LDC-Control Parameters by Plane Determination Using Database Offline in Distribution Networks with PV System

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Abstract—**This paper proposes a method to determine the Line Drop Compensator (LDC)-control parameters of an On-load Tap Changer (OLTC) and step voltage regulator (SVR) using a database with measured data from offline IT-switches. In a conventional determination method, the parameters are calculated based on the relationship between the sending voltage and the absolute value of current at the secondary side of the OLTC/SVR with a fixed power factor. However, the power factor changes with the interconnection of the photovoltaic (PV) system. Hence, in the proposed method, LDC-control parameters are determined by the relationship between active current, reactive current, and sending voltage. In other words, the parameters are determined from the plane by taking these values as axes. The plane is determined by four measured data extracted from the database which have large voltage fluctuations in response to severe power flow. The effectiveness of the proposed method is verified by numerical simulations using a distribution system model with PV systems. Our results show that the proposed method can improve the amount of voltage violation by 35% compared to a conventional method.**

Index Terms—**Distribution systems, IT-switches, Line Drop Compensator (LDC), On-Load Tap Changer (OLTC), photovoltaic (PV) system, Step Voltage Regulator (SVR), voltage control**

I. INTRODUCTION

Distribution System Operators (DSO) regulate the voltage in distribution systems to supply reliable electric power to customers. In Japan, on-load tap changers (OLTCs) and step voltage regulators (SVRs) are mainly utilized for voltage regulation. However, the DSO face new challenges in terms of voltage regulation [1]-[5], because massive photovoltaic (PV) systems, especially residential PV systems, are installed in distribution systems. Active and reactive power generation from PV systems cause inappropriate tap operations, such as exceeding tap operation of the OLTC and SVR, and voltage violation may occur because in a conventional control scheme, the OLTC and SVR operate their taps based on control parameters assuming one-directional power flow from a substation to customers without PV systems [6]-[8]. When the voltage violation occurs, the active power generation from PV systems may be curtailed to maintain the voltages within the proper range [4]. Therefore, the DSO needs to upgrade the voltage control scheme not only to create flexible distribution systems that can support the installation of massive residential PV systems but also to utilize the generation from PV systems efficiently.

Many studies on novel voltage regulation schemes have been conducted previously. They could be divided into two types; one is the cooperation with Reactive Power Control (RPC) [9]-[19] and the other type is upgrading the tap operation scheme of OLTC and SVR [20]-[32]. RPC is performed by static var compensator (SVC) [9]-[11], distributed static compensator (DSTATCOM) [12], [13], battery energy storage systems (BESS) [14]-[17] and distributed generators [18], [19]. The main feature of RPC is the rapid regulation and RPC could mitigate the voltage violation and fluctuation caused by generation from PV systems. Pezeshki *et al*. [12] discussed the efficient placement and sizing of DSTATCOM under several scenario considering the cooperation with BESS. The placement and sizing of DSTATCOM were optimized by particle swarm optimization. To cooperate with RPC devices and voltage regulators, the communication infrastructures are required. In [18], cooperation scheme with distributed generators and SVR was proposed to mitigate exceeding tap operation considering the communication failure. According to these papers, RPC is useful for the voltage regulation in distribution systems, however, the installation cost of SVC, DSTSTCOM and BESS may be expensive. Additionally, the effectiveness of RPC may be less in distribution systems with low X/R ratios of line impedance [3]. Arshad *et al*. [20] suggested the contribution of the OLTC and SVR to maximize the hosting capacities of PV systems based on the Finnish distribution system.

