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Efficient Day-Ahead Scheduling Voltage Control Scheme of ULTC and Var of Distributed Generation in Distribution System

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ABSTRACT Most conventional voltage control schemes in distribution systems are controlled through the tap change of the transformer. However, as large-capacity distributed generations (DGs) are connected to the distribution system, this leads to a new voltage problem. In this paper, we propose a day-ahead scheduling voltage control scheme of under load tap changer (ULTC) and reactive power of DGs in distribution system. The proposed control scheme improves both voltage profile and quality, and it determines the reactive power reference value for the real power output of DGs as well as the sending end reference voltage of the distribution substation. To account for prediction error, the reactive power reference values of DGs are determined for a real power output section. This can mitigate the uncertainty problem and the prediction error problem of DGs with intermittent characteristics. The proposed control scheme is also a very practical control scheme because it can be applied to the existing control systems of voltage control devices. The proposed control scheme is formulated as a quadratic programming (QP) problem, and it is compared with the conventional voltage control scheme in test 32-bus and modified IEEE 69-bus radial distribution systems; the control effect and results verify the effectiveness of the proposed control scheme.

INDEX TERMS Distribution system, distributed generation, under load tap changer, quadratic programming, line drop compensation, voltage control.

NOMENCLATURE

$V_{se}(t)$	Sending end voltage at t-time.
$V_{ser}(t)$	Sending end reference voltage at t -time.
V_{ce}	Compensating voltage.
Z_{eq}	Compensating impedance.
$V_{tap,k}(t)$	MTR's secondary voltage when a tap is located at the k-th position at t-time.
$I(t)$	Load current at t-time.
$Z_{MTR,k}(t)$	MTR's impedance when a tap is located at the k-th position at t-time.
V_i^0	Measure or power flow result voltage at i-th bus (Without voltage control).
ΔV_{ref}	Reference voltage fluctuation of ULTC.
V_i^{ULTC}	State estimate voltage for control of ULTC at i-th bus.
V_S	Sending voltage.
V_R	Receiving voltage.
P_{Load}	Active power of load.
Q_{Load}	Reactive power of load.
P_{DG}	Active power of DG.
Q_{DG}	Reactive power of DG.
ΔV_{DG}	Voltage fluctuation for reactive power of DG.
V_i^{DG}	State estimate voltage for reactive power control of DG at k-th bus.
V_{ref}^t	Reference voltage of ULTC at t-time.
$\Delta Q_{DG,k}^t$	Reference reactive power of DG at t-time to k-th.
V_{nom}	Nominal voltage.
$S_{rated,k}$	Rated capacity of inverter k-th DG.

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I. INTRODUCTION

Globally, renewable energy generation such as photovoltaic power generation and wind power generation are attracting increasing attention in response to the depletion of fossil fuels and climate change, leading to large-scale connection in the system [1]. In recent years, there has been increasing development of DG in the distribution system, which is expected to continue in the future. However, there are technical limitations in terms of the operation of the conventional distribution system. Certain technical problems that occur when DG is connected to the distribution system cause various problems, such as violation of the regulated voltage, deterioration in power quality, and deterioration in the stability of system operation. In particular, due to the connection of large-capacity DG, reverse power flow may occur, which can lead to a voltage increase problem [2]. In addition, the voltage fluctuates frequently in the distribution system due to the intermittent nature of DG's weather effects and resource variability. These characteristics make it difficult for conventional voltage control devices such as the ULTC, step voltage regulator (SVR), and capacitor bank to efficiently control the voltage [3], [4].

Recently, the distribution system maintained the voltage within the specified range by utilizing the conventional voltage control device for the voltage problem caused by the bi-directional current due to the DG. To solve this problem, studies have examined the voltage control strategy of the conventional voltage control device considering DG. In addition, according to IEEE Std. 1547, a reactive power control requirement for voltage recovery at the Point of Common Coupling (PCC) has been proposed [5]. Further, related research includes a tap control method that involves calculating the new Line Drop Compensator (LDC) parameter of ULTC in consideration of the load fluctuation and DG in the distribution system [6]–[8]; a method for controlling the voltage of the distribution system within the specified range through reactive power control of DG [9], [10]; coordinated control methods through optimization using conventional voltage control devices such as ULTC, SVR, capacitor banks, and reactive power control of DG so that the voltage profile is optimally operated according to the purpose [11]–[13]; and a schedule-based ULTC and DG reactive power coordinated control scheme using the predicted value of DG [14]–[18].

The conventional voltage scheme of ULTC is controlled by applying the LDC method. In the distribution system connected with large-capacity DG, the current at the center of load fluctuates severely due to the intermittent DG. Therefore, it is difficult to apply the conventional LDC method. To solve this problem, a multi-line drop compensation (MLDC) method was proposed in [6] to determine the optimal tap position of ULTC based on current measurements in multiple feeders. In addition, a new LDC parameter calculation method considering the output of DG in a three-phase unbalanced distribution system is proposed in [7]. This method has been proven to be effective compared to the conventional method that involves calculating the new LDC parameter based on the current estimation in the distribution system connected with the large-capacity DG in [8]. However, if only ULTC is considered for voltage regulation devices, the control effect is inferior and tap control operation occurs frequently due to the intermittent output characteristic of DG. Therefore, a new voltage control scheme should be proposed in consideration of other voltage control devices.

Most of the voltage control in the distribution system uses the inverter of DG to stabilize the voltage through reactive power control. For local-based voltage control, the optimal control point of DG was proposed to improve the voltage profile of the distribution system [9]. Using this system, the voltage profile was improved compared to the conventional control method, and the results were close to the optimum. In addition, a heuristic-based algorithm that satisfies multiple objective functions, such as minimizing system losses and voltage fluctuations locally, was proposed in [10]. In [11], effective voltage control was performed through the reactive power control of the DG, but it is difficult to apply it to an actual system because that study did not consider conventional voltage control devices. For application to an actual system, a coordinated plan between ULTC and STATCOM based on ANN considering conventional voltage control device was proposed. This has the purpose of minimizing the tap change of the transformer while keeping the voltage of the substation within the allowable range, and this allows for application to the tap mechanism of the conventional voltage control scheme of ULTC. In addition, in [12], reactive power control was proposed through coordinated control between DG and capacitor bank using RTU. Then, an algorithm was proposed to inject reactive power into the grid to estimate the voltage profile and minimize the loss of the grid. In [13], proposed coordinated control of DG, capacitor bank, and ULTC applying dynamic programming. The proposed method reduces the loss of the distribution system and the number of capacitor switches while keeping the system within the allowable range. In addition, in [14], a data structure algorithm is proposed that splits the distribution system into layered zones using a meta-heuristic optimizer. Most of the existing studies are related to voltage control based on real-time measurement, and assuming that the voltage of all nodes of the system are measured accurately, the control effect is the best control scheme. However, the performance of the real-time control scheme substantially affects the performance of the measuring unit, thus requiring high-performance measuring units, which leads to economic problems. This problem can be solved by using the state estimation algorithm, but it also contains errors and requires a lot of communication between control devices.

