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Heuristic Coordinated Voltage Control Schemes in Distribution Network with Distributed Generations

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Abstract: The voltage and reactive power control (Volt/VAR Control, VVC) in distribution networks has become a challenging issue with the increasing utilization of distributed generations (DGs). In this paper, a heuristic-based coordinated voltage control scheme that considers distribution voltage control devices, i.e., on-load tap changers (OLTC) and step voltage regulators (SVR), as well as reactive power control devices, i.e., DGs, are proposed. Conventional voltage control methods using non-linear node voltage equations require complex computation. In this paper, the formulation of simplified node voltage equations accounting for changes in tap position of distribution voltage control devices and reactive power changes of reactive power control devices are presented. A heuristic coordinated voltage control scheme using the proposed simplified node voltage equations is proposed. A coordinated voltage control scheme to achieve voltage control for nominal voltage and conservative voltage reduction (CVR) is presented. The results of the proposed schemes are compared with the results from the quadratic optimization method to confirm that the proposed schemes yields suitably similar results. Furthermore, a tap scheduling method is proposed to reduce the number of tap changes while controlling network voltage. The tap position is readjusted using a voltage control performance index (PI). Simulation results confirm that when using this method the number of tap changes is reduced. The proposed scheme not only produces reasonable performance in terms of control voltage of networks but also reduces the number of tap changes made by OLTC. The proposed control method is an alternative candidate for a system to be applied to practical distribution networks due to its simplified calculations and robust performance.

Keywords: distribution network; distributed generations; OLTC; SVR; voltage control; heuristic algorithm; conservation voltage reduction; volt/var control

1. Introduction

In practice, the voltages of distribution networks are conventionally regulated by changing the tap position of the on-load tap changer (OLTC) at distribution substation and step voltage regulator (SVR) or by switching shunt capacitor banks at feeders. However, coordinated control between these devices is not widely seen in practical distribution systems. In addition, as the interconnection capacity of distributed generations (DGs) increases, their voltage control has become an increasing technical concern. Specifically, due to the intermittent nature of interconnected DG, voltage problems such as the violation of operating voltage ranges, often results in poor voltage quality and we often see overuse of tap changing for the OLTC [1]. Under these circumstances, voltage and reactive power control (Volt/VAR control, VVC) algorithms, which rely on conventional voltage control methods, are no longer feasible. In order to solve these problems, advanced coordinated control algorithms between voltage control devices are required.

Previous studies have been researched in various ways. A modified line drop compensator (LDC) control scheme that considers the effects of DG has been proposed [2–5]. The proposed algorithm controls the load ratio of the transformer, SVR, shunt capacitor (SC), and shunt reactor to provide the optimal voltage profile using a genetic algorithm [6]. However, these studies do not consider the coordinated reactive power control for interconnected DGs.

The various studies using coordinated reactive power control of interconnected DGs have been conducted. In [7], a two-stage control method for the adjustment of OLTC transformers, capacitor banks and DGs is proposed. In the first stage, the tap position of the OLTC is optimally changed using a micro-genetic algorithm, in the second stage, an iterative genetic algorithm is run with the objective of minimizing power loss to determine the optimal reactive power of the DGs. In [8], dynamic programming techniques are utilized to find the optimal VVC for large distribution networks. These dynamic programming techniques manage to maximize the reduction of line losses in a real-time environment. In [9], a reactive power control method of DGs through a remote terminal unit (RTU) in a distribution network is proposed. However, the use of local communication methods does not guarantee that the optimal solution is found. In [10], a distributed control method is designed to properly control the voltage profile for distribution networks with a large penetration of DGs. However, this kind of typical distributed control method does not guarantee an optimal global solution.

In [11], a reactive power control method of DGs is used to control the bus voltage while considering the response delay of the capacitor and OLTC. In [12], a two-stage control method based on a violated bus is proposed. In the first stage, the reactive power required at the nearest DG to control the violated bus voltage is determined. In the second stage, if the voltage is not controlled by the neighboring connected DG (this situation occurs due to the capacity limit), it exchanges information with other controllers in the adjacent bus. Then, the voltages are adjusted to the desired level using another control component. In [13], a method of controlling the voltage to prevent voltage violations when various DGs are connected is proposed. In [14], a coordinated control method for static synchronous compensator (STATCOM) and OLTC is proposed to maximize the capacity margin of STACOM. In [15], a coordinated control method for STACOM and OLTC is proposed based on an artificial neural network (ANN). In [16], a voltage control method is proposed based on state estimation. In [17,18], a real-time voltage control method using fuzzy logic is proposed. In [19,20], a voltage control method using non-linear programming (NLP) is proposed.

However, typical voltage control methods often require a large computational burden because these methods use non-linear equations for accurate node voltage calculation, i.e., load flow calculation. In this paper, to reduce this computational burden, a simplified linear voltage equation for node voltage calculation is proposed. In addition, the voltage control characteristics of tap changing devices, i.e., OLTC and SVR, and reactive compensation devices, i.e., reactive power of DGs, are represented by simplified node voltage equations. For practical application in a real system, it is proposed the heuristic-based coordinated voltage control schemes use two-stage control schemes. In the first stage, the voltage profiles of the feeders are flattened by controlling the reactive power of the interconnected DGs, in the second stage, the voltage profiles of the distribution networks are leveled by adjusting the tap position of the OLTC. Finally, a tap scheduling method is proposed to minimize tap operation times of OLTC while maintaining reasonable voltage control performance. The tap position schedule from the second stage of the proposed algorithms is then re-adjusted using a performance index (PI).

In this paper, a simplified linear voltage equation is proposed to reduce the computation times of the voltage estimation process and heuristic-based coordinated algorithms for voltage control devices, such as tap changing devices and reactive power sources, also are proposed to reduce the computational complexity of the search process for an optimal solution. Therefore, it is easy to convert to program code and can even be installed on a small-sized microprocessor of the controller of the voltage control devices such as the OLTC transformer. Furthermore, the tap scheduling method is proposed to satisfy the practical consideration for tap changing limitation of ULTC and SVR in a practical power distribution system. From the results of the case studies, it can be seen that the proposed method not only has reasonable performance when controlling the voltage of the networks but also reduces the number of tap changes for the OLTC. It is expected that the proposed method is very useful for the practical distribution systems due to the simplified calculation process, robust performance, and practical consideration for limitation of tap changing operations.

2. Formulation of Simplified Node Voltage Equation

The typical voltage control methods require complex nonlinear equations based power flow equation as shown in Equation (1).

$$\begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{1}$$

where,

$\Delta\delta$: Variation of phase angle
$\Delta|V|$: Voltage variation
ΔP: Active power variation
ΔQ: Reactive power variation
$\begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}$: Jacobian matrix

The magnitude of voltage variation can be obtained from power flow equation as shown in Equation (2).

$$\Delta|V| = J_1^{-1}\Delta P + J_4^{-1}\Delta Q \tag{2}$$

However, the Jacobian matrix is non-linear and requires a complicated computational process. Therefore, a difficult and complicated calculation process is required to find precise node voltage estimation. In this paper, a simplified linear equation is proposed based on the variation of tap and reactive power of DGs.

2.1. Simplified Node Voltage Equation

In general, the voltage at each node by the output of DGs is affected by the impedance of the distribution networks. The voltage variation at node i by small active and reactive power outputs of DGs can be represented simply by Equation (3).

$$\Delta V_{i,\,\mathrm{DG},k} \cong R \cdot \Delta P_{\mathrm{DG},j} + X \cdot \Delta Q_{\mathrm{DG},j} \tag{3}$$

where,

i: Node number
j: DG number
$\Delta V_{i,\mathrm{DG},j}$: Voltage variation at node i by the j-th DG
$R_{i.j}$: Resistance at node i by the j-th DG
$X_{i,j}$: Reactance at node i by the j-th DG
$\Delta P_{\mathrm{DG},j}$: Active power variation of the j-th DG
$\Delta Q_{\mathrm{DG},j}$: Reactive power variation of the j-th DG

The impedance in Equation (3) is determined by the topology of the distribution networks. The section impedance is determined by the location of DGs and nodes in Figure 1. For example, the voltage variation of node 1 due to DG1 is determined by section impedance ($Z_{1,1}$) between the substation and DG1 as shown in Figure 1.

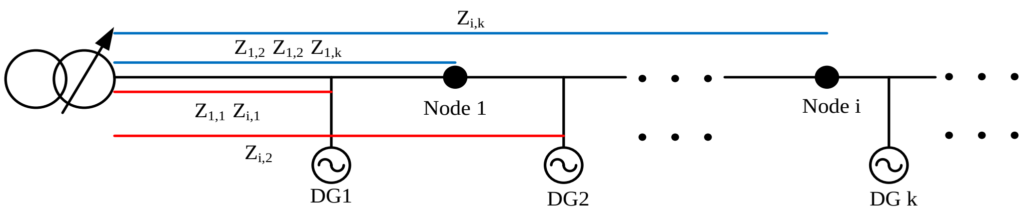

Figure 1. The impedance by location of distributed generations (DGs) and nodes.