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Hence, upgrading the voltage regulation scheme of OLCT and SVR is also important because the effectiveness of the voltage regulation by tap operation does not depend on the X/R ratio of the line impedance. Additionally, the DSO may reduce the operation cost by utilizing the existing voltage regulators effectively. In order to improve supply reliability and to upgrade voltage regulation schemes, Japanese power utilities have developed a Distribution Automation System (DAS), which monitors and controls distribution systems by an optical fiber network [21]. Voltage regulation schemes have been proposed utilizing monitored data by automatic section switches with built-in sensors (IT-switches) and communication infrastructure [22]-[32]. The authors in [23] designed a centralized voltage control scheme for under-load tap changers using the measured voltage data. The voltage regulation using the monitored data was verified in the field demonstration [26]. In [29] and [30], the authors focused on the line drop compensator (LDC)-control scheme, which is widely utilized in OLTCs and SVRs in Japan [33]. The control parameters are updated online every 15 minutes corresponding to the power flow, reactive power from the PV systems, and weather conditions. According to these studies, constant communication is required to coordinate the voltage regulation devices or to update the control parameters considering changes in the power flow by PV systems. However, communication failure may lead to voltage violation. Therefore, the DSO also requires upgrading to a decentralized voltage control scheme, such as LDC-control without constant communication. One of the upgrading methods is to determine the control parameters offline based on the past measured data from IT-switches. The control parameters should be determined to prevent voltage violation and exceeding tap operations in various load and PV system generation conditions. The authors in [32] proposed the method to improve the performance of LDC-control of SVR using the database. However, the method for OLTC has not been discussed well. The determination the parameters of OLTC seems to be difficult, because OLTC controls the voltages in the multiple feeders [6].

This paper proposes a method to determine LDC-control parameters of OLTCs and SVRs based on measured current and voltage and phase angle data from IT-switches. In this method, the LDC-control parameters, namely, i) simulated line resistance R, ii) simulated line reactance X, and iii) reference voltage V_{ref}, are determined by drawing a plane consisting of the 3-axes of active current, reactive current, and sending voltage of the OLTC/SVR to consider power factor fluctuations due to PV system generation. Additionally, the plane is drawn with severe power flow data in terms of voltage conditions corresponding to various load and PV generation conditions. The effectiveness of the proposed method is verified based on the amount of voltage violation and number of tap operations in numerical simulations using a distribution system model with PV systems.

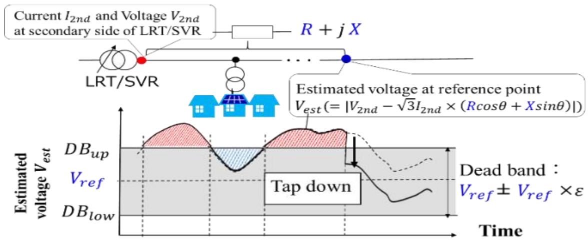


Fig. 1. Overview of the vector LDC-control.

II. Control Scheme of LDC-Control for OLTC and SVR

Herein, the LDC-control scheme is described [33]. The tap position is controlled to maintain the estimated voltage V_{est} at a regulating point within the dead-band. The voltage at the regulating point is calculated using the secondary voltage V_{2nd}, current I_{2nd}, and phase angle θ, which are monitored by the OLTC and SVR, as follows:

$$V_{\text{est}}(t) = |V_{\text{2nd}}(t)| - \sqrt{3}|I_{\text{2nd}}(t)|\left(R\cos\theta(t) + X\sin\theta(t)\right) \quad (1)$$

The upper and lower limits of the dead-band, DB_{up} and DB_{low}, of width ε are defined as

$$\text{DB}_{\text{up}} = V_{\text{ref}} + \varepsilon V_{\text{ref}}, \quad \varepsilon = 0.01 \quad (2)$$

$$\text{DB}_{\text{low}} = V_{\text{ref}} - \varepsilon V_{\text{ref}}, \quad \varepsilon = 0.01 \quad (3)$$

The overview of the tap operation is described in Fig. 1. The tap of OLTC is changed when an integrated value of the V_{est} violation from the dead-band exceeds a predefined threshold. The integrated value of the voltage violation from upper dead-band and lower dead-band are given by

$$\text{VV}_{\text{up}}(t) = \int \left(V_{\text{est}}(t) - \text{DB}_{\text{up}}\right) dt, \quad \text{VV}_{\text{up}}(t) \geq 0 \quad (4)$$

$$\text{VV}_{\text{down}}(t) = \int \left(\text{DB}_{\text{low}} - V_{\text{est}}(t)\right) dt, \quad \text{VV}_{\text{down}}(t) \geq 0 \quad (5)$$

where VV_{up} and VV_{down} are the integrated values of the V_{est} violation from DB_{up} and DB_{low}, respectively.

The formulation for the tap operation is defined as

$$\text{Tap}(t+1) = \begin{cases} \text{Tap}(t) - 1, & \text{if } \text{VV}_{\text{up}}(t) > \text{Th} \\ \text{Tap}(t) + 1, & \text{if } \text{VV}_{\text{down}}(t) > \text{Th} \\ \text{Tap}(t), & \text{otherwise} \end{cases} \quad (6)$$

where Tap is the tap position, and Th is the threshold for the tap operation.

