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Optimal Volt–Var Curve Setting of a Smart Inverter for Improving Its Performance in a Distribution System

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ABSTRACT We propose an algorithm to set the parameters of volt–var curves to improve the performance of distributed generation. Specifically, we optimally set the volt–var curves of the smart inverter for proper control of the distributed generation output. To improve the overall distribution system performance, we consider the minimization of voltage deviation, system loss, and peak of reactive power in an objective function, thereby providing optimal volt–var curve parameters. The proposed algorithm overcomes various limitations of existing studies. First, we use distribution system factors in a multiobjective optimization function to adjust volt–var curve parameters that deviate from the default settings. Second, we consider the service transformers that affect the system voltage according to the photovoltaic generation output in the test model during optimization. Third, we analyze the system improvement according to the number of parameters to be optimized. Fourth, we analyze the implementation of the optimized volt–var curve according to the practical periods when the smart inverter settings can be updated. Fifth, we evaluate different suitable volt–var curves for multiple photovoltaic generators grouped using clustering. Using the proposed algorithm, the distribution system operator can set the optimal volt–var curve according to the system conditions and requirements. We conducted simulations of the proposed method using OpenDSS, a quasistatic time-series simulation, on a test model reflecting the characteristics of a South Korean distribution system. The simulation results confirm that the overall system performance increases when the optimal volt–var curve settings obtained from the proposed algorithm are used.

INDEX TERMS Distribution system, parameter optimization, smart inverter, volt–var curve.

NOMENCLATURE

i	Bus index
t	Time (h) (year: 8760 h; spring: 2208 h; summer: 2208 h, fall: 2184 h; winter: 2160 h)
vv_{new}	Parameter (gene) for newly updated volt–var curve (V_{vv2}, V_{vv3}, Q_{vv1}, Q_{vv4})
vv_{con}	Conventional volt–var curve parameter in Fig. 5
$P_t(vv)$	System loss at time t according to volt–var curve parameter
V_{ref}	Reference voltage, 22.9 kV, 1.00 pu
ω	Weight for system factor (voltage deviation, system loss, peak of reactive power)
$V_{i,t}$	Voltage of bus i at time t according volt–var curve parameter
$\delta V_{i,t}(vv)$	$\frac{V_{ref}-V_{i,t}(vv)}{V_{ref}}$, voltage deviation index of bus i at time t
$Q_i(vv)$	Reactive power output at smart inverter of bus i according to volt–var curve parameter
N_{const}	Constraint condition
ω_{c}	Penalty coefficient
PF_{c}	Constraint weight
E	Disjoint subset of input pattern

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l	Clusters index
k	Number of clusters
S_i	Set of points belonging to cluster i
μ_i	Center of cluster i
$O{\cdot}F$	Objective function

I. INTRODUCTION

To mitigate environmental problems and reduce fossil fuel consumption, distributed generation based on renewable sources, such as photovoltaic (PV) cells, is becoming a popular option in South Korea. According to the renewable energy 3020 implementation plan of the Korean government, the total installed capacity for renewable energy generation is expected to reach 58.5 GW by 2030 [1], [2]. The installed capacity of PV generation connected to distribution systems is expected to increase more rapidly than other sources because of incentive programs [3]–[5]. However, increasing PV penetration in the distribution system may cause overvoltages and other problems [6]–[8], which must then be resolved by distribution system operators (DSOs) to ensure power quality and reliability.

To this end, three solutions have been adopted in South Korea to mitigate voltage variations in the distribution system, namely tap control in the main transformer [9]–[11], voltage control using step voltage regulators in the feeders, and adjustment of the volt–var curves (VVCs) in smart inverters for distributed PV generation. Among these, tap control is unsuitable under large voltage deviations between multiple feeders, and the method by itself needs to be implemented by transmission system operators, which is difficult. Although step voltage regulators allow controlling the voltage of each feeder [12]–[14], their installation is costly, and the few installations that are currently operational in South Korea are plausible only because short-length feeders are available. Therefore, distributed generators such as inverter-based PV systems are being increasingly employed, and the most suitable method to prevent overvoltages may be by adjusting the VVCs in smart inverters.

Several studies have used the VVCs to prevent overvoltages due to increasing PV penetration. A centralized VVC was developed to minimize power system losses while maintaining the voltage profiles within acceptable limits [15]; however, this study did not consider the overall factors of the system as the objective function. The VVC supporting voltages using reactive power were analyzed in field tests [16], [17], but these studies evaluated VVC performance based on daily data within the default function setting. Updating the function parameters hourly or daily according to weather has limitations due to practical problems in the field, such as communication problems. Control strategies of smart inverters connected to numerous distributed PV systems have been proposed, and the same VVC was assigned to multiple PV systems [18]; however, the effect of the service transformer on the voltage was not considered when analyzing the VVC performance. The VVC was also analyzed for energy saving and power quality [19]; however, the overall performance was not obtained. VVC effects on a system with high PV penetration and smart inverters have been analyzed [20]; however, default settings were used for the impact analysis in the study. The VVC needed to support the voltage of the distribution system was obtained in [21] by changing the parameters of each function related to the VVC; however, no formal optimization was conducted, and multiple PV systems were evaluated using daily data and the same VVC. The effects of VVC parameters according to PV penetration and weather conditions have been evaluated [22], but the method of updating parameters had practical limitations. A method for preventing overvoltage in distribution test systems was experimentally validated in [23]; however, there were no details regarding the VVC settings for system performance improvement. In addition, transformers that had substantial effects on the voltage were not considered. In [24], the voltage regulation performance was compared at a fixed power factor for various VVCs; however, comparisons were made using default curves, and the service transformer was not considered. The performances of smart inverter controllers were analyzed in [25] to mitigate overvoltages; however, each of the factors were evaluated individually, and the system performance was not considered. A volt–var–watt function was used in [26] to manage 100% PV penetration, which is difficult to achieve using the VVC; however, in the VVC evaluation process, the default curve was utilized without curve-parameter optimization. If an optimized VVC is used, the goal can be achieved without curtailment. An advanced grid support function was evaluated in [27], where the default curve was used to enable the grid support functions, such as the voltage ride through (VRT) or frequency ride through (FRT). Accurately evaluating the optimized VVC by utilizing advanced functions was thus necessary to effectively support the system, and the overvoltage from PV penetration in distribution systems was addressed in [28]. However, the system performance improvement was limited because the system factors were not considered via multiobjective functions. In [29], the volt–var–watt function was employed to improve system performance; although the curve parameters were optimized, the performance improvement was limited because the system factors were not considered via a multiobjective function. Four objective functions and a genetic algorithm were used for VVC optimization in [30], but the optimization settings were not maximized because the weights were inappropriate.