Generally, to maximize the availability of DGs, DGs of the distribution networks are operated at their maximum active power output. Therefore, the voltages of distribution networks are only controlled using the reactive power of DGs without controlling the active power of DGs. Since the reactive power of DGs is the target of our control, the active power component can be removed. The voltage variation due to small variation of reactive power of the j-th DG can be expressed in Equation (4).

$$\Delta V_{i,\,\mathrm{DG},k} \cong X_{i,j} \cdot \Delta Q_{\mathrm{DG},j} \tag{4}$$

The voltage variation at node i relation to the interconnected DGs can be represented by Equation (5).

$$\begin{bmatrix} \Delta V_{1,\mathrm{DG}} \\ \vdots \\ \Delta V_{i,\mathrm{DG}} \\ \vdots \\ \Delta V_{n,\mathrm{DG}} \end{bmatrix} = \begin{bmatrix} X_{1,1} & \cdots & X_{1,j} & \cdots & X_{1,m} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ X_{i,1} & \cdots & X_{i,j} & \cdots & X_{i,m} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ X_{n,1} & \cdots & X_{n,j} & \cdots & X_{n,m} \end{bmatrix} \cdot \begin{bmatrix} \Delta Q_{\mathrm{DG},1} \\ \vdots \\ \Delta Q_{\mathrm{DG},j} \\ \vdots \\ \Delta Q_{\mathrm{DG},m} \end{bmatrix} \tag{5}$$

where,

n: The total number of nodes
m: The total number of DGs
$\begin{bmatrix} X_{1,1} & \cdots & X_{1,j} & \cdots & X_{1,m} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ X_{i,1} & \cdots & X_{i,j} & \cdots & X_{i,m} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ X_{n,1} & \cdots & X_{n,j} & \cdots & X_{n,m} \end{bmatrix}$: Reactance matrix of distribution networks

The voltage variation at node i of the k-th tap changing device can be represented by the voltage variation ($\Delta V_{Tap,k}$) and the load current variation ($\Delta I_{Load,k}$) caused by the tap change. This can be expressed as shown in Equation (6).

$$\Delta V_{i,\mathrm{Tap},k} = \Delta V_{\mathrm{Tap},k} + \Delta I_{\mathrm{Load},k} \cdot Z_{i,k} \tag{6}$$

where,

k: Tap changing device number
$\Delta V_{i,\mathrm{Tap},k}$: Voltage variation by taps of the k-th tap changing device
$\Delta V_{\mathrm{Tap},k}$: Voltage variation caused by tap changes
$\Delta I_{\mathrm{Load},k}$: Load current variation caused by tap changes
$Z_{i,k}$: Impedance at node i by the k-th tap changing device

As the voltage variation caused by a tap change is small, the load current change is also sufficiently small for the voltage variation by the k-th tap changing device to be expressed as in Equation (7).

$$\Delta V_{i,\mathrm{Tap},k} \cong \Delta V_{\mathrm{Tap},k} \tag{7}$$

Tap changing devices, i.e., OLTC and SVR, can generally control the voltages of nodes in the downstream area of distribution networks shown in Figure 2. However, tap changing devices do not control the voltages of the nodes in upstream areas of the network. Therefore, control area coefficients ($\alpha_{i,k}$) are applied as shown in Equation (8).

$$\begin{bmatrix} \Delta V_{1,\mathrm{Tap}} \\ \vdots \\ \Delta V_{i,\mathrm{Tap}} \\ \vdots \\ \Delta V_{n,\mathrm{Tap}} \end{bmatrix} = \begin{bmatrix} \alpha_{1,1} & \cdots & \alpha_{1,k} & \cdots & \alpha_{1,l} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \alpha_{i,1} & \cdots & \alpha_{i,k} & \cdots & \alpha_{i,l} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ X_{n,1} & \cdots & X_{n,k} & \cdots & X_{n,l} \end{bmatrix} \cdot \begin{bmatrix} V_{Tap,1} \cdot \Delta \mathrm{Tap}_1 \\ \vdots \\ V_{Tap,k} \cdot \Delta \mathrm{Tap}_k \\ \vdots \\ V_{Tap,l} \cdot \Delta \mathrm{Tap}_l \end{bmatrix} \tag{8}$$

$$\alpha_{i,k} = \begin{cases} 1, & \textit{node } i \in k \textit{ control area} \\ 0, & \textit{node } i \notin k \textit{ control area} \end{cases}$$

where,

l: The total number of tap changing devices
$\alpha_{i,k}$: Control area coefficient of the k-th tap changing device at node i
$\Delta\mathrm{Tap}_k$: Tap variations of the k-th tap changing device
$V_{\mathrm{Tap},k}$: Voltage variation per a tap of the k-th tap changing device

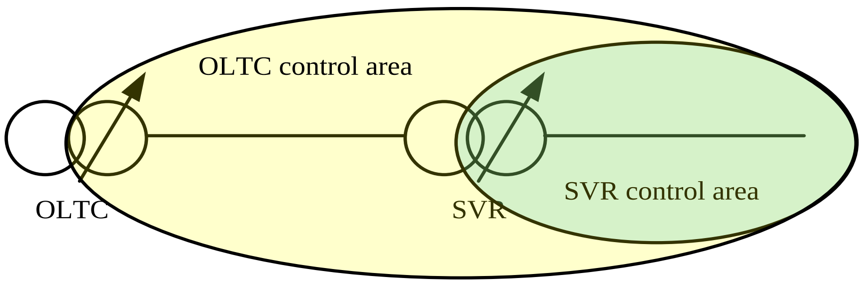

Figure 2. Control area of tap changing devices.

Voltage variation due to control devices can be considered separately. The voltage variation is determined using the superposition principle as shown in Equation (9). The estimated voltage (V_i) is derived from the voltage variation ($\Delta V_{i,\mathrm{DG}}$) of DGs, the voltage variation ($\Delta V_{i,\mathrm{Tap}}$) of tap changing devices and the initial voltage (V_i^0).

$$V_i = V_i^0 + \Delta V_{i,\mathrm{DG}} + \Delta V_{i,\mathrm{Tap}} \tag{9}$$

where,

V_i: Estimated voltage of the i-th node
V_i^0: Initial Voltage of the i-th node

2.2. Objective Function for Voltage Control

In the voltage control of a distribution network, the target voltage is determined according to the control purpose. The overall voltage of the network is controlled to be close to the target voltage as shown in Equation (10). For example, if the control purpose is conservative voltage reduction (CVR) control, the target voltage is set to be the operation lower limit voltage, and if the control purpose is voltage control for nominal voltage, the target voltage is the nominal voltage.

$$\min_{\Delta Q_{\mathrm{DG}},\Delta \mathrm{Tap}} \sum_{i=1}^{N}\left(\left(V_i - V_{Target}\right)^2\right) \tag{10}$$

where,

V_{Target}: Target voltage

Equations (11)–(13) show the constraints on the objective function in Equation (10). Equation (11) is the control range of the reactive power of the DG, Equation (12) is the control range of tap changing devices, and Equation (13) is the operating voltage range.

$$Q_{\mathrm{DG},min,k} - Q^0_{\mathrm{DG},k} \le \Delta Q_{\mathrm{DG},k} \le Q_{\mathrm{DG},max,k} - Q^0_{\mathrm{DG},k} \tag{11}$$

$$\mathrm{Tap}_{min,t} - \mathrm{Tap}^0_t \le \Delta \mathrm{Tap}_t \le \mathrm{Tap}_{max,t} - \mathrm{Tap}^0_t \tag{12}$$

$$V^{limit}_{min} \le V_i \le V^{limit}_{max} \tag{13}$$

where,

$Q_{\mathrm{DG},min,k}$: Minimum limit of reactive power of k-th DG
$Q^0_{\mathrm{DG},k}$: Initial reactive power output of k-th DG
$Q_{\mathrm{DG},min,k}$: Maximum limit of reactive power of k-th DG
$\mathrm{Tap}_{min,t}$: Lowest tap position of the t-th tap changing device
Tap^0_t: Initial position of the t-th tap changing device
$\mathrm{Tap}_{max,t}$: Highest tap position of the t-th tap changing device
V^{limit}_{min}: Minimum operating voltage limit
V^{limit}_{max}: Maximum operating voltage limit

3. Heuristic Coordinated Voltage Control Scheme

The proposed equation can generally be solved by using quadratic programming (QP). In this paper, a simplified scheme is proposed that applies heuristic techniques. The proposed coordination control schemes can be divided into two stages. In the first, the voltage profile of the distribution networks is flattened by using the reactive power of the DGs. As the voltage profile is changed by supplying or absorbing reactive power, the voltage profile of the network can be flattened. In the second, the voltage of the distribution networks is controlled by tap changing devices. As tap control can raise or lower the voltage of the entire control area of the distribution networks, the voltage of distribution networks can be controlled by tap changing devices according to their purpose.