The integrated value returns to zero when the tap position is changed. On the other hand, the tap position of the SVR changes based on the integrated value of the V_{est} violation time from the dead-band.

III. Scheme for Determining LDC-Control Parameters

The procedure of the proposed method for determining LDC-control parameters using the data measured from IT-switches is as follows. The overview of the proposed method is shown in Fig. 2. The scheme consists of two steps: i) construction of the database, and ii) determination of LDC-control parameters from the plane.

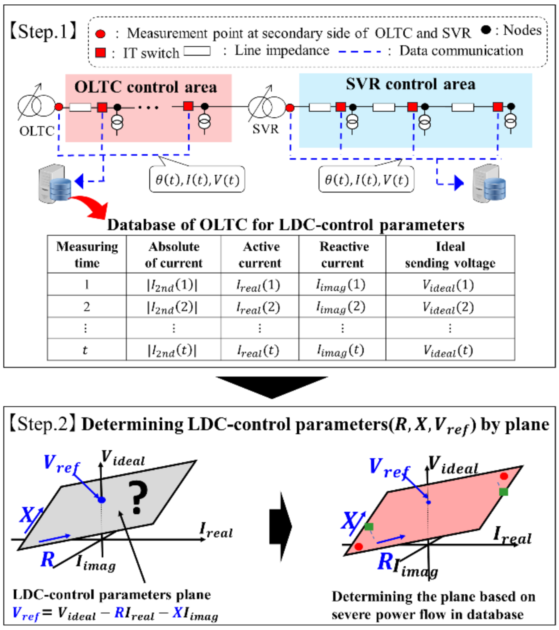


Fig. 2. Procedure of determining LDC-control parameters.

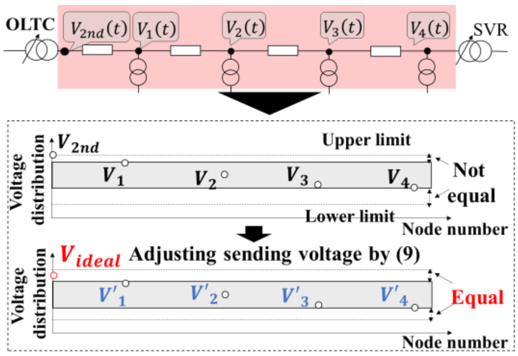


Fig. 3. Concept of ideal sending voltage.

A. Database for Determining LDC-Control Parameters

The database is constructed using voltage data measured from IT-switches and the current, voltage and phase angle measured from the voltage regulators. Each voltage regulator contains the data for the control area. The database consists of four values of the voltage regulators: i) absolute values of the secondary current $|I_{2nd}(t)|$, ii) real part of secondary current I_{real}, iii) imaginary part of secondary current I_{imag}, and iv) ideal sending voltage V_{ideal} in each measured time period. The ideal sending voltage indicates the secondary voltage when the margins between the node voltages in the control area and the upper and lower limits of the proper voltage range are equal, as shown in Fig. 3. The ideal sending voltage is calculated as a continuous value based on the measured voltage data from voltage regulators and IT-switches given by

$$I_{real}(t) = \sqrt{3}\left|I_{2nd}(t)\right|\cos\theta(t) \tag{7}$$

$$I_{imag}(t) = \sqrt{3}\left|I_{2nd}(t)\right|\sin\theta(t) \tag{8}$$

$$V_{ideal}(t) = \frac{\Delta V_{min}(t) + V_{up} + \Delta V_{max}(t) + V_{low}}{2} \tag{9}$$

$$\Delta V_{min}(t) = \left|V_{2nd}(t)\right| - \min_{n\in N}\left|V_n(t)\right| \tag{10}$$

$$\Delta V_{max}(t) = \left|V_{2nd}(t)\right| - \max_{n\in N}\left|V_n(t)\right| \tag{11}$$

where ΔV_{min} and ΔV_{max} are the differences between the sending voltage and the minimum and maximum node voltages in the control area respectively, N is the total node number in the control area, V_n is the voltage in node n, V_{up} and V_{low} are the upper and lower limits of the proper voltage range, respectively.