Dao *et al.* [31] observed that the VVC of a smart inverter had positive as well as negative impacts on voltage profiles, losses, and energy curtailments; however, it was assumed that the function could be updated daily, and the optimization of the curve setting description was insufficient. Bello *et al.* [32] discussed the optimal VVC settings for feeder parameters, such as tap changes, loss, voltage variability, and voltage range violations; however, in their study, the performance was evaluated by changing only the slope and set point, without flexibly setting the function point. Further, the overall system factors were not considered by fixing the weights of the objective function. Rylander *et al.* [33] proposed a method to set the smart inverter function for improving system performance; despite considering the service transformer, this study focused only on the hosting capacity rather than crucial factors such as voltage deviations and system losses. In [34] and [35], the expected performances were optimized with respect to a figure of merit of interest to the DSOs; however, the same VVC was applied to multiple PVs without considering the service transformer. In [36], factors affecting the hosting capacity (e.g., VVC) of the distribution system were analyzed, but the study only focused on increasing the hosting capacity. In [37], the impact of the smart inverter setting on the distribution system was evaluated, but the impacts of the voltage and tap changer were analyzed by changing only the set point and slope without flexibly setting the function point. In [38], the overvoltage was mitigated by absorbing the reactive power from distributed generation, but this study did not optimize the VVC setting for system performance improvement. In [39], factors such as voltage deviation and loss according to PV penetration were analyzed, but the system performance for voltage and system losses were evaluated separately using the default settings. In [40], the system performance was analyzed in terms of voltage deviation, loss, and other factors; however, the study evaluated these factors under the assumption that the VVC could be updated daily, and an inappropriate objective-function weight was selected. In [41], the optimal voltage deviation was obtained using the VVC of a PV inverter, but the performance was evaluated by changing only the set point of the VVC without considering the service transformer. In [42], the system performance was improved by setting the VVC by clustering, but the performance improvement was limited because a multiobjective function was not considered. Although numerous studies have investigated the mitigation of overvoltages in a distribution system using the VVC, we propose here an algorithm that overcomes the six limitations of existing methods, which are summarized in Table 1. The proposed algorithm optimizes the VVC to set the parameters of the smart inverters in PV systems devoted to distributed generation.

The remainder of this paper is organized as follows. Section II details the test model adopted in this study and the proposed algorithm to set the VVC in smart inverters. Section III provides simulation results to verify the effectiveness of the proposed algorithm in different scenarios. In Section IV, we discuss the contributions of this study, and some conclusions are presented in Section V, including the applications and implications of this study.

II. METHODS

A. TEST MODEL

The test model for this study considers the characteristics of the South Korean distribution system to verify the effectiveness of the proposed algorithm [7], [12], [13], [43]. Consequently, the proposed algorithm would be applicable to that system after this verification. Fig. 1 shows the configuration of the test model that connects various PV systems, and Table 2 lists the parameters of the test model. Each PV system in the feeder, modeled as a lumped-type system, has a capacity of 2.8 MW, and the total capacity of the PV systems connected to the feeder is 28 MW. In some cases, large-capacity PV systems are connected to a dedicated line due to thermal limitations, but in South Korea, the connection of small-capacity PV systems to feeders is increasing

TABLE 1. Contributions of the proposed algorithm to overcome limitations of existing methods for improving distribution system performance using VVC.

No.	Limitation	Contribution of proposed algorithm
1	Function of smart inverter has not been set to improve system performance ([15], [20], [21], [25]–[29], [33]–[37], [39])	Overall system performance is improved using multiobjective optimization function to improve voltage deviation, system loss, and peak of reactive power affecting the output (Section III-A)
2	Function setting neglects service transformer that affects voltage ([18], [19], [21]–[25], [28], [30], [32], [34], [36], [42])	Service transformer is included in test model for algorithm verification. The function is set by clustering PV systems considering the behavior of the fixed tap on the transformer (Sections II-A and III-C).
3	Performance is only evaluated in default setting ([16], [17], [20], [21], [24], [26], [27], [32], [33], [36]–[40])	Function parameters are flexibly set via optimization based on genetic algorithm. The effect of the function according to number of parameters is analyzed (Sections II-C and III-A)
4	Function performance is evaluated assuming that parameters can be quickly updated according operation conditions ([15]–[18], [20]–[22], [25], [26], [29]–[31], [40], [42])	As quick parameter update may be infeasible in practice, the function performance is evaluated on annual or seasonal bases for the function to be realistically updated in the smart inverter (Section III-B)
5	The same function is implemented on multiple PV systems distributed in a feeder ([18], [21], [23], [24], [26], [28], [30], [31], [34], [35], [38], [40])	By clustering, appropriate functions are set per cluster to achieve efficient operation of multiple PV systems (Section III-C)
6	Function performance is evaluated using objective function with inappropriate weights ([19], [20], [28]–[32], [39], [40], [42])	Weights of objective function are properly adjusted. The DSOs can achieve optimal operation considering the operation conditions of the system (Section III-D)

TABLE 2. Components in test model for this study [7], [12], [13], [43].