In the case of voltage control to achieve nominal voltage, the average value of the flattened voltage profile is controlled to be close to the nominal voltage value, as shown in Figure 3. In the case of the control to achieve CVR, the flattened voltage profile is lowered as much as possible as shown in Figure 4. In order to achieve the nominal voltage, Equation (14) should be solved using the optimization technique. The network aims to achieve a voltage as close to the nominal voltage as possible.

$$\min_{\Delta Q_{\mathrm{DG}},\Delta \mathrm{Tap}} \sum_{i=1}^{N}\left(\left(V_{nom} - V_i\right)^2\right) \tag{14}$$

$$\begin{aligned} s.t. \quad & V^{limit}_{min} \le V_i \le V^{limit}_{max} \\ & Q_{\mathrm{DG},min,j} - Q^0_{\mathrm{DG},j} \le \Delta Q_{\mathrm{DG},j} \le Q_{\mathrm{DG},max,j} - Q^0_{\mathrm{DG},j} \\ & \mathrm{Tap}_{min,k} - \mathrm{Tap}^0_k \le \Delta \mathrm{Tap}_k \le \mathrm{Tap}_{max,k} - \mathrm{Tap}^0_k \end{aligned}$$

where,

V_{nom}: The nominal voltage

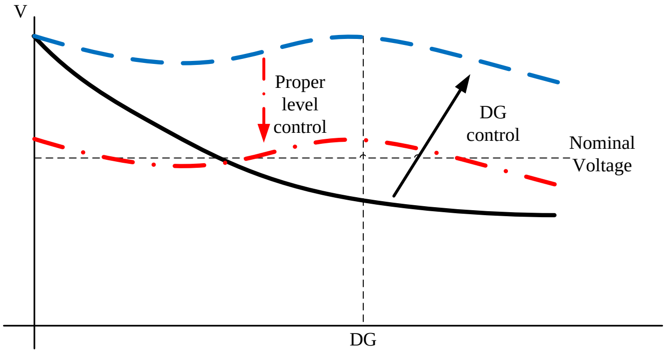

Figure 3. The proposed voltage control method for the nominal voltage.

In the case of the voltage control to achieve CVR, the references of the reactive power and the tap are obtained by solving the optimization equation shown in Equation (15). The lowest voltage of the distribution network is controlled so as to be close to the operating lower voltage limit.

$$\min_{\Delta Q_{\mathrm{DG}},\Delta \mathrm{Tap}} \left(V_i^{min} - V_{min}^{limit}\right)^2 \tag{15}$$

$$\begin{aligned} s.t. \quad & V_{min}^{limit} \leq V_i \leq V_{max}^{limit} \\ & Q_{\mathrm{DG},min,j} - Q_{\mathrm{DG},j}^0 \leq \Delta Q_{\mathrm{DG},j} \leq Q_{\mathrm{DG},max,j} - Q_{\mathrm{DG},j}^0 \\ & \mathrm{Tap}_{min,k} - \mathrm{Tap}_k^0 \leq \Delta \mathrm{Tap}_k \leq \mathrm{Tap}_{max,k} - \mathrm{Tap}_k^0 \end{aligned}$$

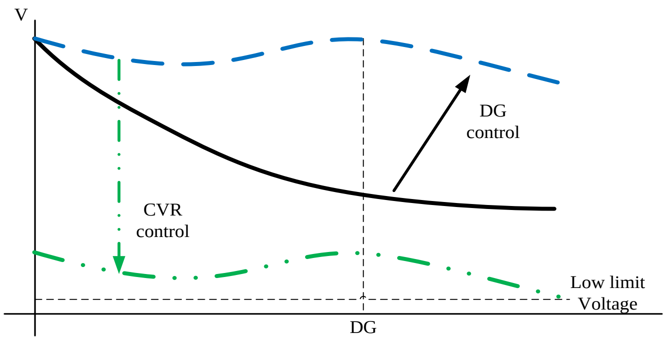

Figure 4. The proposed voltage control method for conservative voltage reduction (CVR).

3.1. Reactive Power Control for Flattened Voltage Profile

In this paper, a method is proposed to be able to derive a result similar to the optimal result without complex optimization. The control references are determined by dividing each into the control components. Coordination control between DGs is undertaken to derive the optimal voltage profile for the distribution network. The optimization equation for flattening the voltage of the distribution networks is given by Equation (16).

$$\min_{\Delta Q_{\mathrm{DG}}} \sum_{i=1}^{N} \sum_{j=1}^{N} \left(V_i - V_j\right)^2 \tag{16}$$

$$s.t.\ Q_{\mathrm{DG},min,j} - Q_{\mathrm{DG},j}^0 \leq \Delta Q_{\mathrm{DG},j} \leq Q_{\mathrm{DG},max,j} - Q_{\mathrm{DG},j}^0$$

Figures 5–8 show the process of controlling reactive power of three DGs in distribution networks. The control references are calculated by iterative operation to consider the effect of voltage variation from interactions. Figure 5 shows the reactive power control of DG 1 at the highest position. The voltage deviation is small even when the maximum reactive power is applied. Owing to the high position, the voltage variation does not change significantly as the reactance is small. However, if more reactive power can be applied, more voltage deviation will be possible.

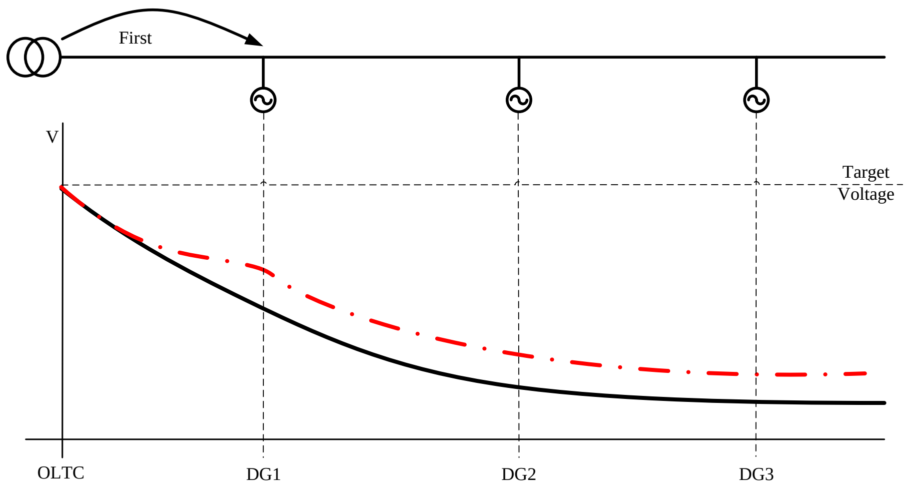

Figure 5. Voltage profile by reactive power of DG 1.

Equations (17)–(19) show the calculation of the required reactive power for the voltage control. Equation (17) calculates the average voltage from the node voltages of distribution networks. Equation (18) derives the amount of voltage deviation to be controlled using the target voltage and the average voltage. Equation (19) yields a reactive power reference for the voltage variation to control the network voltage.

$$mean\left(V_i^0\right) = \frac{1}{N}\sum_{i=1}^{N}\left(V_i^0\right) \tag{17}$$

$$dV = V_{\text{Target}} - mean\left(V_i^0\right) \tag{18}$$

$$\Delta Q_{\text{DG},j} = dV / X_{i,j} \tag{19}$$

To verify whether or not the obtained reactive power reference is out of the DG output range, Equation (20) is used to determine the effective reactive power reference. When the reactive power control is out of range, it is defined as the constraint range limit value. The voltage variation of each node is obtained using Equation (21).

$$Q_{\text{DG},min,j} \leq Q_{\text{DG},j}^0 + \Delta Q_{\text{DG},j} \leq Q_{\text{DG},max,j} \tag{20}$$

$$\Delta V_i = \Delta Q_{\text{DG},j} \cdot X_{i,j} \tag{21}$$

Figure 6 determines the reactive power reference of DG 2 after determining the reactive power reference of DG 1. Figure 6 shows the voltage profile when the voltage is not raised enough owing to the limitation of reactive power. The result is determined by processing through Equations (17)–(21).

