Voltage Control of Multiple Step Voltage Regulators by Renewing Control Parameters

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Abstract—This paper presents a novel method of determining the control parameters and a voltage control method for multiple step voltage regulators (SVRs) in a single feeder. The main feature of the proposed method is the updating of the control parameters at constant intervals to minimize the amount of voltage violations and the tap operation times of the SVRs while maximizing the voltage margin from the proper limits in the distribution system. To determine the SVR control parameters, a combined method of a greedy algorithm and a tabu search is used. To verify the proposed method, numerical and experimental simulation studies based on an actual distribution model with photovoltaic (PV) sources are carried out. The results show that the proposed control method can reduce the amount of voltage violations and tap operation times of the SVRs compared with the conventional voltage control method.

Keywords—Distribution system; photovoltaics (PV); step voltage regulator (SVR); greedy algorithm; tabu search (TS); voltage control

I. INTRODUCTION

Voltage regulation in a distribution system is important to maintain a reliable electric power supply to customers. Load tap changer (LTC) is the main voltage control device in a distribution system and load-ratio control transformers (LRTs) and step voltage regulators (SVRs) installed in distribution substations and feeders are widely used in Japan. In particular, a number of SVRs are installed in a single feeder when a distribution line is extremely long, and voltage violation from a defined range can be avoided by adjusting the tap position of multiple SVRs. However, the number of photovoltaic (PV) systems, especially residential PVs, connected to a distribution system has been growing, and their effects on the voltage regulation in the distribution systems have been reported [1], [2]. Voltage fluctuations due to PVs cause inappropriate tap operations in multiple SVRs and voltage violations in the distribution systems. In the conventional control scheme, SVRs operate according to the control parameters determined under the assumption that the power flow is in one direction from the distribution substation to the customers without PVs. Multiple SVRs might interfere with one another and increase the tap operation times because the control parameters are fixed for a day or year.

To effectively regulate the voltage in a distribution system when a large number of PVs are installed, a novel mechanical specification of the SVRs and several voltage control schemes have been proposed in the literature [3]-[9]. In [3], a basic study on the specification of an advanced SVR was reported to improve the voltage profiles in the distribution system. In [4], a voltage control scheme for multiple feeders based on remote terminal units at each distributed generator, which coordinate with one another, was proposed. A dead-band control algorithm for the multiple line drop compensation of an LTC transformer was proposed in [5]. In [6] and [7], coordination methods for the LTC and other control devices such as shunt capacitors (SCs) and a static compensator (STATCOM) were proposed. The authors of [6] designed a coordinated control strategies of the LTC and SCs at substations and feeders. In [7], an artificial neural network-based coordination control scheme for LTC and STATCOM installed at the same bus was proposed. On the other hand, the authors of [8] developed a reactive-power control method of solar inverters contained in PV systems to improve the node voltage. In [9], a reactive-power control approach to mitigate the voltage rise in the distribution system was proposed. According to previous research, a coordinated control scheme between the LTC and other control devices has been shown to contribute significantly to a proper voltage regulation in the distribution system. However, the above-mentioned methods have not been verified when multiple SVRs are installed in a single feeder, and determining whether the node voltage can be maintained correctly is difficult because reactive-power control by the SCs and STATCOM depends on the reactive-power flow, the capacity of the control devices, and the installation location. In addition, the amount of reactive-power output or PV suppression must be smaller in terms of the utilization of the PV systems.

Therefore, we propose a method in this paper for determining the optimal control parameters of advanced SVRs and a voltage control method for multiple SVRs in a single feeder with a large amount of PVs. In the determination of the control parameters, the objective is to minimize the amount of voltage violations and the tap operation times of the SVRs while maximizing the voltage margin from the proper voltage limits. Further, the parameters are determined without a PV control. The control parameters of the SVRs are updated every 15 min, and the SVRs attempt to mitigate the voltage violation by themselves according to the updated parameters. Thus, the

This research was supported by the Japan Science and Technology Agency (JST), CREST.
PVs support to keep the proper voltage only when a voltage violation cannot be prevented by the SVRs. A combined method of a greedy algorithm and a tabu search (TS) is applied to search for the optimal parameters. To verify the proposed method, numerical and experimental simulation studies using an actual distribution model are carried out.