Component	Parameter
PV capacity per unit	2.8 MW
Power conversion system capacity per unit	3.0 MVA
Load capacity per unit	0.5 MW
Main transformer	154/22.9 kV, 45/60 MVA
Service transformer	22.9/0.38 kV, 3.0 MVA
Line impedance (ACSR 160 mm^2)	$0.182 + j\,0.391$ Ω/km
Line length per section	3 km

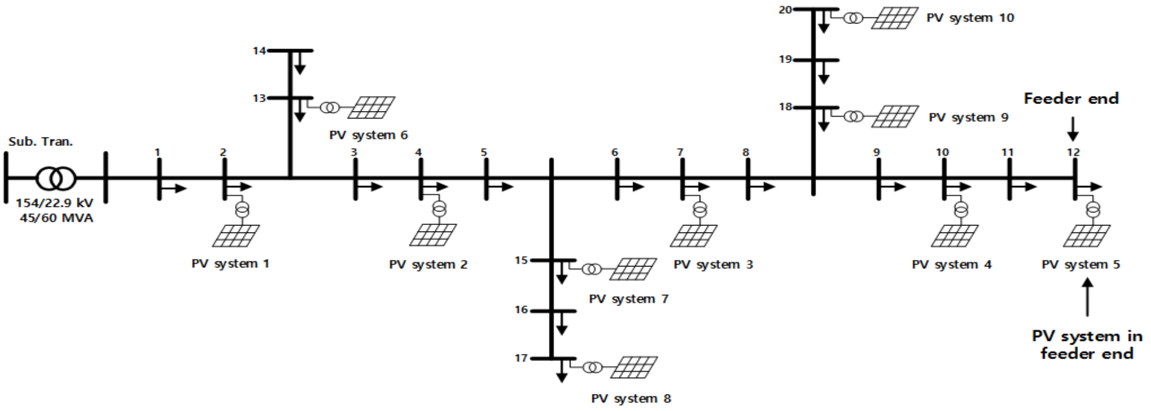
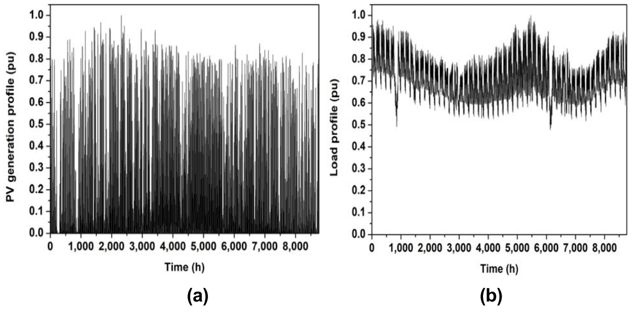


FIGURE 1. **Test model for this study reflecting the characteristics of the South Korean distribution system [7], [12], [13], [43].**

exponentially. Therefore, the voltage problems that arise before reaching the thermal limitation must be solved. The capacity of each load, modeled as a lumped-type load, is 500 kW, and the total capacity connected the feeder is 10 MW. South Korean DSOs limit the permissible load capacity connected to the feeder to 10 MW in the distribution system to account for thermal constraints of the lines and transformers and prevent power outages if a fault occurs because power is received from surrounding healthy feeders.

Small-capacity PV systems can be connected to a distribution system without limitations, and according to the Korean government plan, DSOs must achieve their goals by increasing the permissible capacity of PV systems. Therefore, the test model in this study considers overvoltage because of increasing the installed PV capacity due to the government plan.

Fig. 2 shows the normalized annual profiles of PV generation and loads adopted in [44] and [45]. The x-axis represents time (in hours) for a duration of one year, and the y-axis represents the profile of the PV output or load power usage. The PV output is the highest in May because of the weather in South Korea. In South Korea, power consumption is higher during summer and winter than in other seasons and low during holidays, such as the Korean New Year's Day and Thanksgiving Day. Although algorithm verification using specific PV and load data may limit the generality of the results, the consumption profile of a typical feeder in South Korea is similar to that shown in Fig. 2, thus providing representative data. In addition, the proposed algorithm can be adjusted using data obtained from operation history or prediction during the planning stage, and hence, it can be adapted to any profile in the distribution system.



(a) (b)

FIGURE 2. **Normalized profiles for (a) PV generation and (b) power consumption, as obtained from real data in South Korea [44], [45].**

The VVC parameter update performed on an hourly or daily basis from existing studies is difficult to implement in practice due to factors such as limitations of communication systems and operational constraints. Although communication limitations are not a major problem in large PV systems, most systems in South Korea have small capacities and are widely distributed throughout the feeder. Thus, we analyze the effect of the feasible periods for practical VVC parameter updates in Section III-B.