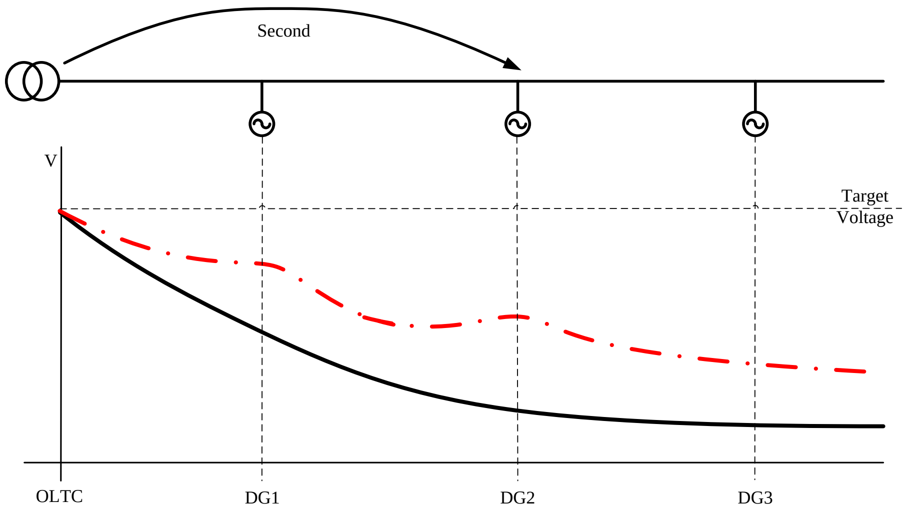

Figure 6. Voltage profile by reactive power of DG1 and DG 2.

Figure 7 shows the determination process of the reactive power reference for DG 3 after determining the reactive power references of DG 1 and DG 2. Similar to the case of the DG obtained earlier, the reactive power is calculated so that the mean voltage of the network is as close as possible to the target voltage. The control reference for DG 3 is determined using Equations (17)–(21). The results of this are shown in Figure 7.

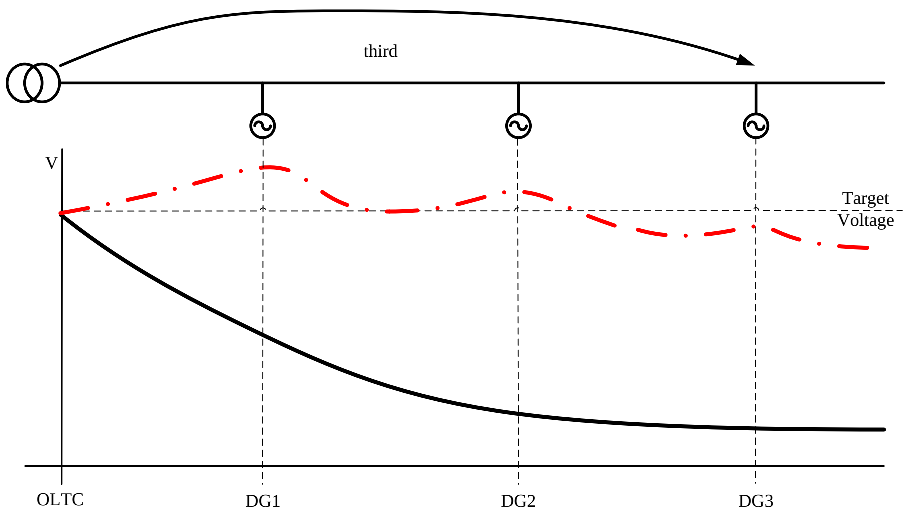

Figure 7. Voltage profile by reactive power of DG1, DG2 and DG 3.

It is possible to control the voltage of the network so it is flattened through iterative calculations of the operations we have performed so far. Finally, as shown in Figure 8, the reactive power references of DGs can be derived by iterative calculations.

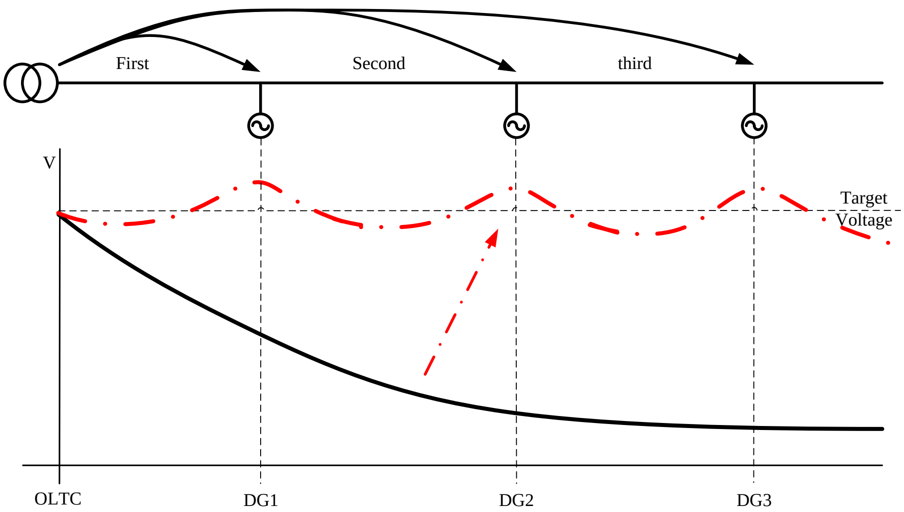

Figure 8. Voltage flattening by reactive power of DGs.

The summary of the voltage control method of DGs is shown using a flowchart in Figure 9. First, the voltage of the distribution networks is measured and entered as an input. After deriving the average voltage of the network in Equation (17), the voltage deviation between average voltage and target voltage is calculated in Equation (18). The reactive power reference which corrects the voltage by using the difference between the average voltage and the target voltage is determined in Equation (19). If multiple DG participate in control, iterative processes are performed as described above. The iterative operation is performed until the voltage control variation ($dV \cong 0$) condition is satisfied.

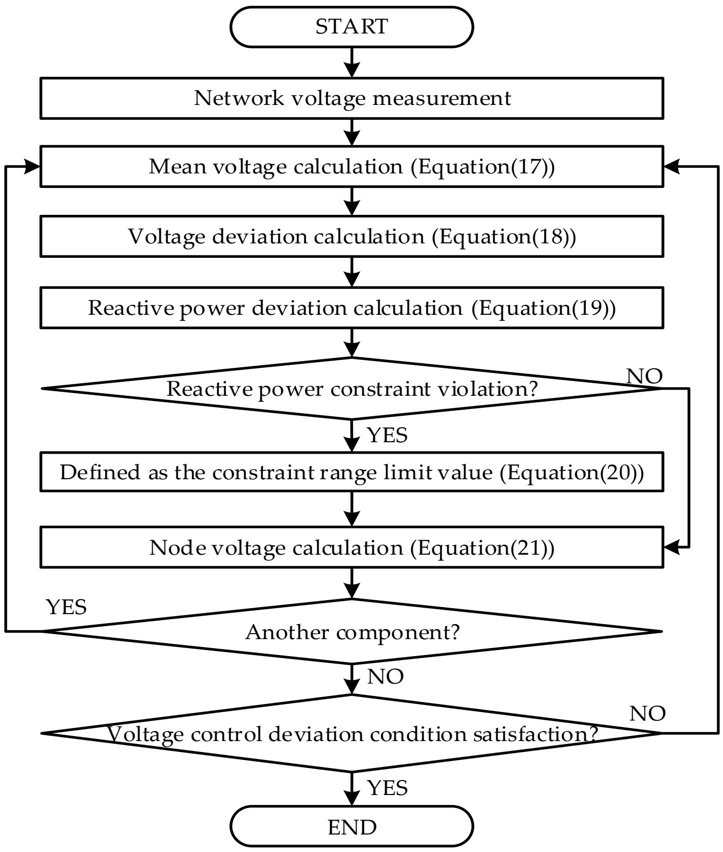

Figure 9. Flowchart of the proposed reactive power control method for voltage flattening.

Figure 10 show the flattened voltage profiles for the case of two DGs with a single feeder using the simulation network. Figure 11 compares enlarged voltage flattening results for the case of two DGs. "Initial" represents the initial voltage and "QP Opt" is the optimization result obtained using QP [21]. From the figures, it can be observed that the proposed scheme's result is almost the same as the optimization result.

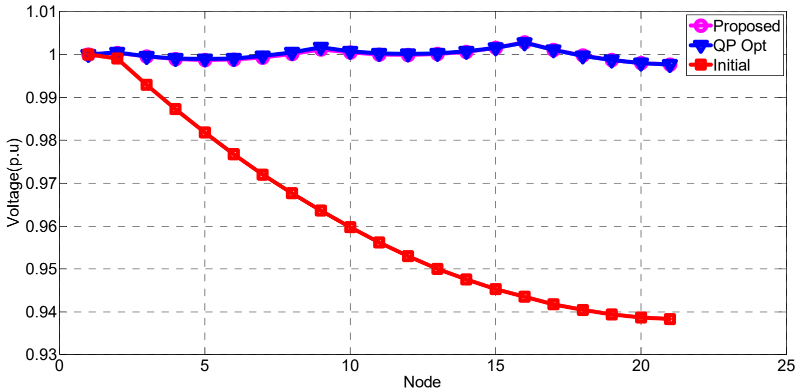

Figure 10. Voltage flattening results for two DGs.