The problem of Volt/Var optimization (VVO) is, in some ways, similar to the unit commitment problem in a transmission system; therefore, to minimize the total generation cost, the status of each unit is to be determined during a certain period of time [15]. In [16], a scheduling technique for minimizing the switching operation of the capacitor bank is proposed with the goal of improving the voltage profile and minimizing the power loss in consideration of the prediction error of the DG. Meanwhile, in [17], a schedule-based coordinated control algorithm is proposed for the inverter reactive power of PV, the tap position of ULTC, and the switch operation of the capacitor bank, which aims to minimize both voltage deviation and power loss. In [18], a proposed coordinated model involving the stochastic programming technique considers the minimization of the energy and reactive power costs of DGs along with the upstream grid. Most of these studies attempt to minimize the voltage deviation and the power loss, while also reducing the number of control times of conventional voltage regulation equipment and considering economic problems in distribution systems [19]. In addition, [20] proposes an optimal voltage control scheme for distribution systems that considers the number of taps for transformers as well as the active power curtailment of PV. Further, many studies deal with the nonlinear optimization problem (NLP), and they attempt to solve this problem through various optimization techniques such as using genetic algorithms, mixed integer NLP, fuzzy algorithm, etc. [21]–[24]. Most studies related to VVO have been formulated as optimization problems to satisfy various objectives such as economic, loss, and operation problems using the predicted profile of load and DGs, and the solutions are derived using various optimization methods. In addition, an accurate solution that satisfies the power flow of a distribution system has been derived using such methods. However, these schemes require complex calculations, which puts the burden of the calculations on the control system, and they make it difficult to quickly respond to real-time prediction errors. They are also difficult to apply in practice in the current distribution system that adheres to the conventional control method.

In this paper, we propose a day-ahead scheduling voltage control scheme for ULTC and Var of DGs that can be practically applied in distribution systems. The status of each control unit is to be determined a day ahead while accounting for the predicted loads and DGs. The objective of the proposed control scheme is to improve both voltage profile and quality. Most studies related to voltage control have considered power losses, but the distribution system has a short line distance, which causes small losses, and the difference in losses is insignificant; therefore, this paper does not consider power losses. In addition, existing studies utilize the ZIP model to consider accurate load modeling, but it is very difficult to make an accurate estimation using this model due to the variability, complexity, and time variability of the loads [25], [26]. Therefore, in this paper, an algorithm was designed using simplified analysis, and this algorithm was shown to derive a solution close to the optimal solution.

The strategy of this paper is illustrated in Fig 1. To apply the practical distribution system, the voltage on the secondary side of the substation is determined for ULTC control, which adheres to the conventional method. In addition, the DGs segment the real power output sections, and a control strategy is suggested for each section. The DG output is divided into a high section and a low section to determine the reactive power set point, and this control method prevents frequent control. In addition, individual strategies for the output range can mitigate some prediction errors. The proposed control scheme is modeled through a QP problem. The main innovative contributions of this paper can be summarized as follows:

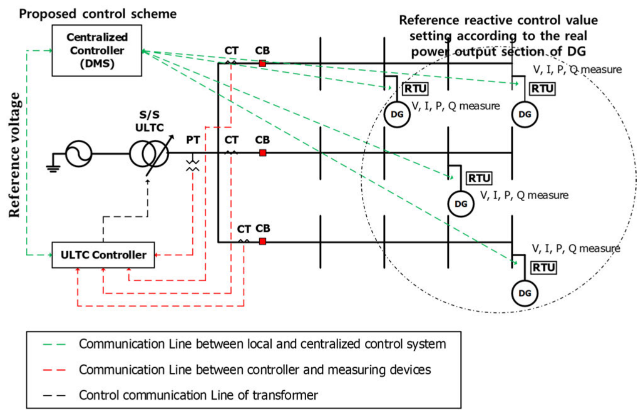

FIGURE 1. The proposed control scheme strategy.

1) the scheme can be applied practically in a distribution system that adheres to the conventional control method, thus improving the voltage profile and quality
2) the scheme can determine the reference secondary voltage of a substation during a certain period of time
3) the scheme can determine the reactive power control set point according to the real power output section of DGs during a certain period of time

The paper is organized as follows. Section II outlines the conventional voltage control of ULTC. Section III details the proposed control scheme. The simulation results are discussed in Section IV, and finally conclusions are offered in Section V.

II. CONVENTIONAL VOLTAGE CONTROL OF ULTC

The voltage control of the distribution system typically involves controlling the voltage by adjusting the transformer tap of the substation. The tap control according to the control block diagram and time delay is shown in Figs 2 and 3. First, the voltage is measured on the secondary side of the primary substation, and the current flowing through each feeder is measured as well. Then, the compensation voltage is calculated using the LDC method. Then, control is performed when the difference between the reference voltage and the compensation voltage falls outside the dead band during the delay time compared to the reference voltage. The conventional LDC method of ULTC measures the sending end voltage and current of the substation to control the voltage at the center of the load. The equations used to calculate the sending end reference voltage and the sending voltage of the conventional LDC method are given as (1)-(2), respectively, and the tap of the transformer is adjusted using the result derived in [6].

$$V_{ser}(t) = V_{ce} + Z_{eq} \times I(t) \quad (1)$$

$$V_{se}(t) = V_{tap,k}(t) + Z_{MTR,k}(t) \times I(t) \quad (2)$$

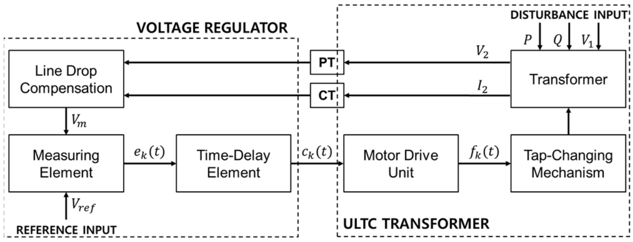

FIGURE 2. Conventional control block diagram of ULTC [6].

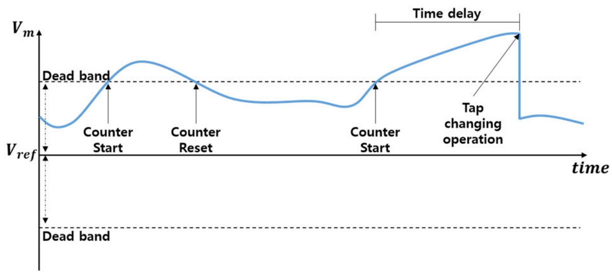

FIGURE 3. Conventional ULTC of control scheme [6].

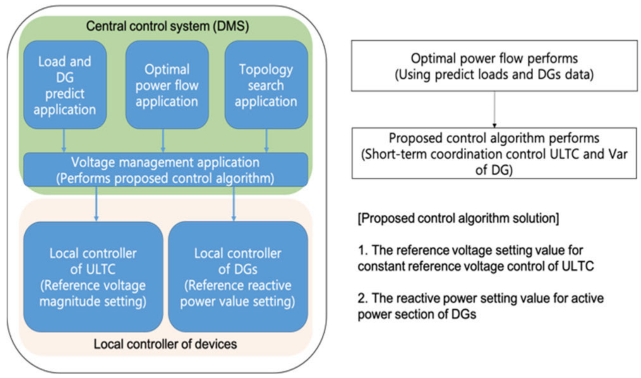

FIGURE 4. Structure of proposed control scheme.

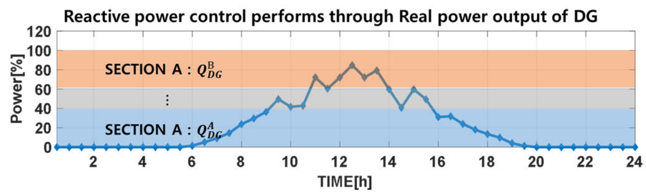

FIGURE 5. Reactive power control strategy of DG.

The compensation voltage most often has a value near the average voltage between the minimum and the secondary voltage in the system, and the compensation impedance most often has a value near the impedance ratio of the line. However, due to the intermittent output characteristics of the DG, the average voltage fluctuates frequently, so the LDC parameter must be recalculated often while considering the DG. Therefore, we need a control scheme that considers the uncertainty of DG. The proposed control scheme determine the reference sending end voltage of primary substation using the loads and DGs forecast data.