Fig. 3 shows the voltage profile at the end of the feeder (bus 12) on a day of high PV output with and without the service transformer in the test model. When the service transformer is considered in the test model, the voltage is lower than without considering the transformer in the distribution system. Thus, unlike previous studies, we consider the service transformer (Fig. 1) to set the smart inverter VVC for improved reliability. Moreover, the service transformer can lead to improved VVC settings [33], [46], [47].

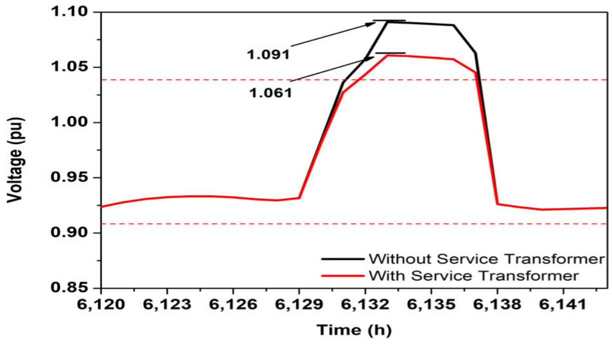


FIGURE 3. **Voltage profiles at feeder end (bus 12) with and without using service transformer.**

Fig. 4 shows the voltage according to the position along the feeder when calculating the power flow in the static mode assuming no PV system connection. The voltage drops as the

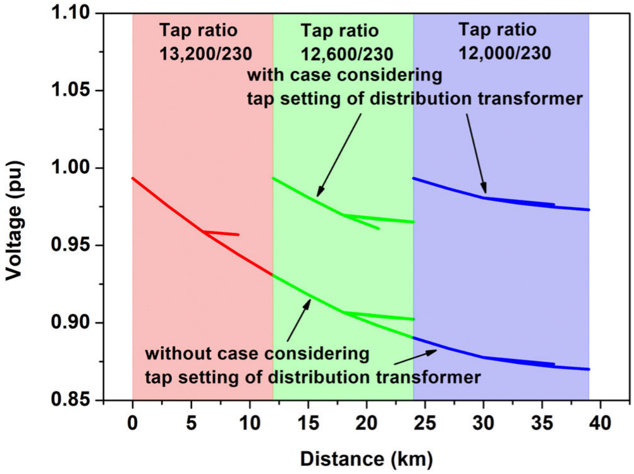


FIGURE 4. Test model voltage according to distance along feeder without considering PV systems.

distance from the substation increases. To supply high-quality power to consumers (load), the fixed tap of the distribution transformer should be set considering the voltage drop. Along the feeder head (0–12 km), the voltage drop is small, and the distribution transformer tap can be set to the secondary voltage (13200/230 V) of the substation. Along the feeder middle section (12–24 km) and end (24–36 km), the distribution transformer tap should be set according to the voltage drop. Similarly, the tap configuration facilitates improvement in the VVC settings. In Section III-C, we detail efficient VVC settings for multiple PV systems obtained from clustering and considering the transformer tap settings suitable for the South Korean distribution systems.

B. SMART INVERTER VVC

We use the smart inverter VVC to prevent overvoltage caused by high PV penetration and increase the overall performance of the distribution system. The VVC can support power quality by controlling the reactive power of the PV system according to the voltage at the point of common coupling. Fig. 5 shows a generic VVC that provides reactive power ($Q_{s,i}$) according to the voltage at the point of common coupling ($V(t)$) as detailed in (1) [22], [26], [33], [48]. When the voltage exceeds an upper level, the PV system prevents further voltage increase by absorbing reactive power. When the voltage falls below a specific threshold, the PV system increases the voltage by supplying reactive power.

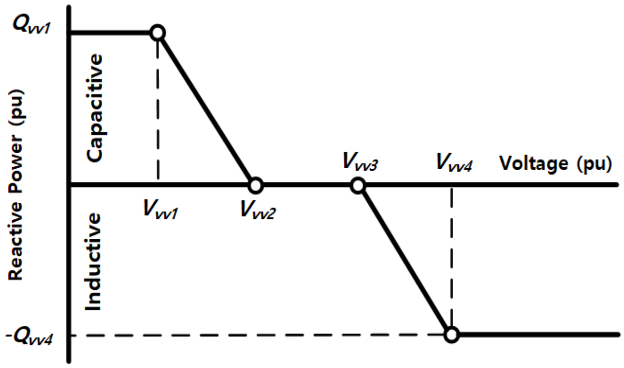


FIGURE 5. Generic VVC to mitigate voltage fluctuations [22], [33], [48].

Fig. 6 shows the voltage profile at the feeder end with and without the VVC. Without the VVC, the voltage at the feeder end most affected by the PV system surpasses the upper (1.039 pu) and lower levels (0.908 pu). The VVC default setting (level 1) in the smart inverter ([22], [33], [48]) facilitates the mitigation of the deviations in voltage, which remain within the normal operating range. However, as the VVC not only affects the voltage but also the system loss and PV output, the optimal setting considering tradeoffs between various factors should be determined, as detailed in Section II-C.

$$Q_{s,i}\left(V\left(t\right)\right) = \begin{cases} Q_{vv1} & V\left(t\right) \leq V_{vv1} \\ -\dfrac{Q_{vv1}}{V_{vv2}-V_{vv1}}\left(V\left(t\right)-V_{vv2}\right) & V_{vv1} < V\left(t\right) \leq V_{vv1} \\ 0 & V_{vv2} < V\left(t\right) \leq V_{vv2} \\ \dfrac{Q_{vv4}}{V_{vv4}-V_{vv3}}\left(V\left(t\right)-V_{vv3}\right) & V_{vv3} < V\left(t\right) \leq V_{vv4} \\ Q_{vv4} & V_{vv1} \leq V\left(t\right) \end{cases} \tag{1}$$