II. CONTROL SCHEME OF ADVANCED SVR AND PV SYSTEM

A. Voltage Control of SVRs

The voltage control of the advanced SVRs is performed by regulating the secondary voltage into a reference voltage by tap operation. The tap control scheme of the advanced SVR, named 90 relay, is shown in Fig. 1. The advanced SVR monitors the secondary voltage; when the secondary voltage exceeds a dead band, a time counter starts. If the secondary voltage returns to the dead band, the total time is decreased. When the time counter reaches a specified time AT, the SVR changes the tap position to regulate the secondary voltage to the reference voltage using an automatic voltage-regulating relay [6]. Thus, the control parameters of the advanced SVR are the adjustable reference voltage \( V_{ref} \) (0.972–1.02 pu), the dead band \( \varepsilon \) (1.0%–2.5%), and the active time \( AT \) (15–180 s). During voltage regulation by the advanced SVR, these control parameters are set remotely for a fixed period of time to mitigate unnecessary tap operations and voltage violation from the proper voltage range.

![Fig. 1. Voltage control scheme for the advanced SVR.](image)

B. PV Output Control

In Japan, a number of residential PVs have been connected to the low-voltage distribution system. To protect the overvoltage at the receiving point, solar inverters have a function to control PV output. As the PV output control, three reactive-power control methods, namely, constant voltage control, proportional voltage control, and constant power-factor control, were described in [8]. In these methods, the node voltage is controlled by injecting reactive power using the available capacity of solar inverters. The active power is suppressed when the voltage rise is not mitigated. However, the effectiveness of these strategies is unclear because the reactive control depends on the capacity of the solar inverters and the distribution system configuration, and the standard parameters have not yet been determined. In addition, a PV suppression control is widely adopted as the control technique using solar inverters of residential PV in Japan. Therefore, a simple proportional active-power suppression control is applied in our study. The objective of PV suppression control is just to mitigate voltage rise because of residential PVs. Fig. 2 shows the basic PV suppression system. When the PV system detects the voltage deviation from the upper limit \( V_{ref} \) at the customer level, the PV active power is suppressed until the node voltage becomes lower than \( V_{ref} \), \( P^* \) is the real active power, and gain \( K_p \) is the PV active-power reduction rate.

III. DETERMINATION ALGORITHM OF THE OPTIMAL CONTROL PARAMETERS OF SVRS

A. Problem Definition

The optimal control parameters of the multiple advanced SVRs, which are \( V_{ref} \), \( \varepsilon \), and \( AT \), are updated with a 15-min interval. Thus, 96 different parameter sets are necessary in one day. The goal is to minimize the amount of voltage violations and the number of tap operations of the advanced SVRs while maximizing the voltage margin from the node-voltage limits. Then, the parameters are determined without a PV output control because the SVRs do not need the reactive power of the PVs, and the purpose of the PV suppression is simply to support in maintaining a proper voltage. The optimal control parameters are obtained by minimizing the objective function \( F(x) \), as given in the following equations:

Minimize

\[
F(x) = w_1 \cdot V_{Ts_{\text{arg.in}}}(x) + w_2 \cdot \text{Tap}_{\text{num}}(x) + V_{T}_{\text{ref}}(x)
\]

\[
V_{Ts_{\text{arg.in}}}(x) = \frac{1}{T_{\text{base}}} \sum_{i=1}^{T} \sum_{n=1}^{N} \max \left( V_{Ts}^{i,n} - V_{Ts}^{i,n}(x) \right)^2
\]

\[
V_{Ts}^{i,n} = \frac{V_{max} + V_{min}}{2} - K_c \cdot \left( V_{Ts_{\text{arg.in}}}^{\text{up}}(x) + V_{Ts_{\text{arg.in}}}^{\text{low}}(x) \right)
\]