B. Determination of LDC-Control Parameter Plane

Here, the LDC-control parameter plane is first defined before presenting the method to determine the plane. The equation of the LDC-control parameter plane is derived from the conventional method for determination of LDC-control parameters. The concept is illustrated in Fig. 4. In the conventional method, the parameters are determined from the straight line drawn with the absolute secondary current and ideal voltage in the heavy and light load periods (t_{heavy} and t_{light} respectively), given as

$$t_{heavy} = \underset{t\in T}{\operatorname{argmax}}\left(\left|I_{2nd}(t)\right|\right) \tag{12}$$

$$t_{light} = \underset{t\in T}{\operatorname{argmin}}\left(\left|I_{2nd}(t)\right|\right) \tag{13}$$

$$V_{ref} = V_{ideal}(t_{heavy}) - \sqrt{3}Z\left|I_{2nd}(t_{heavy})\right| \tag{14}$$

$$Z = \frac{V_{ideal}(t_{heavy}) - V_{ideal}(t_{light})}{\sqrt{3}\left|I_{2nd}(t_{heavy}) - I_{2nd}(t_{light})\right|} \tag{15}$$

$$R = Z\cos\phi, \quad \cos\phi = 0.95 \tag{16}$$

$$X = Z\sin\phi, \quad \sin\phi = 0.31 \tag{17}$$

In the conventional method, the power factor of power flow is fixed as $\cos\phi$=0.95 when LDC-control parameters R and X are calculated. However, the power factor of the power flow will fluctuate due to the generation from PV systems. To consider the fluctuation of power factor, the absolute secondary current $|I_{2nd}(t)|$ is divided into its real and imaginary parts, as shown in (7) and (8). Thus, the LDC-control parameters are determined by drawing the plane (18), as shown in Fig. 4.

$$V_{ref} = V_{ideal} - RI_{real} - XI_{imag} \tag{18}$$

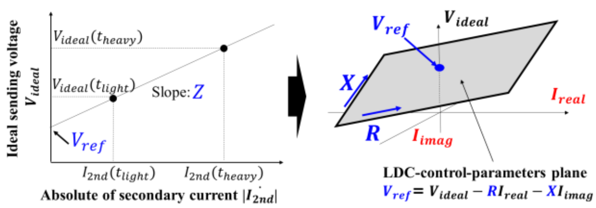


Fig. 4. Concepts of the conventional and proposed determination schemes.

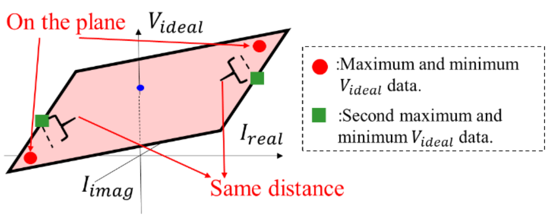


Fig. 5. Proposed method to determine LDC-control parameter plane.

In the proposed method, the LDC-control parameter plane is drawn with the four data values in the database consisting of two time periods of maximum V_{ideal} and two time periods of minimum V_{ideal}, to correspond to the severe voltage conditions in the database, as shown in Fig. 5. Specifically, the plane is drawn by solving the simultaneous equations (19)-(21) to determine LDC-control parameters R, X and V_{ref}:

$$V_{\text{ref}} = V_{\text{ideal}}(t_{\max 1}) - RI_{\text{real}}(t_{\max 1}) - XI_{\text{imag}}(t_{\max 1}) \quad (19)$$

$$V_{\text{ref}} = V_{\text{ideal}}(t_{\min 1}) - RI_{\text{real}}(t_{\min 1}) - XI_{\text{imag}}(t_{\min 1}) \quad (20)$$

$$\frac{\left|-RI_{\text{real}}(t_{\max 2}) - XI_{\text{imag}}(t_{\max 2}) + V_{\text{ideal}}(t_{\max 2}) - V_{\text{ref}}\right|}{\sqrt{R^2 + X^2 + 1^2}} = \frac{\left|-RI_{\text{real}}(t_{\min 2}) - XI_{\text{imag}}(t_{\min 2}) + V_{\text{ideal}}(t_{\min 2}) - V_{\text{ref}}\right|}{\sqrt{R^2 + X^2 + 1^2}} \quad (21)$$

Equations (19) and (20) describe that the maximum and minimum V_{ideal} data on the plane. Additionally, (21) shows that distances from the plane to the second maximum and second minimum data are equal.