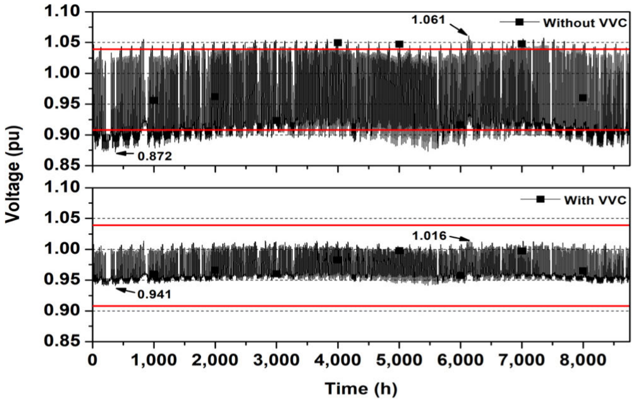


FIGURE 6. Voltage profiles at feeder end (bus 12) with and without VVC.

A PV system produces energy according to the solar irradiance and weather conditions. The generated energy is delivered to the distribution system via the power conversion system, whose capacity is smaller than the panel capacity for economic feasibility, because a PV system does not always operate at its maximum capacity. However, as the contribution of reactive power increases by applying the VVC, the active power may be affected by the low capacity of the power conversion system. In the test model, the capacity of the power conversion system is larger than that of the panel to comprehensively evaluate the proposed algorithm. Fig. 7 shows the capacity relationship between active and reactive power [18], [19], [22], [41], [42], [48]. The reduced active power by increased reactive power leads to a profit

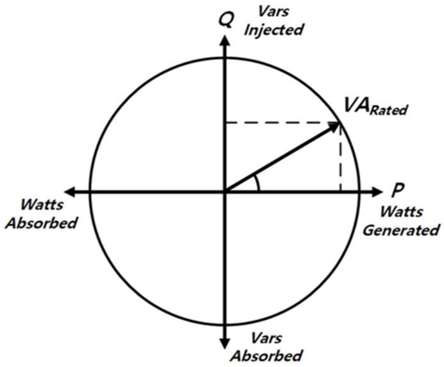


FIGURE 7. Capacity relationship between active and reactive power at an inverter [18], [19], [22], [41], [42], [48].

loss for PV system owners. In the South Korean distribution system, most PV system owners are individuals who cannot reduce the active power according to reactive power. Therefore, the peak of reactive power must be limited when implementing the VVC in a smart inverter.

C. VVC SETTING ALGORITHM TO IMPROVE SYSTEM PERFORMANCE

We use a genetic algorithm as the optimization method to set the VVC parameters. Globally, genetic algorithms are widely used metaheuristic methods to optimize distribution system problems [12], [13], [42], [43]. To set the smart inverter optimally using the GA algorithm, three challenges must be overcome. The first challenge involves limited applicability owing to complexity; this is not a significant limitation because the proposed algorithm derives the optimal parameters based on the input data. Moreover, the clustering technique, which is an integral part of the proposed algorithm, simplifies the complex distribution system. In the field, it is easy to apply this algorithm as it can be used by converting from MATLAB to C, C++, or Fortran through OpenMP [49]. The second challenge concerns avoiding the algorithm from falling into local minima. This problem was addressed by setting the starting point randomly [50]. In addition, the iterations were increased by increasing the generation and initial value was newly set to perform repeated calculation. The third challenge was regarding the calculation time. Although the algorithm is a part of the planning stage, the computational time required can increase when the number of iterations increase. This problem was effectively improved via parallel computation, which divides the algorithm into modules and calculates them simultaneously [50]. Through parallel computing, the calculation time was reduced by about 70% (number of CPU cores: 10). The algorithm will thus determine the optimal setting of the smart inverter more rapidly using the distribution system operator's workstation with multiple cores.

Fig. 8 shows the optimization flowchart for VVC parameters. For optimization, we consider details of the distribution system, PV system, and load profile. The algorithm provides different options according to various scenarios.