III. DAY-AHEAD SCHEDULING CONTROL SCHEME

This section describe detail proposed control scheme composed to the objective function, constraints, and the optimization algorithm.

A. CONCEPT

The conventional voltage control that is applied using real-time measure power flow information lacks coordination among different voltage control devices. By contrast, this paper proposed scheduling control scheme and determine a pre-set control value for the local control devices. We used inverters of DGs and a ULTC tap changer as voltage regulation facilities. This was done because other existing voltage regulation facilities were not considered, and the voltage problem can be sufficiently solved by using the DG's inverter. The framework structure of the proposed control scheme is illustrated in Fig. 4.

In a typical distribution system with DGs, the DGs are managed using each RTU. The RTU applied in this paper includes a function through which it can receive the reactive power setting value from the centralized control system and command the inverter. The proposed control algorithm is included in the centralized control system, and it determines the setting value of each control device. Our purpose is to improve both voltage profile and quality for practical usage in a distribution system with DGs. However, the predicted profile of the hourly loads and DGs contains errors. Specifically, the predicted profile of DGs contains many errors due to resource variability and climate impacts. Therefore, we need to consider prediction error, so we suggest the following strategy, as depicted in Fig 5:

1) we divided the real power output of DG to determine the reference reactive power control value for each section
2) we determined the reactive power value according to the relevant section of the measured real power output of the DG

As mentioned earlier, we determine the reference reactive power control value according to the active power output section of DG. The sections are determined by the distribution system operator (DSO), and these control strategies can successfully mitigate prediction error.

B. OBJECTIVE FUNCTION

The objective function for improved voltage quality and profile is expressed as shown in (3), which was taken from [27], [28]. The voltage of the buses in the distribution system aims to operate close to the objective voltage through reference voltage control of secondary for substation and reactive power control DGs. The secondary reference voltage control in the substation can be used to achieve our purpose

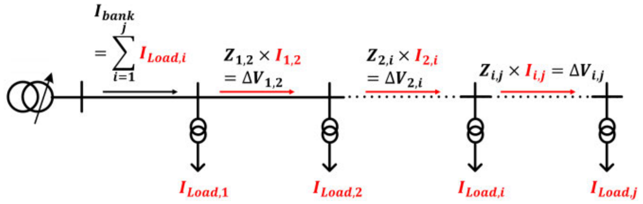

FIGURE 6. Voltage deviation between each bus in distribution system.

regardless of the primary voltage in the substation.

$$\text{Minimize}\, f(\Delta V_{ref}^t, \Delta Q_{DG,k}^t) = \sum_{t=1}^{NTIME} \sum_{i=1}^{Nbus} (V_i^t - V_{obj})^2 \qquad (3)$$

where *NTIME* is the total amount of time required for the voltage control planning, and *Nbus* is the total number of buses.

C. MODELING VOLTAGE CONTROL OF ULTC AND VAR

In this paper, voltage control uses the tap changer of the ULTC and the reactive power control of the DGs, which is an applied linear model. Conventional voltage control most often applies a nonlinear equation using a power flow equation, but this problem is complex. Complex calculations require a lot of system memory and storage capacity. The simplified linear model is easy to apply to the system as it has the advantage of a faster calculation time and less error than the nonlinear equation in [29].

1) MODEL FOR ULTC

The secondary voltage of the substation is determined by the change in the position of the tap and the magnitude of the current flowing through the main transformer, and this determines the voltage level of the buses in the sub-area. Considering that the load is treated as a current source in the distribution system, the voltage difference between each bus is shown in Fig 6. Assuming that the load is constant, the voltage deviation of each bus is also constant regardless of the voltage fluctuation on the secondary voltage of the substation. With this characteristic, the voltage of the buses in the area can be expressed as

$$V_i^{ULTC} = V_i^0 + \times \Delta V_{ref} \qquad (4)$$

2) MODEL FOR REACTIVE POWER CONTROL

The reactive power control has a characteristic that the voltage varies according to the impedance of the line by injecting or absorbing reactive power into the line. Fig 7 shows a simplified 2-bus distribution system with DG, and the general voltage fluctuation of the distribution system is expressed as

$$|V_S - V_R| = \Delta V \cong \frac{R(P_{Load} - P_{DG}) + X(Q_{Load} \pm Q_{DG})}{V_R} \qquad (5)$$

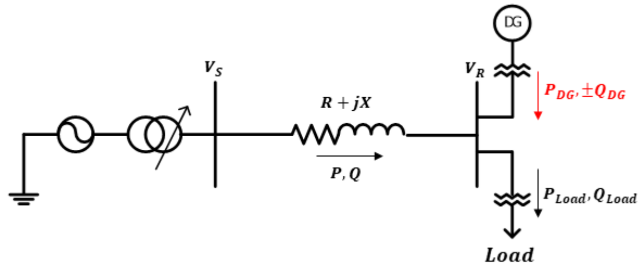

FIGURE 7. Simplified 2-bus distribution system.

If the reactive power output of DG is treated as a variable from (4), it can be expressed as

$$f(\Delta Q_{DG}) = \frac{R(P_{Load} - P_{DG}) + XQ_{Load}}{V_R} \pm \frac{X}{V_R}\Delta Q_{DG} \qquad (6)$$

Which can be used to determine the voltage deviation due to the reactive power control of DG.

Assuming that the load and the output of the DG are constant, the magnitude of the voltage deviation due to the reactive power control of the DG can be expressed as

$$\Delta V_{DG} = \left[\frac{\partial V}{\partial Q_{DG}}\right] \times \Delta Q_{DG} \qquad (7)$$

The voltage due to the active and reactive power flowing through the current line can be replaced by the current voltage level of each bus. Therefore, each bus after the reactive power control of the DGs can be expressed as

$$V_i^{DG} = V_i^0 + \left[\frac{\partial V_i}{\partial Q_{DG,k}}\right] \times \Delta Q_{DG,k} \qquad (8)$$

3) COORDINATED VOLTAGE CONTROL MODEL

By treating the load and DG as a current source model, the principle of superposition can be applied in the manner shown in Fig 8 [30], and the voltage of each bus can be estimated after the coordinated control ULTC and reactive power of DGs in the following as

$$V_i = V_i^0 + \Delta V_{ref} + \sum_{k=1}^{NDG} \left[\frac{\partial V_i}{\partial Q_{DG,k}}\right] \times \Delta Q_{DG,k} \qquad (9)$$

We have the coordinated control model ULTC and the reactive power of DG through a simplified linear equation.

D. CONSTRAINTS FUNCTION

1) BUS VOLTAGE CONSTRAINTS

The voltage magnitude of the buses constraints is expressed as

$$V_{\min} \leq V_i^t \leq V_{\max}$$
$$\forall i \in \{1, 2, \ldots, Nbus\}, \quad \forall t \in \{1, 2, \ldots, NTIME\} \qquad (10)$$

where V_{min} and V_{max} are the lower and upper allowable bounds of voltage, respectively.

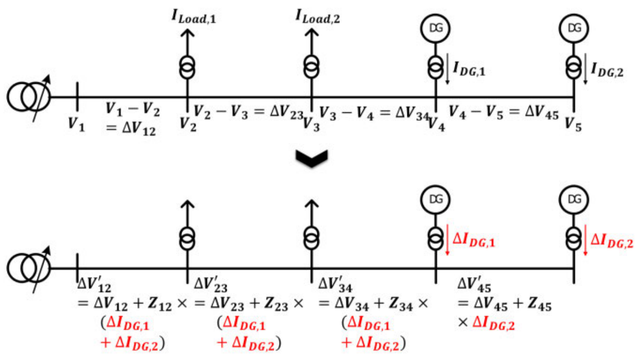

FIGURE 8. Voltage deviation between each bus in distribution system.