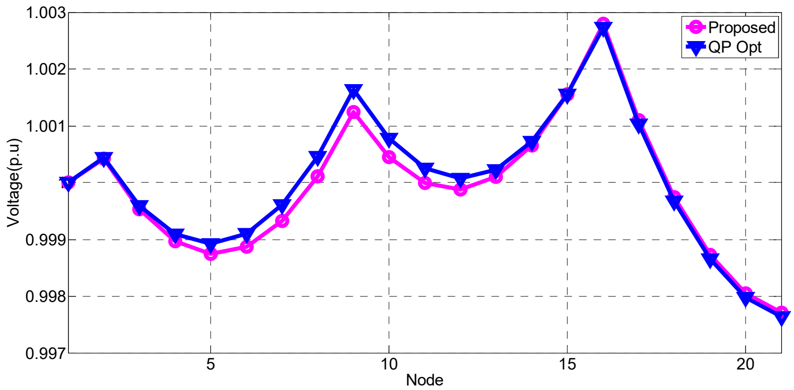

Figure 11. Enlarged comparison of voltage flattening results.

3.2. Tap Control for Control Purpose

The voltage of distribution networks is controlled by raising or lowering the tap position with the control purpose, as shown in Figure 12. Tap control methods to derive the optimal control reference for raising or lowering the tap are proposed in the following.

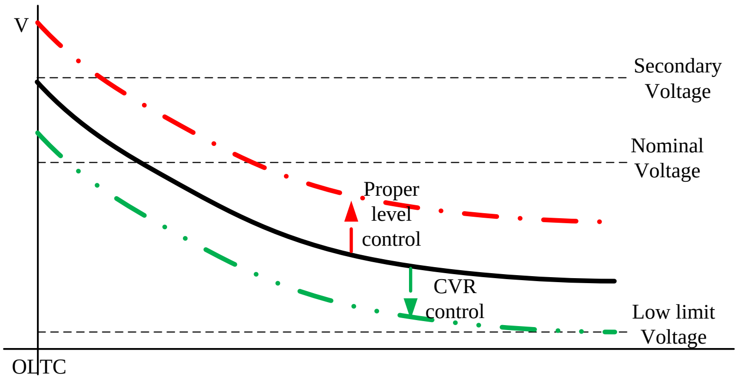

Figure 12. Voltage variation by tap changing device.

3.2.1. Voltage Control for Nominal Voltage

An optimization equation for nominal voltage is shown in Equation (22).

$$\min_{\Delta \mathrm{Tap}} \left| V_{nom} - mean(V_i) \right| \tag{22}$$

$$s.t \quad \begin{array}{c} V_{min}^{limit} \le V_i \le V_{max}^{limit} \\ \mathrm{Tap}_{min,k} - \mathrm{Tap}_k^0 \le \Delta\mathrm{Tap}_k \le \mathrm{Tap}_{max,k} - \mathrm{Tap}_k^0 \end{array}$$

Figure 13 shows the flowchart for determining the tap control reference. The voltage profile reflecting the reactive power of DGs is entered as an input. Whether the input voltage has voltage violation is checked, if there is a violation, tap control to resolve the violation is undertaken. If there is no violation, the average voltage of the voltage profile is calculated as shown in Equation (23) and the voltage variation is obtained.

$$dV = V_{nom} - mean(V_i) \tag{23}$$

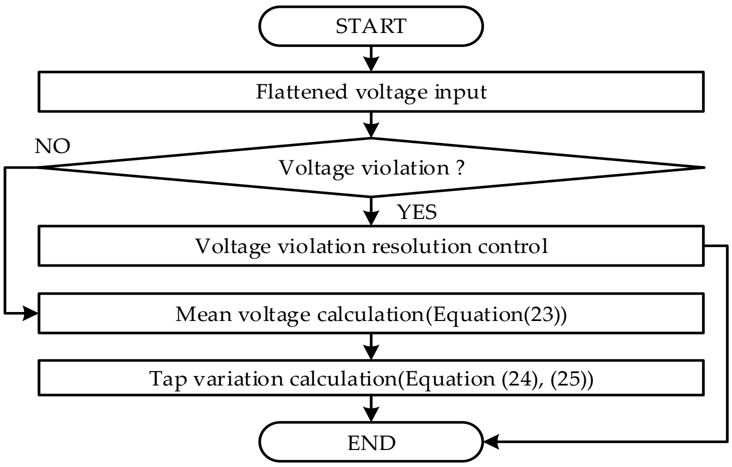

Figure 13. Flowchart of proposed tap control method for nominal voltage.

The calculated voltage variation is converted to the tap variation as shown in Equation (24). The final tap reference is determined to select the tap closest to the target voltage as shown in Equation (25).

$$\Delta\mathrm{Tap}_k = fix\left(\frac{dV}{V_{\mathrm{Tap},k}}\right) \tag{24}$$

$$\begin{array}{l} if \quad dV > 0 \\ if \left(dV - V_{\mathrm{Tap},k} \times \Delta\mathrm{Tap}_k\right) > V_{\mathrm{Tap},k}/2 \\ \qquad \Delta\mathrm{Tap}_k = \Delta\mathrm{Tap}_k + 1 \\ else \\ if \left(V_{\mathrm{Tap},k} \times \Delta\mathrm{Tap}_k - dV\right) > V_{\mathrm{Tap},k}/2 \\ \qquad \Delta\mathrm{Tap}_k = \Delta\mathrm{Tap}_k - 1 \\ end \end{array} \tag{25}$$

3.2.2. Voltage Control for Conservative Voltage Reduction (CVR)

Equation (26) shows an optimization equation for deriving the optimal reference in the case of CVR control. Figure 14 shows a flowchart for determining the tap control reference.

$$\min_{\Delta \mathrm{Tap}} \left| min(V_i) - V_{min}^{limit} \right| \tag{26}$$

$$s.t \quad \begin{array}{c} V_{min}^{limit} \leq V_i \leq V_{max}^{limit} \\ \mathrm{Tap}_{min,k} - \mathrm{Tap}_k^0 \leq \Delta\mathrm{Tap}_k \leq \mathrm{Tap}_{max,k} - \mathrm{Tap}_k^0 \end{array}$$

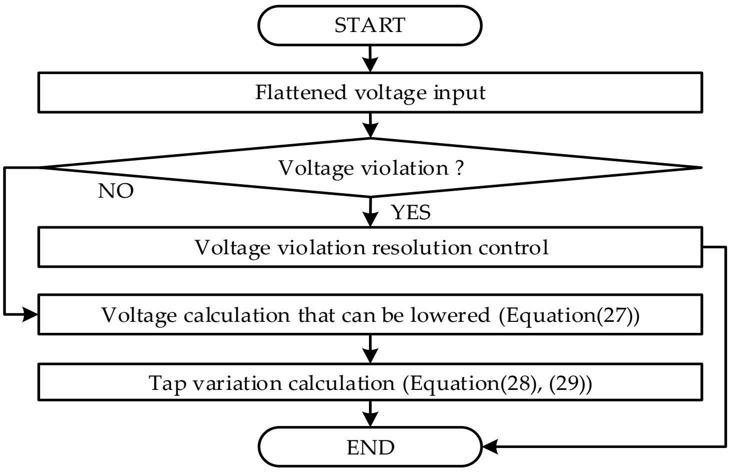

Figure 14. Flowchart for proposed tap control method for CVR.

In the same way as voltage control for nominal voltage, the voltage profile that reflects the reactive power is entered as input. After whether the input voltage has a voltage violation is checked, the voltage deviation is calculated as shown in Equation (27).

$$dV = min(V_i) - V_{min}^{limit} \tag{27}$$

The calculated variation is converted to the tap variation as shown in Equation (28). The final tap reference is determined as shown in Equation (29) in order to select the tap closest to the lower limit voltage.

$$\Delta\mathrm{Tap}_k = fix\left(\frac{dV}{V_{\mathrm{Tap},k}}\right) \tag{28}$$

$$\begin{array}{l} if \quad dV > 0 \\ \ \Delta\mathrm{Tap}_k = \Delta\mathrm{Tap}_k + 1 \\ else \\ \ \Delta\mathrm{Tap}_k = \Delta\mathrm{Tap}_k \\ end \end{array} \tag{29}$$

3.3. Tap Scheduling of Voltage Control Device

In general, the optimal tap position is changed according to the load variation in each time zone. An optimal tap position can maximize the effect of voltage control, but frequent alterations to the tap position can reduce the lifetime of the tap changing device. Therefore, in this paper, a method for reducing the number of tap changes is proposed. After determining the tap position of the voltage control device according to the time zone for the next 24 h, the tap position schedule is then readjusted by PI. First, the optimal tap position for each time zone is derived via the proposed method in this paper using the prediction load and the DG output forecast in each time zone. The PI is calculated using optimal tap position results, as shown by Equation (30).

$$PI = \frac{1}{N}\sum_{i=1}^{N}\left(\left(V_i - V_{\mathrm{Target}}\right)^2\right) \tag{30}$$

After deriving the optimal schedule (green line), the +1 tap schedule (blue line) and −1 tap schedule (red line) for each time zone are derived as shown in Figure 15. In addition, the reactive power for each time zone is again derived in the two tap schedules and PI is also obtained.