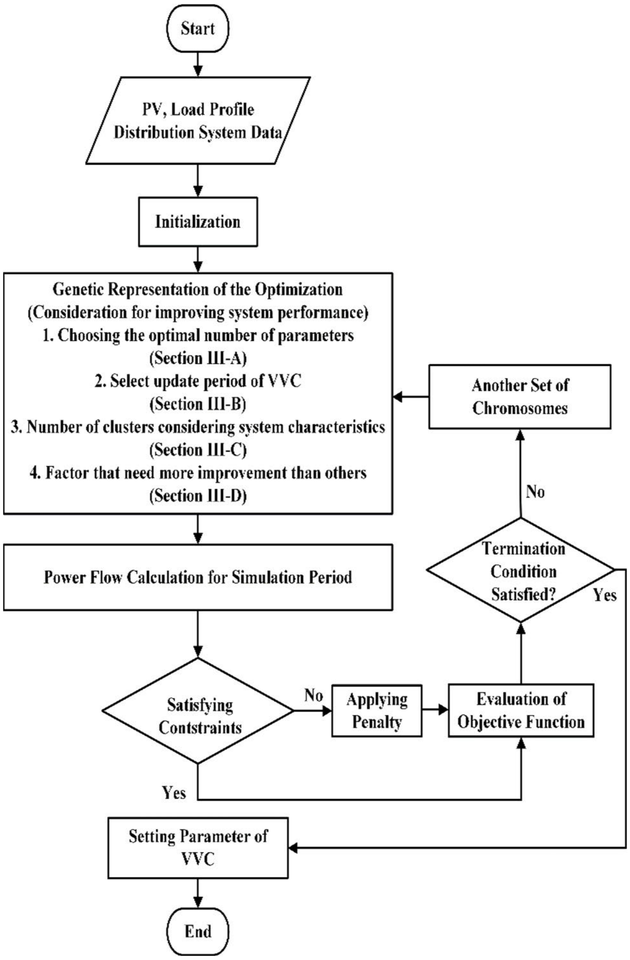


FIGURE 8. Flowchart of the proposed algorithm for optimal VVC setting.

1) The number of VVC parameters to optimize is selected. Although more parameters increase the VVC effectiveness, the computational burden may be excessively large. In addition, the effectiveness does not improve linearly with the number of parameters, as analyzed in Section III-A.
2) The periods for VVC update in the smart inverter are set. In previous studies, the VVC was assumed to be updatable on a daily or hourly basis without considering communication and implementation constraints. In practice, however, it is difficult to establish fast communication and reliable updates for numerous small-capacity PV generators connected to the distribution system. In Section III-B, we analyze the period for VVC updates in the smart inverter considering seasonal and annual time frames.
3) We use clustering to efficiently set the VVC in multiple PV systems. In previous studies, the same VVC was implemented across PV systems in a feeder. However, to improve performance, the VVC should be set according to each PV system, whose characteristics depend on its position along the feeder. The efficient VVC setting in several small-capacity PV systems using

clustering for grouping similar systems is detailed in Section III-C.

4) The factor that contributes the most toward the improvement in performance should be determined considering the operation conditions. In previous studies, various factors from the distribution system were considered for multiobjective optimization. However, the factors were not properly weighted. For instance, a weight of 0 excluded the corresponding factor from multiobjective optimization. For weight selection, the proposed algorithm allows DSOs to set the VVC for effective operation according to different conditions by prioritizing specific factors, as detailed in Section III-D.

After considering the four scenarios for the algorithm, we evaluate constraints (3) and (4) through power flow calculations. Thereafter, the VVC is set by determining the optimal parameters that minimize the objective function (5).

Equation (2) represents the multiobjective optimization function to improve system performance via optimal VVC setting. We iteratively determine the minimum value of the objective function by considering the voltage deviation ($\delta V_{i,t}$), system loss (P_t), and peak reactive power (Q_i). The values in the denominator and numerator represent the results from a conventional method (default setting) and the optimized VVC, respectively. With these three system factors, the denominator represents the conventional method, and the numerator represents the new setting. Thus, when the weight of a factor is 1, a fitness value below 3 indicates an improvement over the conventional method.

The VVC is formed using a gene (V_{new}) from the genetic algorithm corresponding to the minimum fitness value. The weight (ω) for each factor is evaluated to provide different options to the DSOs, as detailed in Section III-D.

$$\begin{aligned} & \mathit{MinO}\cdot F\,(vv_{\text{new}}) \\ & = \min\left[\left(\omega_1 \frac{\sum_{t=1}^{8760}|\delta V_{i,t}\,(vv_{\text{new}})\,|}{\sum_{t=1}^{8760}|\delta V_{i,t}\,(vv_{\text{con}})\,|}\right)\right. \\ & \quad \left. +\left(\omega_2 \frac{\sum_{t=1}^{8760}|P_t\,(vv_{\text{new}})\,|}{\sum_{t=1}^{8760}|P_t\,(vv_{\text{con}})\,|}\right) + \left(\omega_3 \frac{max|Q_i\,(vv_{\text{new}})\,|}{max|Q_i\,(vv_{\text{con}})\,|}\right)\right] \end{aligned} \tag{2}$$

Table 3 lists the voltage operation range for South Korean distribution systems [51], and (3) shows the corresponding constraint for VVC parameter optimization:

$$V_i^{\min} \leq V_{i,t} \leq V_i^{\max} \tag{3}$$

where $V_i^{\min} = 0.908$ pu and $V_i^{\max} = 1.039$ pu.

Equation (4) establishes parameter constraints for the VVC to be implemented in the smart inverter. The VVC dead band depends on V_{vv2} and V_{vv3}. Unlike existing optimization methods, we optimally set parameters Q_{vv1} and Q_{vv2} related to the reactive power to minimize adverse effects on the PV output. As the PV output (Fig. 7) is directly related to profitability, the DSOs should minimize the adverse effects when optimizing the VVC parameters.

TABLE 3. Voltage range required in the South Korean distribution system [51].

Nominal voltage	Voltage operating range
22,900 V 1.00 pu	20,800–23,800 V (−2,100–900 V) 0.908–1.039 pu

$$\begin{gathered} V_{vv1} < V_{vv2} \leq V_{vv3} < V_{vv4} \\ 0 \leq |Q_{vv1}| \leq 1, \quad 0 \leq |Q_{vv4}| \leq 1 \end{gathered} \tag{4}$$

Equation (5) represents the fitness value to improve the system performance at each iteration by using (2) and constraints (3) and (4). The constraint coefficient (ω_{c}) is set to a very large value (close to infinity) to determine the parameters within the ranges that satisfy the constraints. The large weight aims to determine the optimal value to conform to the constraints. When a fitness value lower than 3 is obtained, the constraint is considered as satisfied, and the performance of the parameter setting is better than that obtained using a conventional method.

$$\mathit{MinF}\,(vv_{\text{new}}) = \min\left[O\cdot F(vv_{\text{new}}) + \sum_{c\in N_{\text{const}}} \omega_{\text{c}}\cdot PF_{\text{c}}\right] \tag{5}$$

III. SIMULATION RESULTS

We verified the effectiveness of the proposed algorithm through simulations using OpenDSS, a quasistatic time-series simulator.