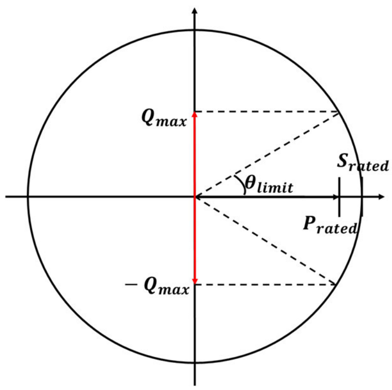

FIGURE 9. Relation between active power and reactive power of DG [31].

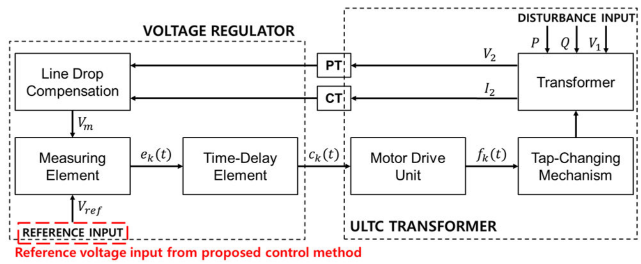

FIGURE 10. Modified control block diagram of ULTC.

2) INVERTER OF DG CONSTRAINTS

The reactive power control constraints of the DG controllable range are expressed as

$$-S_{rated,k} \times \sqrt{1-PF_{\text{limit}}^2} \leq \Delta Q_{DG,k}^t \leq S_{rated,k} \times \sqrt{1-PF_{\text{limit}}^2} \quad (11)$$

where PF_{limit} is the allowable bound power factor of DG. Fig 9 shows the relationship between the active power and the reactive power of DG. The reactive power control range of DG is determined by the inverter capacity of DG and the power factor limit magnitude. Regardless of the active power, the reactive power can be controlled independently within the setting range, and active power control of DG is impossible [31]. In addition, in this paper, the reactive power control variables of DG are divided according to sections. This is a strategy used to mitigate the problems of prediction error and extreme fluctuations in DGs. (12), as shown at the bottom of the page, where, **N** is the number of divided sections for reactive power control to the output of DGs

3) REFERENCE VOLTAGE OF ULTC CONSTRAINTS

The reference voltage magnitude of ULTC constraints is expressed as

$$0.9 \leq V_{ref}^t \leq 1.1 \quad (13)$$

The controllable range of ULTC is ±10% in [32]. Further, in this paper, the constant reference voltage control is applied in the control of ULTC, and it is expressed as

$$\Delta V_{ref}^1 = \cdots = \Delta V_{ref}^{24} = \Delta V_{ref} \quad (14)$$

The constant voltage control of ULTC is a method of controlling the reference voltage in the same manner every time, and the control can be maintained through the tap changing controller of the ULTC. In addition, if the reference voltage for controlling the ULTC frequently changes, it will be difficult to maintain the level of the reference voltage due to the control characteristics. Unlike the existing LDC method, the ULTC control proposed in this paper applies the transmission voltage derived from optimization as a reference voltage, and the modified control block diagram is shown in Fig 10. The voltage deviation in the block diagram is calculated by comparing the magnitude of the measured voltage on the secondary of the substation with the reference voltage from the solution of the proposed control method. Then, the control is performed in the same way using the control mechanism.

E. OVERALL PROPOSED CONTROL SCHEME

The proposed voltage control scheme improves the voltage profile in the distribution system; the control variables are the reference secondary voltage of the substation and the reactive

$$\Delta Q_{DG,k}^t = \begin{cases} \Delta Q_{DG,k}^{s1} \left(\text{if } P_{rated,k} \times \frac{n-1}{N} \leq P_{DG,k}^t \leq P_{rated,k} \times \frac{n}{N}, n=1 \right) \\ \Delta Q_{DG,k}^{s2} \left(\text{if } P_{rated,k} \times \frac{n-1}{N} \leq P_{DG,k}^t \leq P_{rated,k} \times \frac{n}{N}, n=2 \right) \\ \Delta Q_{DG,k}^{sN} \left(\text{if } P_{rated,k} \times \frac{n-1}{N} \leq P_{DG,k}^t \leq P_{rated,k} \times \frac{n}{N}, n=N \right) \end{cases}$$
$$\forall n \in \{1, 2, \ldots, N\} \quad (12)$$

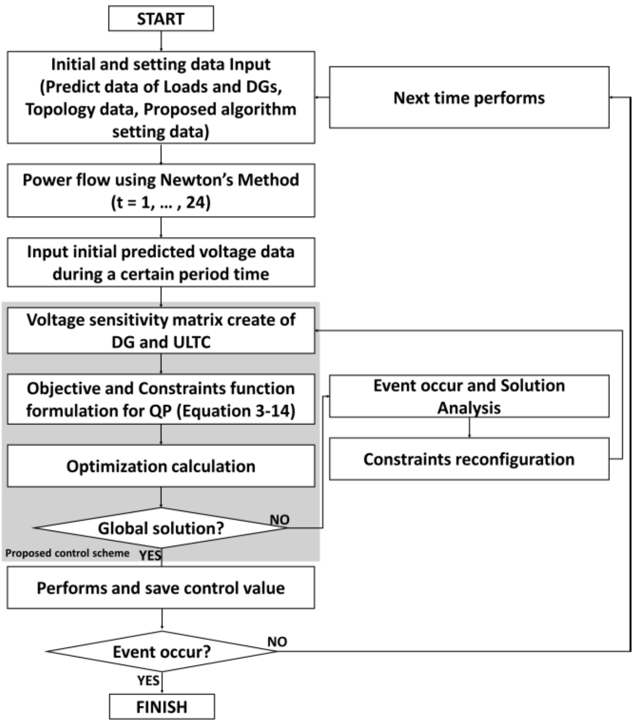

FIGURE 11. Flowchart of proposed control scheme.

power of PVs. Fig 11 shows a flowchart of the proposed control scheme, and the solution steps are as follows:

1) The distribution system operator selects the control mode for the reactive power control of DGs, which is done to divide the reactive power control section of DGs. The operator also inputs the topology data and the forecast data of loads and DGs.
2) Next, the optimal power flow is performed using Newton's method.
3) Using the input data, the forecast voltage profile is derived through the optimal power flow. Then, the derived forecast voltage profile is input to the proposed control algorithm.
4) To formulate the objective function and the constraints in the proposed scheme, we use the topology data to generate a voltage sensitivity matrix for the voltage control devices.
5) The objective and constraints function for QP is formulated using the sensitivity matrix of DG. Then, the solution is derived through QP using the optimization tool box of MATLAB 2021a.
6) The solutions derived from QP are reviewed. If the derived solution is not a global solution, then the events on the right side of the Fig 11 are performed, and the scheme instructs the DSO to raise an alarm and reset the constraint. This part aims to derive the global solution by modifying the constraints to derive the solution.

Finally, the proposed control scheme in this paper detects alarms caused by large prediction errors of DGs and loads, topology reconfiguration, system expansions, or new generator installations, and re-executes them using the updated information. However, this process is not detailed in this paper.

TABLE 1. Parameters of test 32-bus distribution system.

Rated Voltage [kV]	Line impedance [p.u./km]	MTR's impedance [p.u.]
22.9[kV]	0.0347+j0.0746	j0.26

TABLE 2. Information for each feeder at CASE 1.

Feeder No	Total Load Capacity [MVA]	Line length [km]	Voltage drop at full load [%]
1	6	15	3
2	9	30	10
3	8	17	5.6
4	5.5	22	4.6

TABLE 3. Rated capacity of DG at CASE 1.