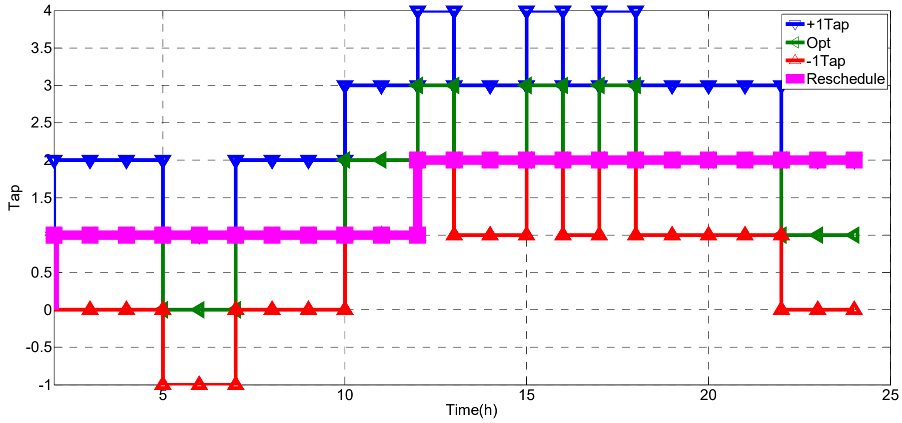

Figure 15. Illustration of tap schedule adjustment of the proposed method.

Without considering the tap changing, it can be confirmed that the tap schedule is readjusted along with the tap position of the smallest PI as shown by the green line in Figure 15. Because there is no weighting due to tap changing, the tap schedule follows the smallest PI. In order to reduce the number of tap changes, the schedule is readjusted according to the PI. The PI for each time zone is shown in Figure 16. To readjust the tap schedule, the tap position of the smallest PI is chosen for each time zone. If the tap position changes, a large weighting is given to this PI. The readjusted result is shown by the thick line (pink line) in Figure 15. If a voltage violation occurs in the voltage control result, the PI is set to a certain large value (0.1).

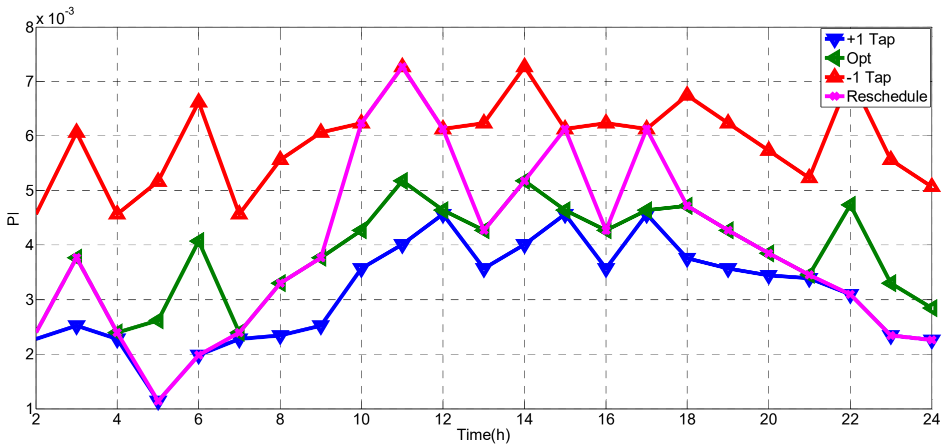

Figure 16. Performance index (PI) of each tap position schedule.

4. Case Studies

4.1. Coordinated Control Simulation

A simulation is conducted using the simple simulation network shown in Figure 17. The voltage operating range of the distribution network is set to ±6% of the nominal voltage. The installed OLTC can control 0.0125 (p.u.) per tap with a control range of ±8 taps. The total load is 10 MVA (0.9PF), simulated as a network with uniformly distributed load (UDL). The distribution line is 20 km with ACSR 160^2. The DG output is 0.5 MW and the reactive power constraint range is set from −2 MVar to 2 MVar. The output range of the DG is shown in Table 1.

Table 1. Parameters of DGs for case 1.

Installed Bus	Type	Active Power	Maximum Reactive Power	Minimum Reactive Power
9	DG1	0.5 MW	2.0 MVar	−2.0 MVar
16	DG2	0.5 MW	2.0 MVar	−2.0 MVar

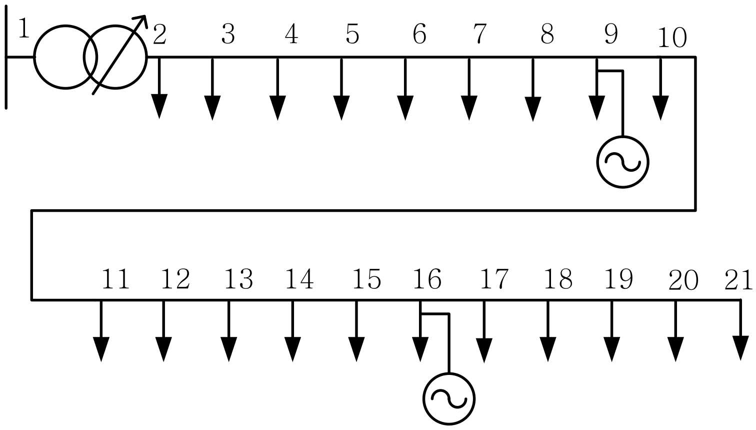

Figure 17. Single diagram of distribution network for case 1.

There are two types of simulation result. The first is the control results for voltage control of nominal voltage, these are shown in Table 2 and Figure 18. The proposed schemes are compared with the results obtained via optimization of QP in Figure 18 [21]. "Optimal" is the result of the optimization method and "Proposed" is the result obtained using the scheme proposed in this paper. The tap position is the same as the optimization result, but the reactive power control reference is different to the optimization result. However, the voltage results from the proposed scheme are almost the same as the optimization results.

Table 2. Simulation results of the tap position and reactive power for nominal voltage in case 1.

Control Component	Control Reference	
	Optimal	Proposed
OLTC	2 tap	2 tap
DG 1	2.0 MVar	1.2117 MVar
DG 2	2.0 MVar	2.0 MVar

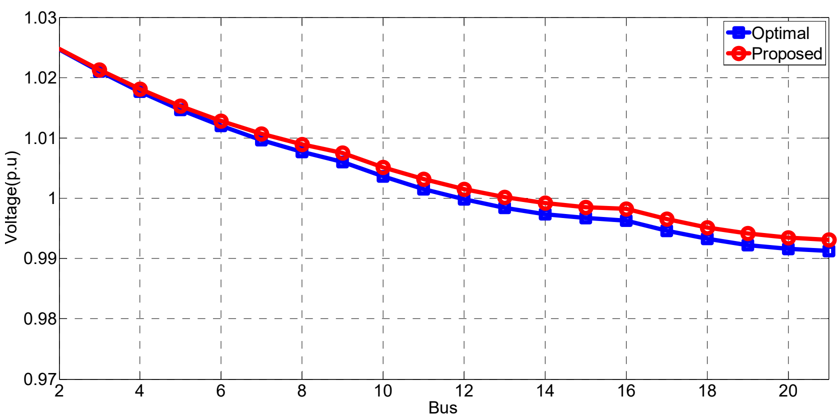

Figure 18. Comparison of results for nominal voltage in case 1.

The second kind, displayed in Table 3 and Figure 19, show the voltage control results for voltage control of the CVR. The tap positions of the OLTC are the same for both methods, but the reactive power result of the DG is different. However, voltage control results are almost the same. The two DG control reference results are different because the reactive power of the two DG interacts to affect the voltage.

Table 3. Simulation results of the tap position and reactive power for CVR in case 1.

Control Component	Control Reference	
	Optimal	**Proposed**
OLTC	−2 tap	−2 tap
DG 1	0.9852 MVar	1.38 MVar
DG 2	2.0 MVar	1.70 MVar

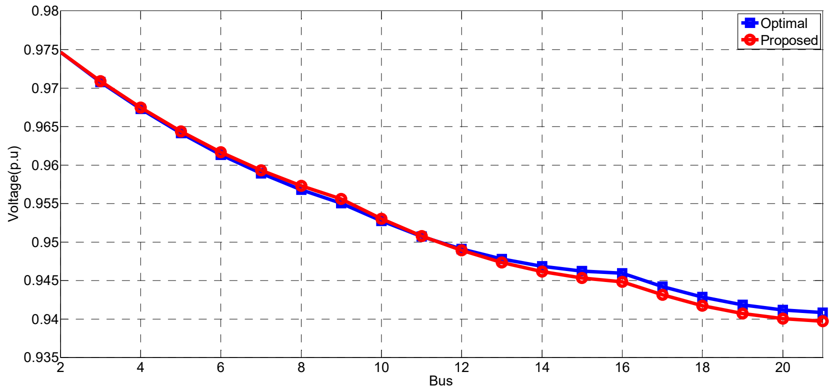

Figure 19. Comparison of results for CVR in case 1.