A. NUMBER OF OPTIMIZED VVC PARAMETERS

We first analyzed the effect of the number of optimized parameters on the proposed algorithm. Few optimal parameters limit the performance improvement, whereas several optimal parameters increase the computational burden and hinder practical applicability. Therefore, a tradeoff between performance and efficiency should be determined. Table 4 lists various cases to evaluate the number of parameters to be optimized. Case A-1 presents the VVC of the conventional method for comparison. Case A-2 considers two voltage parameters in Fig. 5 for optimization. Case A-3 considers two

TABLE 4. Cases to evaluate the number of optimized parameters (Fig. 5) in proposed algorithm.

Case	V_{vv1}	V_{vv2}	V_{vv3}	V_{vv4}	Q_{vv1}	Q_{vv2}	Q_{vv3}	Q_{vv4}
A-1 (conventional method)	0.92	0.98	1.02	1.08	0.44	0	0	–0.44
A-2	0.92	Var.	Var.	1.08	0.44	0	0	–0.44
A-3	0.92	Var.	Var.	1.08	Var.	0	0	Var.

Var. = Parameter to be optimized

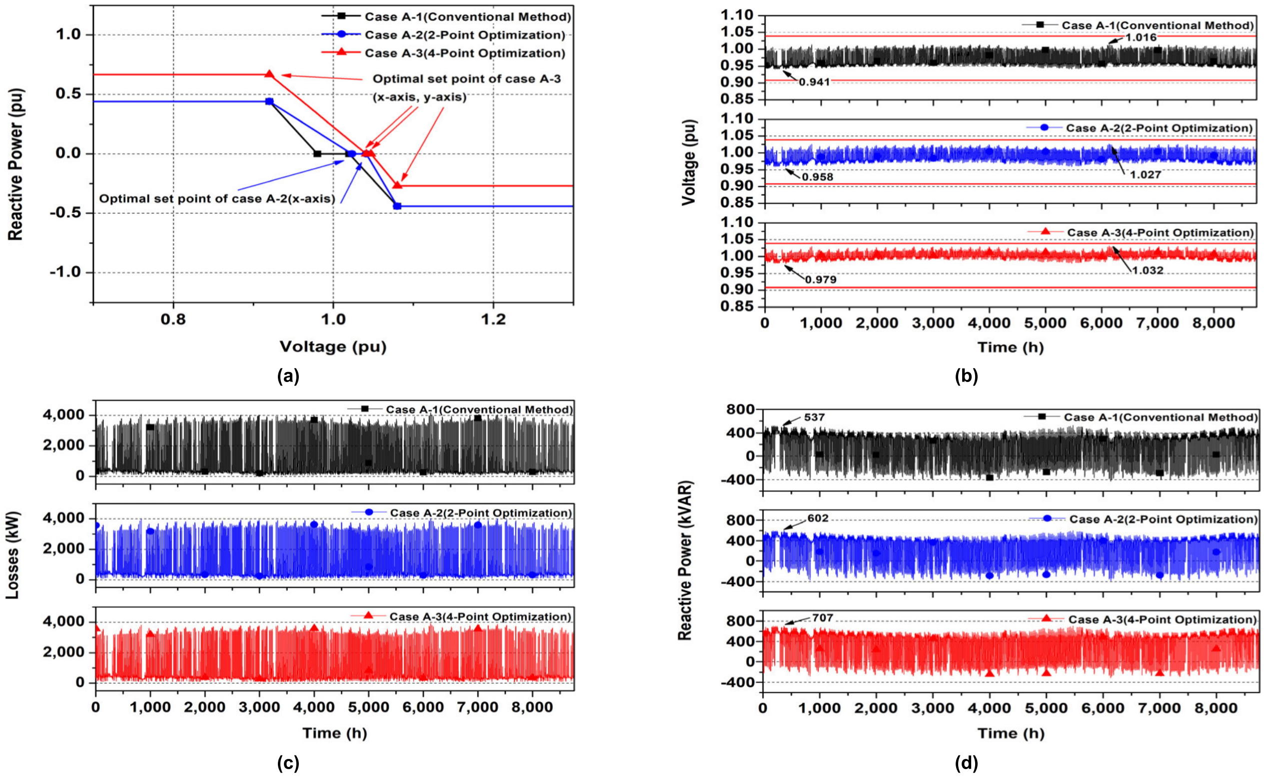


FIGURE 9. System performance according to number of optimized parameters. (a) VVCs obtained from cases in Table 4. (b) Voltage at bus 12, (c) system loss, and (d) reactive power at PV system 5 for each case.

voltage and two reactive power parameters in Fig. 5 for optimization. Therefore, case A-2 allows adjusting the parameters along the *x* axis, and case A-3 allows adjusting the parameters along the *x* and *y* axes in Fig. 5.