DG Name	Bus no for installation of DG	Rated Capacity [MW]
PV 1	8	6
PV 2	18	6
PV 3	22	1.2
PV 4	26	4.8
PV 5	29	1.2
PV 6	32	4.8

TABLE 4. Constraints for voltage and reactive power of DG at CASE 1.

Voltage max [p.u.]	Voltage min [p.u.]	Reactive power Max	Reactive power Min
1.02	0.96	$S_{rated,k} \times 0.44$	$-S_{rated,k} \times 0.44$

IV. SIMULATION AND ANALYSYS

The proposed control scheme was verified through two case studies. In the first case study, the validity of the proposed control scheme was verified in the test 32-bus distribution system, and in the second case study, it was verified in the modified IEEE 69-bus radial distribution system.

A. CASE 1: TEST 32-BUS DISTRIBUTION SYSTEM

Fig 12 shows the test 32-bus distribution system, which was designed based on the Korean distribution system. The system parameters are listed in Table 1, and the information for each feeder is presented in Table 2. In Table 1, the line impedance and transformer impedance are represented based on 100[MVA], while in Table 2, the voltage drops at full load mean that the voltage drops at the full load of the load when there is no DG. And, the DGs used in the simulation were assumed to be PV, and the inverter capacity was selected as 120% of the rated capacity. The rated capacity for each DG is listed in Table 3. Table 4 shows the upper and lower limits of the voltage regulation range and the reactive power control range of DG, while Table 5 provides the conditions used for the tap control of ULTC.

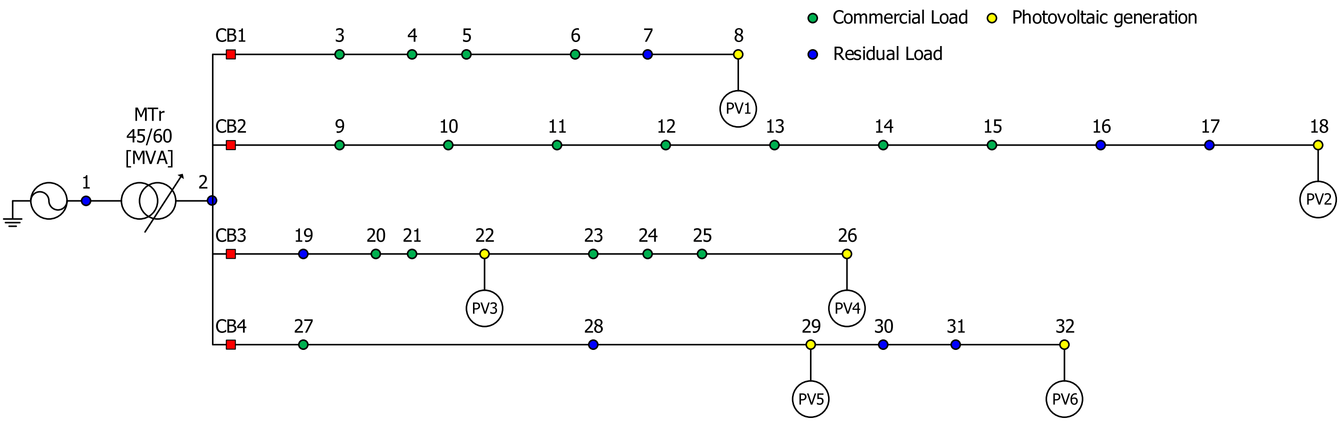

FIGURE 12. TEST 32-bus distribution system.

TABLE 5. Condition of ULTC at CASE 1.

Initial position of Tap	Dead band
0	-1.25[%] ~ + 1.25[%]

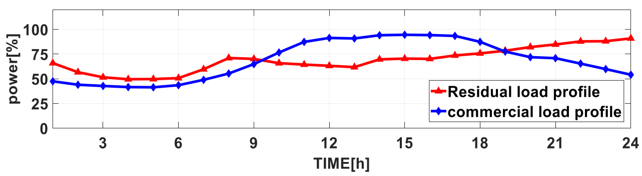

FIGURE 13. Residual and commercial load prediction profile at CASE 1.

The proposed control scheme is validated by comparing its performance with the conventional control scheme. The performance index can be expressed as

$$PI = \sum_{t=1}^{NTIME} \sum_{i=1}^{Nbus} (V_i^t - V_{nom})^2 \times 100 \qquad (15)$$

The performance index is the same as the objective function, but since it has a very small magnitude, it was multiplied by 100 for improved readability. To verify the proposed control scheme, CASE 1 performs simulations in two scenarios. In scenario 1, PVs are assumed to lead to forecast profiles of sunny days, while the other scenario is assumed to be a cloudy day. The results of this simulation are compared to the control effects of the conventional voltage control scheme and the proposed control scheme. The conventional control scheme applied the LDC method of ULTC without the control of DGs and the real-time coordinated volt/var control of the DGs scheme, and the proposed control scheme performs four control schemes. For all proposed control schemes, the constant reference voltage control is applied in ULTC, and Table 6 shows the application of the proposed control scheme. Fig 13 shows the load profiles for residual and commercial loads; these are expressed in % compared to the rated capacity.

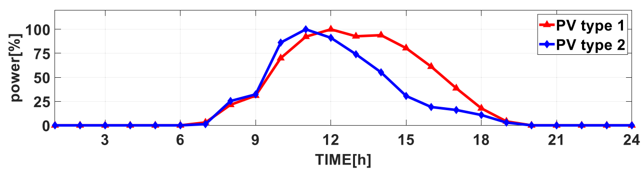

FIGURE 14. DG prediction profile of two types during sunny day.

1) CASE 1-1: SCENARIO 1

The PVs are assumed to be two types of prediction profiles during sunny days. Fig 14 shows the prediction profiles while Table 7 presents the installed bus for the DG type. Regarding the assumed data, the forecast data on the same day was used to the two PVs that were actually installed. Fig 14 shows the voltage profiles for the conventional voltage control schemes. Fig 15 (a) illustrates the application of the conventional LDC method in [6], without the reactive power control of DGs. Fig 15 (b) illustrates the application of the real-time coordinated volt/var control scheme in [29]. In Fig 15 (a), it can be seen that there are many sections outside the specified voltage operating range, while in Fig 15 (b), the voltage was maintained within the specified voltage operating range. Further, Fig 15 (b) shows the striking control performance, as the voltage magnitude of buses is operated close to the nominal voltage. The results of the proposed control schemes are shown in Fig 16 and Fig 17: Fig 16 shows the reactive power control result of DGs for each proposed control scheme and Fig 17 shows the voltage profile for each proposed control scheme. The voltage profile is represented box plot, and the red dotted line in plot means the upper and lower voltage limit. Also, the tap position result of each control scheme at CASE 1-1 is shown in Fig. 18, and the total results of performance index, the number of tap position, total reactive power of DGs shown in Table 8.

2) CASE 1-2: SCENARIO 2

In CASE 1-2, the PVs are assumed to have prediction profiles of a cloudy day. Fig 19 shows the prediction profiles of the PVs; all PVs have the same profile. As in scenario 1,

TABLE 6. The proposed control scheme applied to simulation.

Control scheme	Description
Proposed control scheme 1	No diving into section
Proposed control scheme 2	Constant reactive power control at all-time
Proposed control scheme 3	Two diving into section according to the active power of each DG (Section A : 0~50%, Section B : 50~100[%])
Proposed control scheme 4	Four diving into section according to the active power of each DG (Section A : 0~25[%], Section B : 25~50[%], Section C : 50~75[%], Section D : 75~100[%])

TABLE 7. DG installation bus information.