Figure 20 shows the second simulation network with a different network topology but under the same conditions as the simulation 1 network. The condition of DGs is shown in Table 4.

Table 4. Parameters of DGs for case 2.

Installed Bus	Type	Active Power	Maximum Reactive Power	Minimum Reactive Power
16	DG 1	0.5 MW	2.0 MVar	−2.0 MVar
21	DG 2	0.5 MW	2.0 MVar	−2.0 MVar

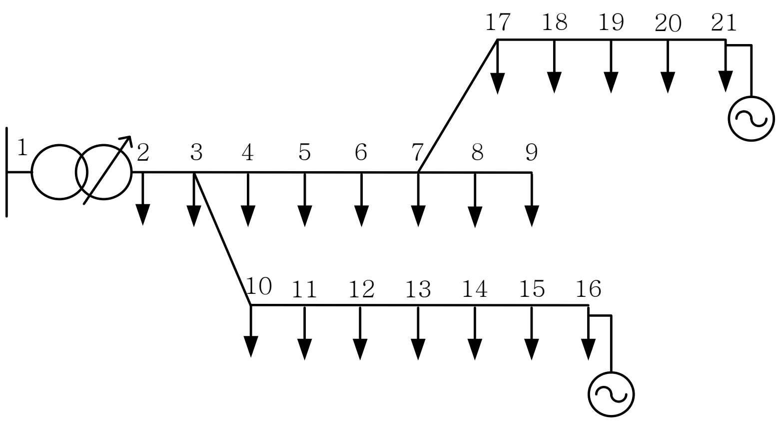

Figure 20. Single diagram of distribution network of case 2.

Table 5 and Figure 21 show the control results of voltage control for nominal voltage. The tap position result of the proposed method is the same as the optimization result and the reactive power control reference results are the same as the optimization, as we can see from Table 5. As shown in Figure 21, the difference between the proposed scheme results and the optimization results is caused by the accumulated errors through iterative calculations using simplified equations.

Table 5. Simulation results of the tap position and reactive power for nominal voltage in case 2.

Control Component	**Reference**	
	Optimal	**Proposed**
OLTC	0 tap	0 tap
DG 1	2.0 MVar	2.0 MVar
DG 2	2.0 MVar	2.0 MVar

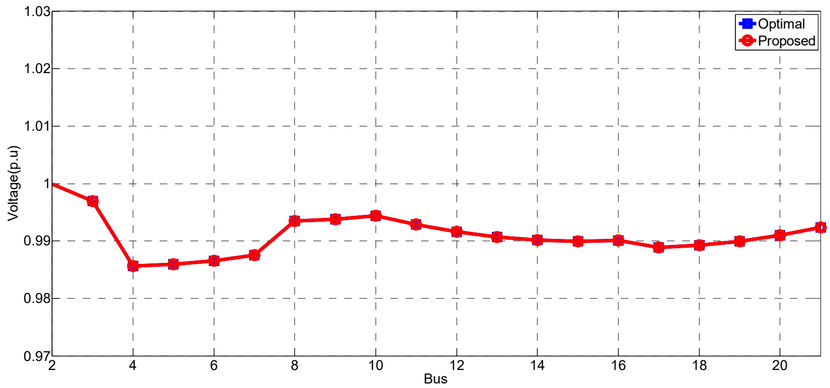

Figure 21. Comparison of optimal and proposed voltage profile for nominal voltage in case 2.

Table 6 and Figure 22 show the voltage control results of voltage control for CVR. The tap position result of the OLTC is the same as the optimization result, and the reactive power of the DG shows different results. However, the voltage profile shows almost identical results.

Table 6. Simulation results of the tap position and reactive power for CVR in case 2.

Control Component	**Reference**	
	Optimal	**Proposed**
OLTC	−4 tap	−4 tap
DG 1	1.6302 MVar	1.57 MVar
DG 2	2.0 MVar	1.99 MVar

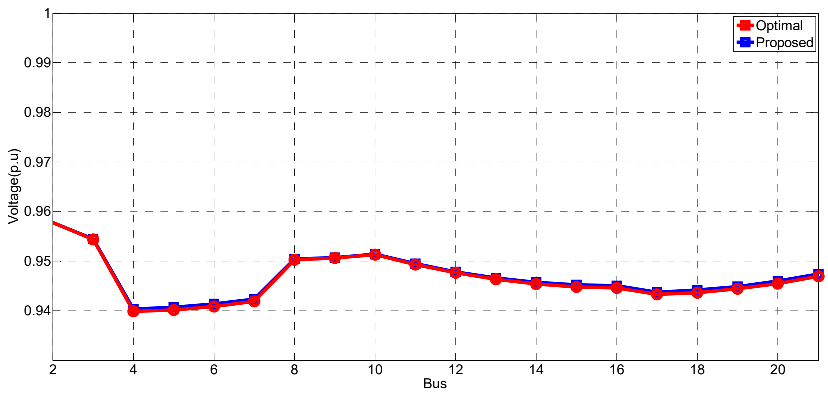

Figure 22. Comparison of optimal and proposed voltage profile for CVR in case 2.

4.2. Simulation of Tap Scheduling

The simulation networks are used as shown in Figures 17 and 20. The load prediction schedule is used as the input load for the tap schedule shown in Figure 23. Hourly variations ranged from a minimum of 2 MVA to a maximum of 10 MVA.

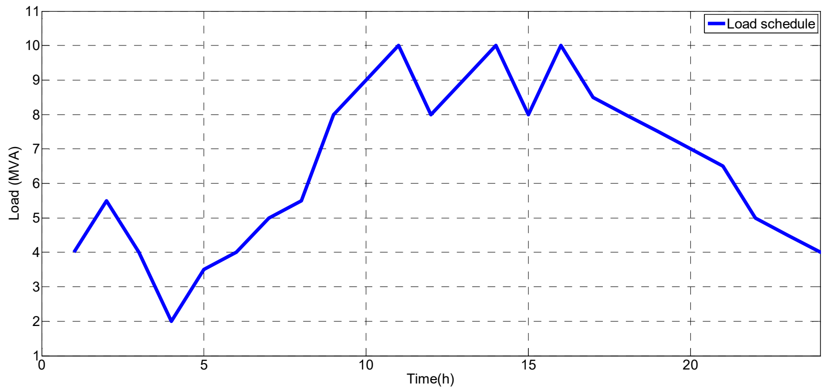

Figure 23. Load prediction schedule for simulation.

4.2.1. Tap Scheduling Results for Case 1

The "Opt" graph in Figure 15 is determined by the voltage control for nominal voltage. Based on the optimal tap position, the result of "+1 tap" and "−1 tap" can also be derived. The reactive power result is obtained again at each tap position. The PI weight for tap change is set to 0.1, which is significantly larger than the PI at each tap position. Finally, the schedule readjustment results confirm that 1 tap change occurs in a full schedule. In other words, with our scheme 10 tap changes are reduced to 1 tap change. The hourly PI at each tap position is shown in Figure 16. The reactive power reference is calculated from the tap schedule as shown in Figure 24. The maximum reactive power output of DG 1 is shown in Figure 24 due to its location in the upper area of the distribution network. The results from the adjustment of the tap schedule are summarized in Table 7.

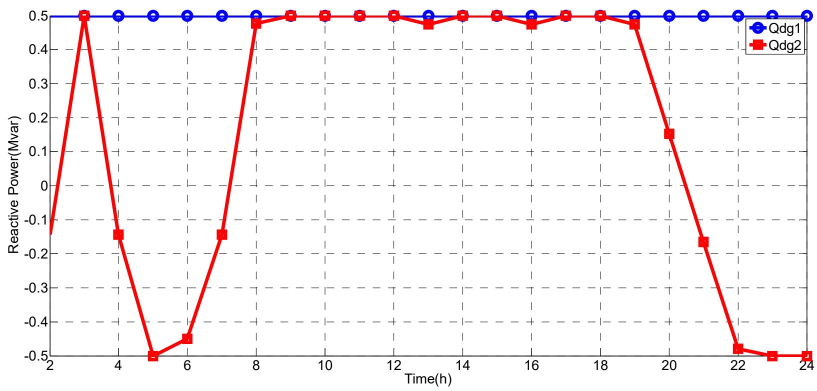

Figure 24. Reactive power reference of case 1 for nominal voltage.

Table 7. Comparison of the number of tap operations, PI total, sum of reactive power with/without proposed schedule method of case 1 for nominal voltage.

Category	Before Readjustment	After Readjustment
The number of Tap Operations	10 times	1 time
PI Total	0.503	0.671
Sum of Reactive Power	21.0748 MVarh	21.0748 MVarh

The tap schedule obtained for CVR control is shown in Figure 25. The PI result from each tap position is shown in Figure 26. Because voltage violations occur when the CVR control drops a tap (−1 Tap), the "−1 Tap" graph shows a constant value of 0.1.