IV. Numerical Simulations

A. Simulation Condition

To evaluate the contribution of the proposed method in terms of the mitigation of voltage violation, numerical simulations are performed utilizing a 6.6 kV three-feeder distribution system model with PV systems, as shown in Fig. 6. One OLTC and three SVRs are installed in the model. The load capacity of each feeder is 1400 kW. PV systems are installed in residential feeders A and B. Table I shows the detailed simulation conditions. The PV system penetration ratio indicates the ratio of the number of households with PV systems to the total number of households on a feeder. The number of households in each residential feeder is about 700, and the rated capacity of the PV system in one household is 4.0kW. The verification days are sunny, cloudy, and rainy days in summer, autumn, and winter, i.e., 9 days. There are three determination methods for the LDC-control parameters: i) conventional method, ii) comparison method, and iii) proposed method. In the comparison method, the control parameters are determined by drawing the plane based on multiple regression with all the data in the database, shown in Fig. 7 [34]. Lastly, the evaluation index is the average of the amount of voltage violation from the proper range. The proper range is defined by translating the proper range in a low voltage system (101±6V) to that in a 6.6 kV middle voltage system considering the voltage rise in the low voltage systems due to reverse power flow.

TABLE I. DETAILED SIMULATION CONDITIONS

Contents	Setting
PV system penetration ratio	60, 70, 80 %
Period for making database	180 days
Verification days	9 days
Determination methods of LDC-control parameters	i) Conventional method; ii) Comparison method; iii) Proposed method
Evaluation index	The average amount of the voltage violation per day during verification days

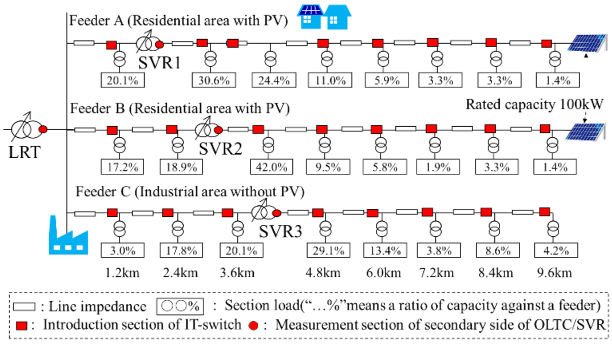


Fig. 6. Three-feeders distribution system model.

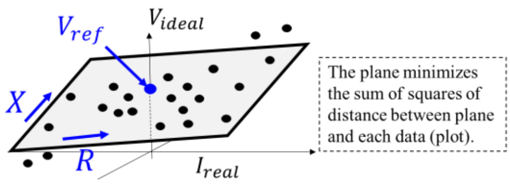


Fig. 7. Comparison method based on multiple regression.

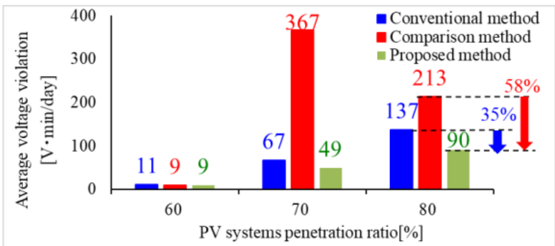


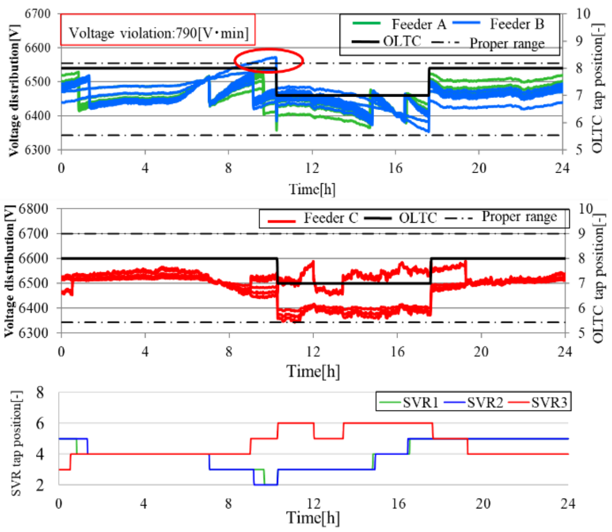
Fig. 8. Results of the voltage violation in each method.