DG type	Bus no for installed of DGs
Type 1	22 29
Type 2	8 18 26 32

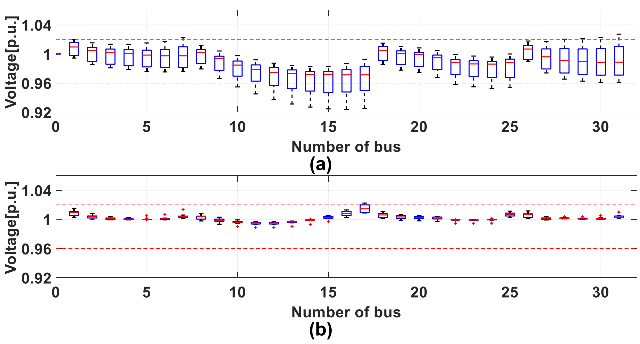

FIGURE 15. Voltage profile at CASE 1-1 for (a) conventional LDC method [6], (b) conventional real-time coordinated volt/var control scheme [29].

six control schemes were executed in the test 32-bus distribution system to verify the effectiveness of the proposed control scheme. Table 9 presents the control scheme result for each control scheme. The proposed control schemes 2, 3, and 4 showed the same control results, because the PVs output is lower than 25[%] due to the cloudy day.

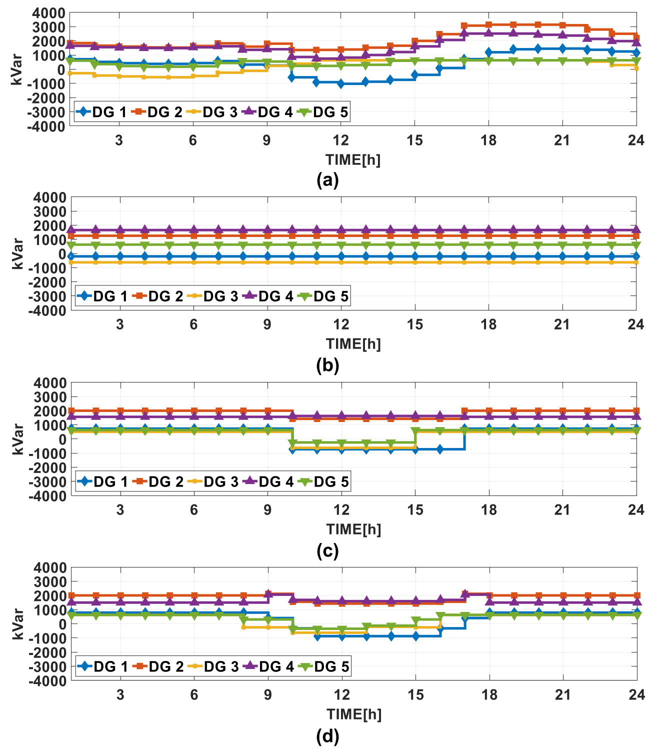

FIGURE 16. Result of reactive power control of DGs at CASE 1-1 for (a) proposed control scheme 1, (b) proposed control scheme 2, (c) proposed control scheme 3, (d) proposed control scheme 4.

B. CASE 2: IEEE 69-BUS DISTRIBUTION SYSTEM

In CASE 2, the proposed control scheme for effective validation is implemented on a modified IEEE 69-bus radial distribution system as described in [33]. Fig 20 shows the modified IEEE 69-bus radial distribution system, which has PVs installed in five locations. Table 10 lists the rated capacity of the DGs in CASE 2, and each inverter capacity was selected as 120% of the PV-rated capacity. The load and PV profile applied in CASE 2 are shown in Fig 20, have a 30-minute cycle.

Unlike CASE 1, CASE 2 compared the results of each control scheme while including the forecast error. The load and DG profiles shown in Fig 21 were assumed to be real-time profiles for a day, and the error was reflected through a random function of MATLAB. Table 11 presents the maximum forecast errors of load and DG for each case. Since the forecast error of PV is substantially affected by weather variability, it is assumed to be larger than the load forecast error. Fig 22 shows the forecast profile reflecting the applied load and DG error in each case.

Figs 23 and 24 show the voltage profile results for each control scheme in the absence of load and DG forecast errors. The voltage profile is represented as a boxplot, and the red dotted line in the plot marks the upper and lower voltage limits. Further, Table 12 presents the overall result of CASE 2, including PI, the number of tap controls, and the amount of total reactive power control.

C. SIMULATION ANALYSIS

In CASE 1, the proposed control scheme was applied to a test 32-bus distribution system. CASE 1 was performed in two

TABLE 8. Result of each control scheme at CASE 1-1.

Control scheme	PI	Reference voltage of ULTC [p.u.]	The number of tap changing	Total reactive power [MVarh]						
				DG 1	DG 2	DG 3	DG 4	DG 5	DG 6	Total
Conventional LDC method [6]	35.46	-	19	-	-	-	-	-	-	-
The real-time control scheme [29]	1.86	-	9	24.13	52.90	12.67	42.00	12.19	24.52	168.41
The proposed control scheme 1	3.8	1.0082	3	18.59	49.83	11.62	40.17	11.20	21.78	153.19
The proposed control scheme 2	8.24	1.0126	3	4.88	30.09	15.02	39.72	15.06	22.54	127.32
The proposed control scheme 3	4.85	1.0089	4	17.52	43.91	12.74	37.94	13.15	16.92	142.19
The proposed control scheme 4	3.8	1.0088	4	17.65	44.50	13.11	37.93	12.25	17.21	142.65

TABLE 9. Result of each control scheme at CASE 1-2.

Control scheme	PI	Reference voltage of ULTC [p.u.]	The number of tap changing	Total reactive power [MVarh]						
				DG 1	DG 2	DG 3	DG 4	DG 5	DG 6	Total
Conventional LDC method [6]	69.63	-	11	-	-	-	-	-	-	-
The real-time control scheme [29]	2.5	-	11	22.62	64.19	10.71	52.69	13.52	24.72	188.44
The proposed control scheme 1	8.43	1.0124	1	14.48	57.66	13.57	48.08	6.95	22.22	162.96
The proposed control scheme 2	10.74	1.0116	2	15.67	48.71	8.98	55.76	5.46	21.29	155.87
The proposed control scheme 3	10.74	1.0116	2	15.67	48.71	8.98	55.76	5.46	21.29	155.87
The proposed control scheme 4	10.74	1.0116	2	15.67	48.71	8.98	55.76	5.46	21.29	155.87

TABLE 10. Rated capacity of DG at CASE 2.

DG Name	Bus no for installation of DG	Rated Capacity [kW]
DG 1	16	575
DG 2	27	575
DG 3	45	575
DG 4	59	370
DG 5	61	1500

scenarios: a sunny day and a cloudy day. All of the control schemes except for the conventional LDC method were maintained within the voltage specified range, and the objective function and constraints were satisfied. Further, as can be seen in Tables 8 and 9, the conventional real-time voltage control scheme showed the best performance. On the other hand, the conventional LDC method had poor control performance and the largest number of tap changes. This is because it only considered ULTC tap changing, and it showed the limitations of the conventional LDC method in the distribution system with large-capacity DGs. Then, except for the conventional LDC method, the control scheme with the most tap changes was the conventional real-time control scheme. In addition, the conventional real-time scheme had the largest amount of total reactive power control for DGs. This is because it was used as much as possible within the limits of the voltage control devices to achieve that purpose. Therefore, the real-time control scheme showed better control performance than other control schemes, but it included unnecessary control. The proposed control schemes showed performance indices similar to that of the real-time control scheme, and the number of tap changes of ULTC was lower than those in the conventional control schemes. Most of the proposed control schemes maintained the secondary side reference voltage of the substation at a similar level, and the overall reactive power requirements showed similar results. In CASE 1-2, proposed control schemes 2, 3, and 4 showed the same control results, because the PVs output was lower than 25[%] due to the cloudy day. However, the results of applying the proposed control schemes in CASE 1-2 were similar to those of applying the same schemes in CASE 1-2. When analyzed comprehensively, the proposed control schemes were shown to be effective.