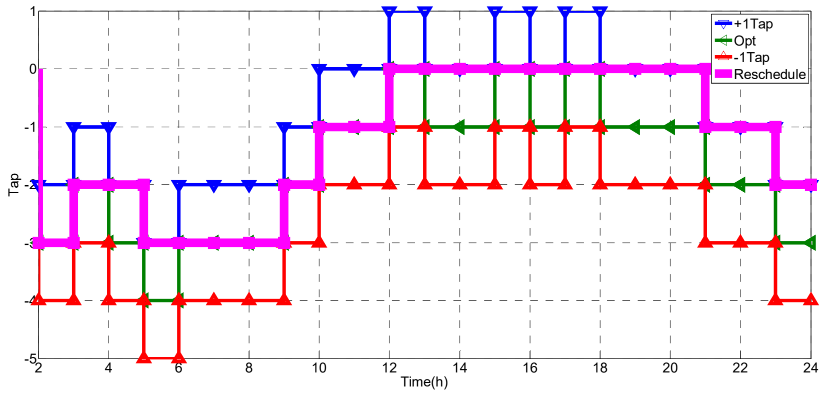

Figure 25. Schedule adjustment by the proposed scheme of case 1 for CVR.

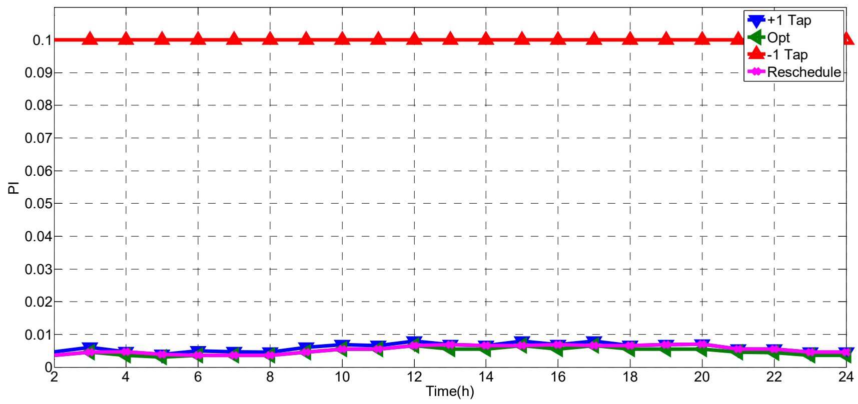

Figure 26. PI of case 1 for CVR.

The reactive power control reference from the readjusted tap schedule is shown in Figure 27. It can be clearly seen that the output of reactive power for DG 1 and DG 2 follows a similar pattern. The results from the CVR control are summarized in Table 8.

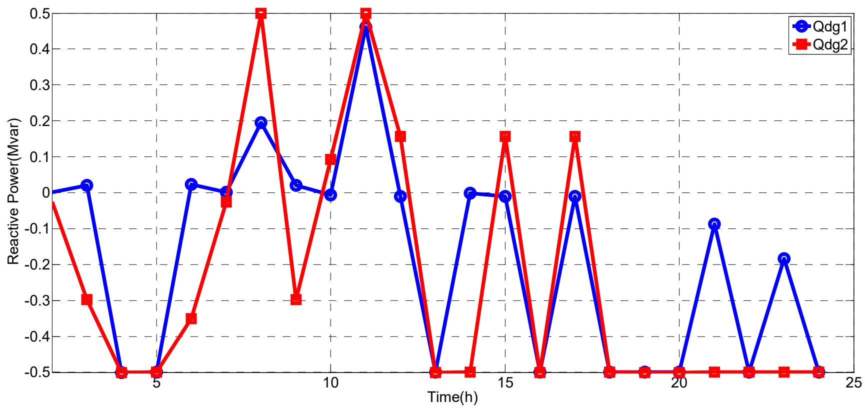

Figure 27. Reactive power reference of case 1 for CVR.

Table 8. Comparison of the number of tap operations, PI total, sum of reactive power with/without proposed method of case 1 for CVR.

Category	Before Readjustment	After Readjustment
The number of Tap Operations	14 times	7 times
PI Total	0.1100	0.1936
Sum of Reactive Power	14.0943 MVarh	13.0943 MVarh

4.2.2. Tap Scheduling Results for Case 2

To verify the performance of the algorithms, the same simulation was performed in case 2. The tap schedule results of voltage control for nominal voltage with the case 2 network are shown in Table 9. The number of tap operations are reduced from 2 times to 0 time. Although the PI total is increased from 0.0203 to 0.0397, the sum of reactive power is not changed.

Table 9. Comparison of the number of tap operations, PI total, sum of reactive power with/without the proposed method of case 2 for nominal voltage.

Category	Before Readjustment	After Readjustment
The number of tap operations	2 times	0 times
PI Total	0.0203	0.0397
Sum of reactive power	22.9359 MVarh	22.9359 MVarh

The tap rescheduling, PI results and reactive power reference for CVR with the case 2 network are shown in Table 10. Through this simulation, it is confirmed that the proposed scheme can reduce the number of tap operations for OLTC without requiring more reactive power of DGs.

Table 10. Comparison of the number of tap operations, PI total, sum of reactive power with/without proposed method of case 2 for CVR.

Category	Before Readjustment	After Readjustment
The number of tap operations	4 times	1 time
PI Total	0.0784	0.0887
Sum of reactive power	18.3809 MVarh	18.3809 MVarh

4.3. Discusion of Simulations

In order to verify the validity of the proposed method, two case studies are simulated. In this paper, the coordinated control results are compared with results of the QP method to verify the accuracy of the proposed method. For the accuracy of voltage estimation, it is confirmed that differences between voltage estimation values of the proposed method and that of the optimization method have an error range of 0.001(p.u) or less. It has been proved that the optimal solution of the QP method is close to the global optimal solution [21]. Thus, the accuracy of the proposed methods using simplified linear voltage equations with heuristic coordination algorithms is very reasonable for practical applications.

The proposed tap rescheduling schemes are evaluated through the simulations. Although the PI of the proposed method increased, it is confirmed that the number of tap changing operations decrease dramatically. Moreover, the sum of the reactive power requirements of DGs has become the same or less. Despite the disadvantage of increasing PI, the proposed method may have advantages due to a reduction in the number of tap changing operations. Because frequent tap change operations may reduce the lifetime of tap changing device, utilities generally limit the tap changing operations of the OLTC transformer. Thus, the introduction of the proposed tap scheduling algorithms in practical power distribution system can delay the replacement of the tap changing device.

Since the proposed heuristic method adapts a simple iterative process using a linearized voltage estimation formula, it can be easy to convert to program code. Thus, the proposed method does not require a lot of computational resource, so it can even be installed in a small sized micro-controller instead of large sized management system such as a DMS (distribution management system). Therefore, it is possible to reduce the total cost of the voltage control function of the distribution system. As a result, the proposed method is very useful for the practical distribution systems due to the simplified calculation process, robust performance, and practical consideration for limitation of tap changing operations.

For future work, a real-time scheduling technique will be studied by introducing the control method for an imperfect dynamic system [22]. The scheduling method that considers error by comparing real-time information and prediction information will be proposed. In addition, the proposed method will be verified for field applications through real time-based digital simulation.

5. Conclusions

The voltage of a given distribution network can be regulated by conventional voltage control methods. However, as the interconnection of DGs increases, we see increases in voltage problems that result in poor quality. In order to solve these problems, various studies for advanced control algorithms have been undertaken. Previously suggested control methods have required complex computation because these methods use non-linear equations for accurate node voltage calculation. In this paper, to reduce this computational burden, a simplified linear voltage equation is proposed. A simplified linear equation according to variation of tap position and reactive power was presented.

A heuristic-based coordinated voltage control scheme using two-stage control schemes was proposed. In the first stage, voltage profiles of distribution networks are flattened using the reactive power of DGs. The voltage profile is flattened through an iterative operation. In the second stage, the flattened voltage profiles are lowered or raised by controlling the tap position. In the case of voltage control for CVR, the voltage of the distribution networks is controlled to be as close as possible to the operating lower voltage limit. In the case of voltage control for nominal voltage, the average voltage of the distribution networks is controlled to be as close as possible to the nominal voltage. Through simulations, it was shown that the proposed scheme yields similar results to the result from a computationally complex, full optimization method. Therefore, the accuracy of the proposed method is very reasonable for practical applications.

In addition, a method for readjusting the tap schedule is proposed to reduce the number of tap changes. The optimal control reference for each time zone is calculated by the proposed scheme. The tap schedule was readjusted to minimize tap changes by assigning PI weighting to tap changes. It is confirmed that the number of tap changes is reduced using the proposed method without using an additional control resource. The proposed scheme can be expected to reduce the cost of equipment investment.

It is expected that the proposed scheme can be applied to actual on-side cases in the near future. The actual effects of the proposed scheme can be analyzed based on on-site research.

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