\[
V_{Ts_{\text{arg.in}}}^{\text{up}} = \frac{1}{T} \sum_{i=1}^{T} \max \left( V_{Ts_{\text{arg.in}}}(x) - \frac{V_{max} + V_{min}}{2} \right)
\]

\[
V_{Ts_{\text{arg.in}}}^{\text{low}} = \frac{1}{T} \sum_{i=1}^{T} \min \left( V_{Ts_{\text{arg.in}}}(x) - \frac{V_{max} + V_{min}}{2} \right)
\]

\[
\text{Tap}_{\text{num}}(x) = \frac{1}{T_{\text{base}}} \sum_{i=1}^{T} \sum_{n=2}^{N} \left( \text{Tap}_{i,j}(x) - \text{Tap}_{i,j-1}(x) \right)^2
\]

\[
V_{Ts_{\text{ref}}}(x) = \frac{T}{T_{\text{base}}} \sum_{i=1}^{T} \sum_{n=1}^{N} \left( V_{Ts_{\text{ref}}}(x) - \frac{V_{max} + V_{min}}{2} \right)^2
\]
subject to
\[0.972 \leq V_{ref_k} \leq 1.02 \text{ [p.u.] } (k = 1, 2, \ldots, K) \] (8)
\[1.00 \leq e_k \leq 2.50 \text{ [%]} \quad (k = 1, 2, \ldots, K) \] (9)
\[15 \leq AT_k \leq 180 \text{ [s]} \quad (k = 1, 2, \ldots, K) \] (10)

\[x_2 = [AT_1 \quad AT_2 \quad \cdots \quad AT_K]^T \] (12)

where
\[w_1, w_2 \] weight coefficients for the voltage margin and the number of tap operations;
\[V_{margin}(x) \] sum of the squared maximum differences from the median value of the proper voltage range at time stage \(T_s\);
\[Tap_{num}(x) \] sum of the squared number of tap operations at time stage \(T_s\);
\[V_{viol}(x) \] voltage violation from the proper voltage range at time stage \(T_s\);
\[V_{base} \] high-voltage reference value, i.e., 6.6 kV;
\[V_{c} \] modified median value of the proper voltage range at time stage \(T_s\);
\[V_{n,t}(x) \] voltage at node \(n\) at time \(t\) at time stage \(T_s\);
\[V_{max}, V_{min} \] maximum proper voltage, minimum proper voltage;
\[K_c \] weight coefficient for the past trend of the voltage profiles;
\[V_{up}^{T_s-1} \] mean value of upward differences from the median value of the proper voltage range at time stage \(T_s-1\);
\[V_{low}^{T_s-1} \] mean value of downward differences from the median value of the proper voltage range at time stage \(T_s-1\);
\[Tap_{base} \] maximum daily number of tap operations in a single SVR, i.e., 27 times;
\[Tap_{3,f}(x) \] tap position of \(SVR_k\) at time \(t\);
\[Ts \] number of time stages, i.e., \(T_s = 1, 2, \ldots, 96\);
\[T \] 15-min interval, i.e., 900 s;
\[N \] total number of nodes.

The objective function (1) aims to determine the best control parameters for each time stage \(T_s\). In the proposed method, the median value of the proper voltage range is modified based on the trend of the voltage profiles in the distribution system as shown in (3)-(5).

### B. Procedure for the Proposed Method

Fig. 3 shows the proposed control system diagram. The control parameters of each SVR are updated at a 15-min interval, and the tap position is adjusted according to the updated parameters. The tap operation is performed by the 90-relay scheme described in Section II.

In determining the optimal parameters of the SVRs, a short searching time is desired. Thus, a combined method of the greedy algorithm and TS, which are local search algorithms, is used because the available parameters are discrete, and the two methods are suitable to solve discrete optimization problems.