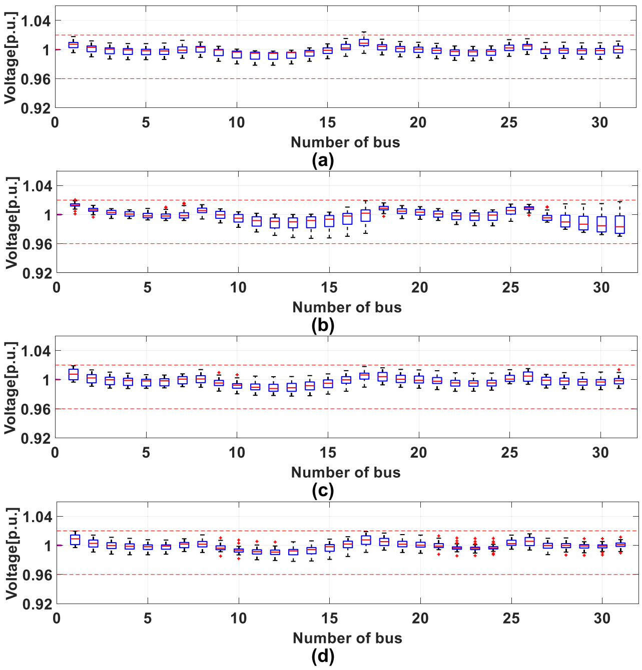

FIGURE 17. Voltage profile at CASE 1-1 for (a) proposed control scheme 1, (b) proposed control scheme 2, (c) proposed control scheme 3, (d) proposed control scheme 4.

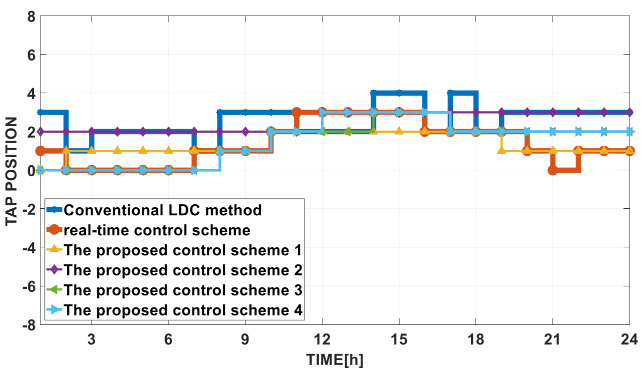

FIGURE 18. Tap position result of each control scheme at CASE 1-1.

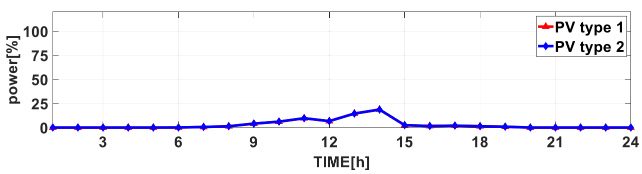

FIGURE 19. DG prediction profile of two types during cloudy day.

In CASE 2, the proposed control scheme was applied to the modified IEEE 69-bus radial distribution system, and the forecast error was reflected. If the error was not reflected, the results were similar to those of CASE 1, and the control scheme with the best control performance was the conventional real-time voltage control scheme. However, it also showed the most frequent tap changes. On the other hand, the proposed control schemes had similar voltage profiles, as shown in Fig 24, and the lowest number of tap changes, as listed in Table 12. In particular, proposed control schemes 1 and 4 showed the most similar results to the

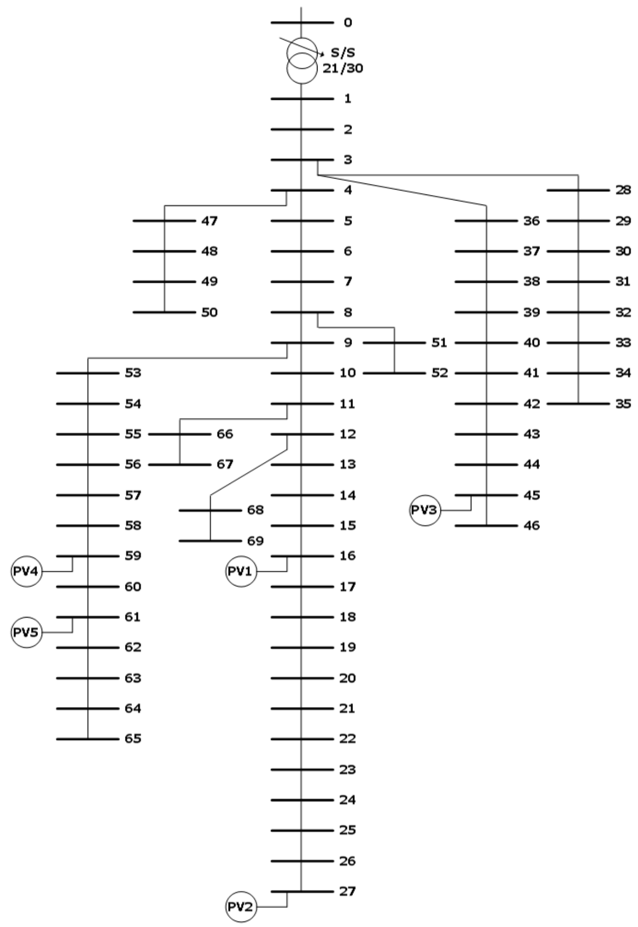

FIGURE 20. IEEE 69-bus radial distribution system with PVs.

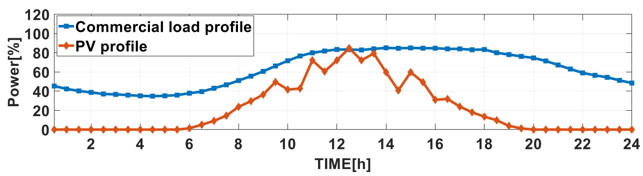

FIGURE 21. Load and PV 30-minute cycle profile in CASE 2.

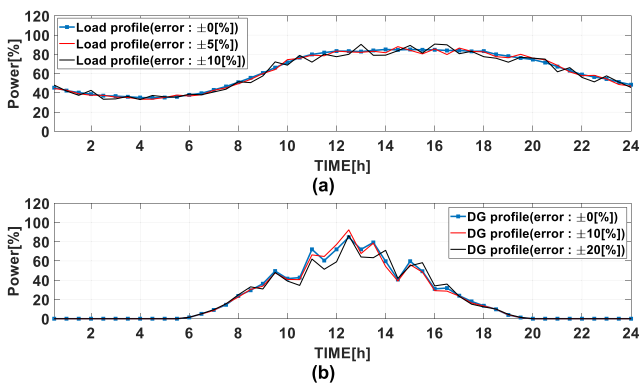

FIGURE 22. Load and PV forecast profile reflecting error of each case.

TABLE 11. Scenario of CASE 2.

Cases	Description
CASE 2-1	Load error : 0[%], PV error : 0[%]
CASE 2-2	Load error : ±5[%], PV error : ±10[%]
CASE 2-3	Load error : ±5[%], PV error : ±20[%]
CASE 2-4	Load error : ±10[%], PV error : ±10[%]
CASE 2-5	Load error : ±10[%], PV error : ±20[%]

TABLE 12. Result of each control scheme at CASE 2.