B. Results of Numerical Simulations

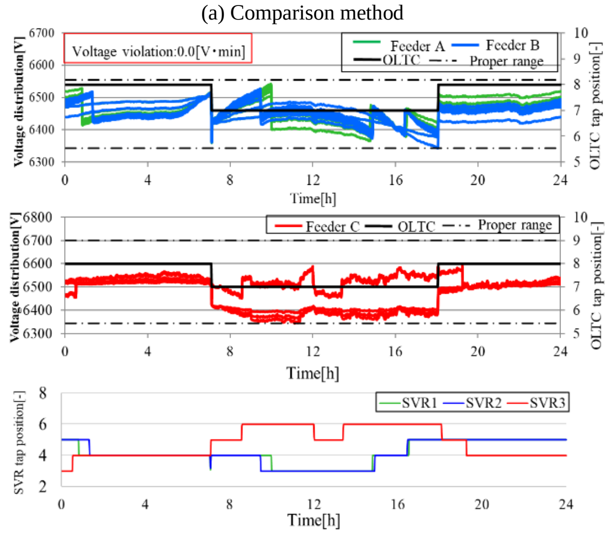
Fig. 8 shows the amount of average voltage violation per day in each determination method. In PV systems with a penetration ratio of 60%, the amount of voltage violation in the comparison and proposed methods are less than that in the conventional method. Accordingly, the scheme of determining the plane seems to be effective. In PV systems with a penetration ratio over 70%, the values are improved by the proposed method compared to other methods. In PV systems with a penetration ratio of 80%, the proposed method improves the amount of voltage violation by 35% compared to the conventional method and by 58% compared to the comparison method.

On the other hand, the amount of voltage violation in the comparison method deteriorated significantly compared to the conventional method. The voltage violation in the comparison method is 367 Vmin/day and that in the conventional method is 67 Vmin/day. The reason for this deterioration in the comparison method may be because of determining the LDC-control parameter plane based on all the data. The parameters tend to correspond with the average power flow; however, the voltage regulation for the severe voltage condition, such as a sunny day, may be difficult. To discuss the reason of the voltage violation in each method, the voltage profiles in sunny day and cloudy day are shown in Fig. 9 and Fig. 10, respectively.

In Fig. 9 (a), the voltage violation occurred in Feeder B around 10am because the tap operation of the OLTC is delayed. In Fig. 9 (b), the voltage violation is prevented by the appropriate tap operation of OLTC in the proposed method. Compared to the LDC-parameters, V_{ref} of the comparison and proposed methods in the case of PV penetration ratio of 80% are 6455.1 V and 6442.0 V, respectively, as shown in Table II. Therefore, the proposed method seems to correspond to the voltage rise by setting the reference voltage V_{ref} lower. In Feeder C without PV systems, the voltage violation did not occur in each determination method.



(a) Comparison method



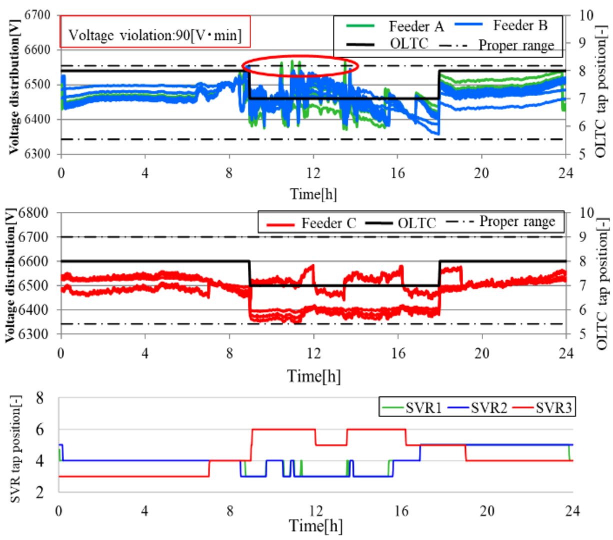
(b) Proposed method

Fig. 9. Voltage profiles in PV systems with a penetration ratio of 80% (summer, sunny day).