Fig. 4 shows the diagram for determining \(V_{ref}\) and \(e\) of a single SVR. To quickly search the optimal parameters, the determination method consists of two stages: 1) determination of \(V_{ref}\) and \(e\) and 2) determination of \(AT\). Thus, \(V_{ref}\) and \(e\) are initially determined while the initial value of \(AT\) is fixed. Then, \(AT\) is determined by fixing the computed values of \(V_{ref}\) and \(e\). The initial values for searching the optimal parameters are the applied parameters for voltage control in the previous time interval to mitigate the instantaneous tap operations when the parameters are updated. Moreover, using the previous control parameters as the initial parameters can reduce the search time when voltage violation does not occur. However, when the local search alone is not enough to alleviate the voltage violation, the initial parameters are set within the different search ranges determined from the estimated voltage drop and voltage rise according to the load and PV profiles to reduce the amount of voltage violations. The following is the summary of the procedure of the proposed method:

**Step1** Preparing eight parameter sets centered around the initial values \(\{V_{ref_k}^{(0)}, e_k^{(0)}, AT_k^{(0)}\}\) on the coordinate axes;

**Step2** Calculating the objective function values using (1) and comparing the objective function values;

**Step3** Renewing the current best parameters with the highest improvement in the eight parameter sets;

**Step4** Counting the number of times that the central objective function values is at a minimum \(C_{min}\);

**Step5** Executing **Steps1–4** from the closest SVR to the distribution substation to the load-side SVR and renewing the current best parameters; then, renewing the control parameters one at a time on each SVR;

**Step6** Decreasing the value of \(AT\) and executing **Steps1–4** again when a voltage violation occurs using the current best parameters;

**Step7** Setting the initial parameters within the priority search range designed from the estimated voltage drop and voltage rise if a voltage violation cannot be avoided after reducing \(AT\); then, repeating **Steps1–4**;

**Step8** Repeating **Steps1–7** until the iteration count in the TS or \(C_{min}\) reaches the specified stopping criterion;
Step9) Determining the optimal value of $AT$ from Steps 1–7 while fixing the computed values of $V_{ref}$ and $\varepsilon$.

IV. NUMERICAL SIMULATION

A. Distribution System Model

To verify the efficiency of the proposed method, numerical simulation studies were conducted. The proposed method was simulated in an actual 6.6-kV distribution system shown in Fig. 5. The distribution system has a long feeder, and four SVRs were installed in a single feeder. The load and PV profiles and the sending-voltage profile $V_0$ are shown in Fig. 6. The total load capacity was 3105 kVA and distributed to each node at a rate shown in Fig. 5. The total PV capacity in this distribution system model was 1107 kVA, calculated from the projected PV capacity in Japan for 2030. The PVs were installed according to the load capacity of each node.

B. Numerical Simulation Results

The control parameters of each SVR in the proposed method were updated every 15 min using the determination method described in Section III, and the SVRs operated according to the updated parameters. In the determination of the parameters, the weight coefficients $w_1$ and $w_2$ in (1) and $K_c$ in (3) were set to 0.5. The tabu length was eight, and the iteration count and $C_{min}$ in Step8 were set to 80 and 25, respectively. In the conventional method, the control parameters were fixed at their initial values ($V_{ref} = 1.01$ pu, $\varepsilon = \pm 1.00\%$, and $AT = 45, 60, 75, \text{ and } 90$ s) discussed in [3] during a single day. The PV suppression parameters $V_H$ and $V_{H-min}$ were set to 1.015 and 1.0095 pu, respectively and determined based on the anticipated voltage drop in the low-voltage distribution system. The simulation case studies are listed in Table I.
Figs. 7 and 8 show the voltage profiles obtained by the conventional and proposed methods. The proposed method can prevent voltage violation compared with the conventional method. For the conventional method, all node voltages were maintained at a high voltage because the reference voltage of every SVR was 1.01 pu. Thus, voltage violation from the upper limit tended to occur in the conventional method owing to the voltage rise from the PVs. The significant amount of voltage violations in the conventional method was due to the mutual interference among the SVRs. In this case, a possibility exists that the PV suppression control did not function well to support the maintenance of the proper voltage. On the other hand, the voltage violation during the daytime was avoided using the proposed control method although consecutive tap operations occurred when the parameters were updated. Moreover, the voltage margin from the limits could be extended, and the tap operations of the SVRs were reduced. The numerical simulation results are listed in Table II. Tap operations in each SVR in the conventional method were frequently performed throughout the day and were larger than the acceptable number of daily tap operations, especially in Case2. The number of tap operations in the proposed method was less than half of that of the conventional method by updating the control parameters. The amount of PV suppression was significantly reduced compared with that of the conventional method because the SVRs attempted to improve the voltage profile without PV suppression control in the proposed method.

