$$= \arg \min_{\psi} \left\{ w_q \cdot \sum_{i=1}^{N} Q_{out}^i (\psi) + w_p \cdot \sum_{i=1}^{N} P_{cur}^i (\psi) \right.$$
$$\left. + w_l \cdot \sum_{l=1}^{L} P_{loss}^l (\psi) \right\} \tag{A2}$$

$$\text{s.t. } V_l \leq V_t^i \leq V_h \quad \forall i, \tag{A3}$$
$$V_3^{vv} \leq V_4^{vv} = V_5^{vv} \leq V_6^{vv}, \tag{A4}$$
$$P_{max}^{vv} = 1.0, \quad Q_{min}^{vv} = -0.44 \tag{A5}$$

where Q_{out}^i and P_{cur}^i are the amount of reactive power and active power curtailment for customer i, respectively, P_{loss}^l is distribution loss at line l, w_q, w_q, and w_q are weighting coefficients for each objective, V_t^i is voltage at customer i, V_h and V_l are the upper and lower voltage limit, respectively, L is the number of distribution lines. The optimal control parameter set is determined by an exhaustive approach assuming that all load demand and PV output for an evaluation period of 20 days are given in detail, thus the global solution can be obtained. For simplicity, the same control parameters are applied to all smart inverters and the maximum active and reactive power for the volt-VAR and volt-watt control are the same to the proposed method.

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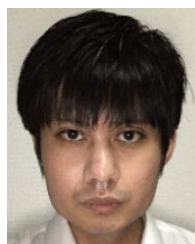
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