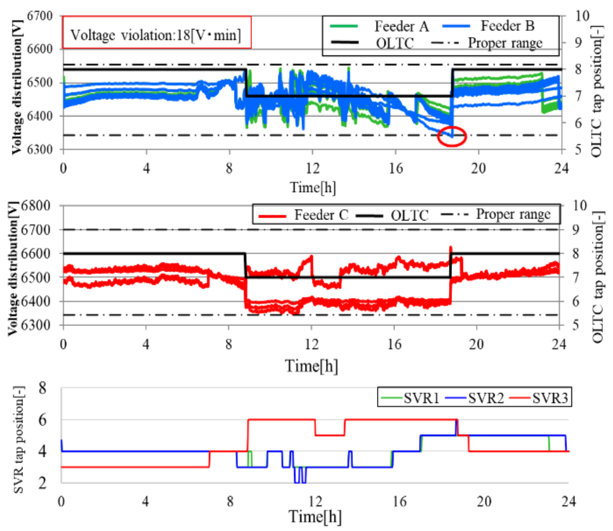
TABLE II. DETERMINED LDC-CONTROL PARAMETERS FOR OLTC AND SVR IN PV SYSTEM PENETRATION RATIO 80%

Devices	Values	Conventional method	Comparison method	Proposed method
OLTC	V_{ref}	6443.9	6455.1	6442.0
	$\%R$	6.2	5.3	6.2
	$\%X$	2.0	18.8	12.5
SVR1	V_{ref}	6466.1	6448.5	6448.2
	$\%R$	3.4	3.4	3.4
	$\%X$	1.1	4.2	4.2
SVR2	V_{ref}	6458.6	6448.3	6448.1
	$\%R$	2.9	2.9	2.9
	$\%X$	0.9	3.4	3.4
SVR3	V_{ref}	6491.0	6521.8	6522.8
	$\%R$	2.8	3.0	2.9
	$\%X$	0.9	5.1	5.2

According to Fig. 10 (a), the voltage violation occurred in during daytime in the conventional method by the inappropriate tap operations of SVRs. The inappropriate tap operation caused by the the voltage fluctuation due to the rapid fluctuation of generation from PV systems. In the proposed method, the voltage violation is cleared during the daytime. Compared to the LDC-parameters of SVRs, $\%X$ in the conventional method is lower than the one in the proposed method. Additionally, as the LDC-control parameters of each control device in the proposed method are different, the proposed method seems to be able to determine the LDC-control parameters considering the power flow in each control area. These results indicate the effectiveness of the proposed method at minimizing voltage violation. The number of tap operation did not increase drastically. Therefore, the proposed method is valuable to utilize OLTC and SVR effectively, because the parameters from proposed method could mitigate the voltage violations and exceeding tap operations without a constant communication in the numerical simulation.



(a) Conventional method



(b) Proposed method

Fig. 10. Voltage profiles in PV systems with a penetration ratio of 80% (summer, cloudy day).

However, the proposed method has still challenges. For example, the voltage violation from the lower limit occurred around 7 pm in Fig. 10 (b). The reason of the voltage violation may be that the load around 7pm was heavier than the one in database. Thus, the robustness of the voltage regression is important to achieve this challenge. To improve the robustness, the cooperation scheme between the OLTC, SVR, and rapid voltage control devices, such as static var compensator (SVC) or distributed generators, seems to be required. Additionally, the three-phase imbalance condition needs to be considered in the future, because three-phase balance is assumed in this work.

V. Conclusion

In this work, the determination method of LDC-control parameters for OLTC and SVR is proposed based on plane determination with four measured data from a database offline to reduce the amount of voltage violation. The plane consists of active current, reactive current, and ideal sending voltage. In the proposed method, the plane is determined based on four measured data that have maximum and minimum ideal sending voltages to correspond with severe power flow. Numerical simulations were performed using a 6.6 kV distribution network with high-penetration PV systems. The results indicate the effectiveness of the proposed method at minimizing voltage violations. The proposed method improved the amount of voltage violation by 35% compared to the conventional method and by 58% compared to the multiple regression method.

The main contribution of this paper is that the proposed method could be applied in various distribution systems because this method focuses on LDC-control, which is widely applied in the existing voltage regulators, OLTCs, and SVRs. It is economical for the DSO to utilize the existing voltage regulators efficiently to integrate more PV systems without exceeding tap operations.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Akihisa Kaneko conducted numerical simulation and wrote this paper. Prof. Yasuhiro Hayashi and associate Prof. Masakazu Ito gave comments and advises about this proposed method and simulation setting and reviewed this paper to clear the contribution of this research. Takaya Anegawa, Hideyasu Hokazono and Masayuki Oyama gave the knowledges based on the actual operation in the electric power utility and discussed the results. All authors had approved the final version.

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