However, the tap operation times of SVR4 in the proposed method, which is a load-side SVR, were particularly larger than those of the other SVRs because of voltage fluctuations. Fig. 9 shows the secondary voltage, $\varepsilon$, and $AT$ of SVR4 in the proposed method. The dead band $\varepsilon$ became narrow, and $AT$ was shortened to adjust the tap position to avoid voltage violation during daytime. In addition, the proposed method tried to lengthen $AT$ according to the time to reduce the tap operations. Generally, prevention of voltage violation and reduction of tap-change operations maintain a trade-off relationship. Therefore, the appropriate weight coefficients must be determined according to the time of day.

### V. EXPERIMENTAL SIMULATION

An experimental simulation was performed using the active network simulator with energy resources (ANSWER), which is a 200-V experimental system designed for three-phase, three-wire, and non-grounded simulations of a Japanese 6.6-kV distribution system. The ANSWER shown in Fig. 10 is made at Waseda University and includes LTCs, single- and three-phase...
inverters to simulate a load and PV generation, and distribution line devices with switches and sensors. In the experimental implementation, the control parameters of the LTCs, loads, and PV profiles can be freely controlled by an external control signal from an online control computer system. To validate the proposed method, a real-time experiment was carried out. The model configuration, load, PV, and sending voltage profiles were the same as those of the numerical simulation.

The experimental voltage profiles for each control method are shown in Figs. 11 and 12. An instantaneous voltage violation due to the mutual interference among SVRs occurred in both cases using the conventional method. In the experimental simulation, precipitous voltage fluctuation occurred more frequently than in the numerical simulation. However, the use of the proposed method could not perfectly prevent voltage violation in the distribution system. This is due to the differences between the actual voltage drop and rise and the calculated values in the numerical simulation. The distribution line length and impedance in the experimental simulation were determined based on the voltage drop at peak load in a day. However, the voltage drop and rise at off-peak were slightly different from those of the numerical simulation.

As a result, each SVR did not function predictably and the voltage violation could not be avoided by using the proposed method. In addition, voltage violations occurred during daytime in both cases because of the increase in the tap
operations of the load-side SVRs when the parameters were updated. Therefore, the appropriate time period to update the control parameters for each SVR must be improved. On the other hand, the total amount of PV suppressions was reduced due to the unanticipated voltage drop during daytime compared to the numerical simulation. Table III lists the experimental simulation results. Clearly, the proposed control method can reduce significantly not only the instantaneous voltage violation and the amount of voltage violations from the proper limits but also the total number of tap operations of the SVRs even though the experimental results show slight differences compared with the numerical simulations results.

### VI. CONCLUSION

In this paper, a novel voltage control method for multiple SVRs in a single feeder has been proposed. The main feature of the proposed method is the updating of the control parameters with constant intervals to reduce the amount of voltage violations and the tap operations of the SVRs in the distribution system. In addition, a combined method of the greedy algorithm and the TS to quickly determine the optimal parameters of the SVRs has been proposed. To verify the effectiveness of the proposed method, numerical simulation and real-time simulation studies based on an actual distribution model with PV suppression control were performed. The simulation results clearly showed that the proposed method prevented voltage violation in the distribution system and reduced the tap-change operations of the SVRs. Moreover, the amount of voltage violations in the proposed method was significantly small compared with that of the conventional method, and the validity of the proposed method was confirmed through the case studies.

### REFERENCES