Cases	Control scheme	PI	Reference voltage of ULTC [p.u.]	The number of tap changing	Total reactive power [MVarh]
CASE 2-1 (Load error : ±0[%], DG error : ±0[%])	Conventional LDC method [6]	302.290	-	5	-
	The real-time control scheme [29]	104.138	-	7	42.56
	The proposed control scheme 1	129.207	1.007	1	42.48
	The proposed control scheme 2	231.853	1.005	0	42.28
	The proposed control scheme 3	219.690	1.006	0	45.09
	The proposed control scheme 4	121.379	1.006	1	44.46
CASE 2-2 (Load error : ±5[%], DG error : ±10[%])	The proposed control scheme 1	131.363	1.007	1	42.12
	The proposed control scheme 2	233.035	1.007	0	42.10
	The proposed control scheme 3	222.106	1.007	0	44.79
	The proposed control scheme 4	120.736	1.007	1	43.95
CASE 2-3 (Load error : ±5[%], DG error : ±20[%])	The proposed control scheme 1	136.934	1.007	1	42.09
	The proposed control scheme 2	229.015	1.005	0	42.72
	The proposed control scheme 3	219.405	1.006	0	45.13
	The proposed control scheme 4	233.058	1.007	0	44.44
CASE 2-4 (Load error : ±10[%], DG error : ±10[%])	The proposed control scheme 1	131.386	1.007	1	42.43
	The proposed control scheme 2	232.622	1.007	0	42.16
	The proposed control scheme 3	223.970	1.007	0	44.57
	The proposed control scheme 4	120.509	1.007	1	43.32
CASE 2-5 (Load error : ±10[%], DG error : ±20[%])	The proposed control scheme 1	134.717	1.007	1	42.56
	The proposed control scheme 2	230.163	1.007	0	42.54
	The proposed control scheme 3	219.405	1.007	0	45.13
	The proposed control scheme 4	230.808	1.007	0	44.27

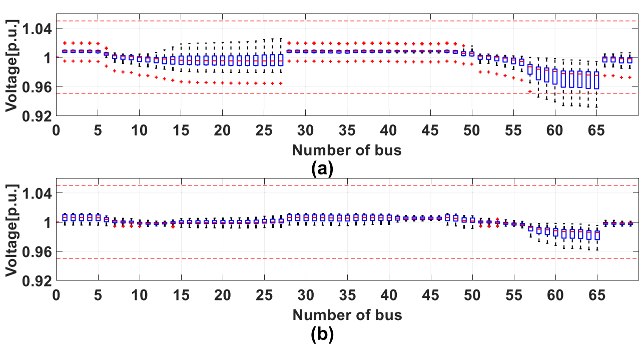

FIGURE 23. Voltage profile at CASE 2-1 for (a) conventional LDC method [6], (b) conventional real-time coordinated volt/var control scheme [29].

real-time voltage control scheme. Proposed control scheme 1 showed worse performance than proposed control scheme 4, which was caused by an error in the simplified voltage equation we used; however, as shown in Fig 23, the difference was negligible.

In addition, in CASE 2, the results of each control scheme were compared by reflecting the error. The maximum forecast error range of load was set to either ±5[%] or ±10[%], and the PV maximum forecast error range of PV was set to either ±10[%] or ±20[%]. The maximum error range of PV was set to be larger than the maximum error range of the load because the output characteristics of PV have many variables, such as weather fluctuations and temperature. Table 12 presents the results of each control scheme according to the forecast errors of the load and PV. First, CASE 2-2 showed very similar results to CASE 2-1, and proposed control scheme 4 showed better results than CASE 2-1. This was attributed to the error of the simplified voltage equation we used, and the difference was very small. CASE 2-3 shows different results from CASE 2-1.

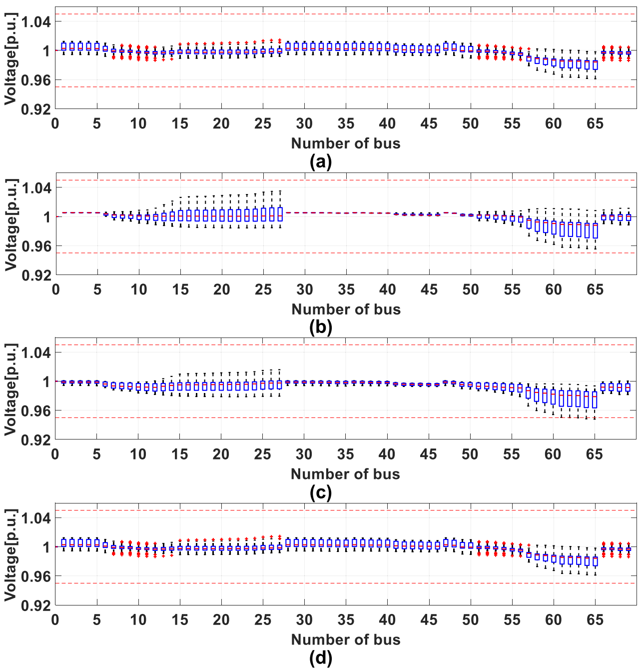

FIGURE 24. Voltage profile at CASE 2-1 for (a) proposed control scheme 1, (b) proposed control scheme 2, (c) proposed control scheme 3, (d) proposed control scheme 4.

The performances of the other control schemes, except for that of proposed control scheme 1, were clearly degraded. The reason for this was that the forecast error of PV was as high as ±20[%]. However, except for proposed control scheme 1, all other control schemes maintained the voltage within the specified range and satisfied all the constraints. The other cases showed very similar results.

The proposed control scheme in this paper improved the voltage profile in a distribution system with DGs, and its effectiveness was verified through a comparison with conventional control schemes in case studies. Although its performance was inferior to that of the real-time control scheme, which had the best control performance, the number of tap changes was reduced through the constant reference voltage control of the substation. In addition, some forecast errors were mitigated through the reactive power control for each section of DGs, and frequent control was not performed. This can reduce the amount of communication with the centralized system, and the proposed control scheme was designed to be easily applied in the current infrastructure. Therefore, the proposed control scheme is easy to apply in a practical distribution system with DGs, and it can help the DNO determine the effective volt/var control when there are not many instruments installed.

V. CONCLUSION

This paper proposed a day-ahead scheduling voltage control scheme for ULTC and var in the distribution system. The proposed control scheme outlines a control strategy with the secondary voltage of ULTC and the reactive power of DG. The secondary voltage of the substation was treated as one variable to maintain a constant reference voltage. DGs segmented the real power output sections and suggested a control strategy for each section. The proposed control scheme is formulated for the quadratic programming problem, as the objective function is a nonlinear formulation while the constraint function is a linear formulation. The proposed control scheme has an error compared to conventional voltage control models that involve applying the linear characteristics of the voltage control devices, but the errors are negligibly small, thus ensuring a near optimal solution. In addition, compared to the conventional control scheme, applying the linear characteristic of the control devices reduces the weight occupied by the operation system and the computational burden.

The performance of the proposed control scheme was verified through a simulation. The proposed control scheme is shown to have a similar performance index as the conventional voltage control scheme. In addition, the number of tap changes in the proposed scheme is small, which is attributed to the constant reference voltage control of the substation, and since this control method does not change the reactive power control value frequently, the burden on the reactive power control device is reduced. Further, some forecast errors were mitigated through reactive power control according to each real power section of DGs.

An important feature of the proposed control scheme is that it is possible to predetermine the control value that sets the reference voltage of ULTC and the reactive power of DGs. Therefore, we proposed a control scheme that does not require large communication and measuring devices. In addition, since it uses a controller installed in the existing infrastructure, the proposed control scheme can be easily applied to the current distribution system. Therefore, our proposed control scheme can be a good alternative for effective voltage operation in a distribution system with penetration DGs.

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