Fig. 9(a) shows the curve (Fig. 5) obtained from the three cases listed in Table 4. For case A-2, only the dead-band parameters are optimized, whereas for case A-3, the voltage and reactive power parameters are optimized. Figs. 9(b)–(d) show the system performance when implementing the VVC settings for the three cases. Table 5 lists the performance results obtained from the evaluated cases. The voltage deviation was the largest at the feeder end (bus 12), and the peak of reactive power was the largest at PV system 5 connected to the feeder end. Case A-3 provides the smallest voltage deviation, whereas case A-2 provides the smallest loss. The optimized parameters (cases A-2 and A-3) provide higher peaks of reactive power than that of the conventional method (case A-1).

TABLE 5. Performance results according to the number of optimized parameters.

Case	Cumulative voltage deviation	Loss (MWh/year)	Peak of reactive power (kVAR)	Fitness value in (5)
A-1	283.89	10,649	537	3
A-2	151.73	10,468	602	2.640
A-3	76.91	10,586	707	2.582

Although the results vary for different cases, case A-3 provides the best fitness value. In addition, the system performance is improved by optimally setting the parameters along the *x* and *y* axes in Fig. 5 to implement the VVC in the smart inverter. Therefore, optimizing more parameters has a better effect on the objective function. Although various parameters were not considered for optimization (e.g., V_{vv1}, V_{vv4}, Q_{vv2}, and Q_{vv3}), most VVCs can be derived from the four parameters optimized in case A-3. Hence, the overall system performance is improved by optimizing the four parameters from case A-3.

B. UPDATE PERIOD OF VVC IN SMART INVERTERS

We analyzed the effect of the VVC updating period in the smart inverters. Although most conventional studies consider hourly or daily updates to improve performance, such regular updating over long terms may be difficult due to problems such as communication limitations. Large-capacity PV systems have no problems for frequent updates. In contrast, numerous small-capacity PV systems connected to the distribution system face challenges for frequent updating due to economic reasons.

Table 6 lists the cases for analyzing the effects of VVC update periods. As Korea has four well-defined seasons, we consider seasonal updates because small-capacity PV systems are usually checked every season by their owners. Case A-1 corresponds to the conventional update method, whereas case A-3 corresponds to the setting with the

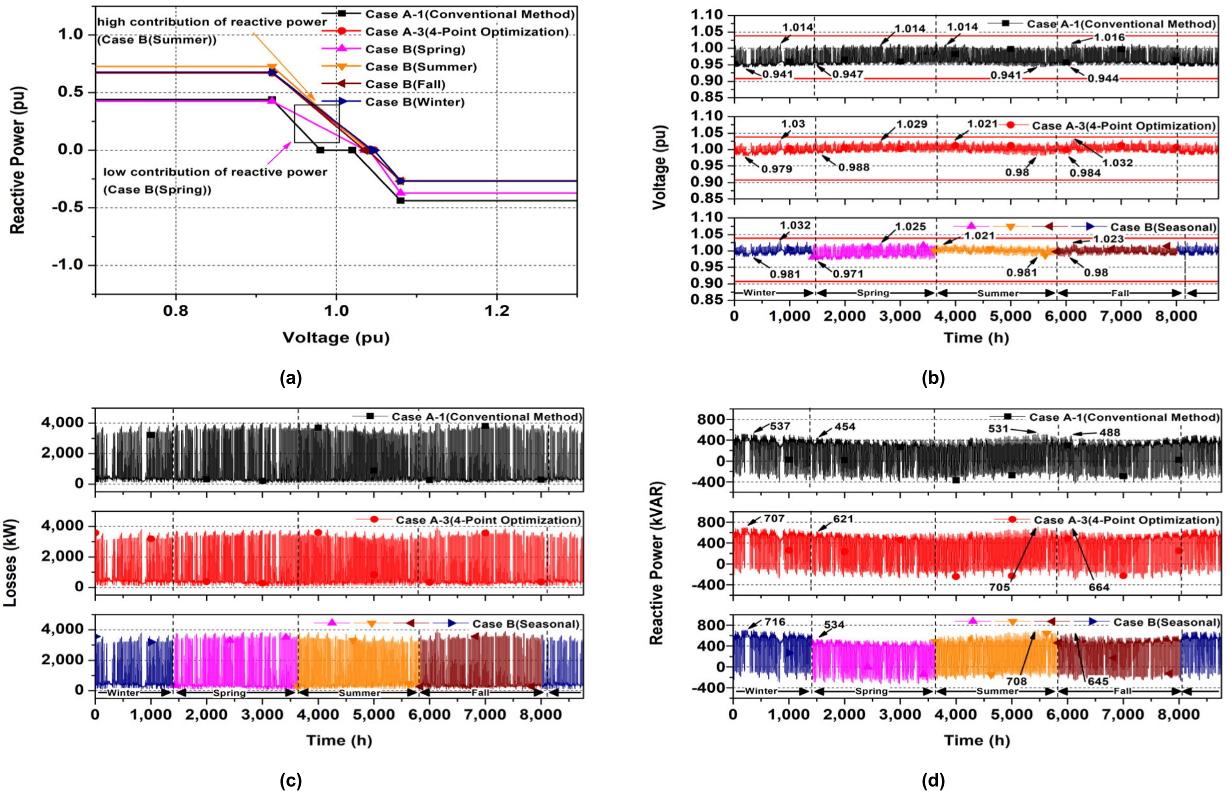


FIGURE 10. System performance according to VVC update period. (a) VVCs obtained from cases in Table 6. (b) Voltage at bus 12, (c) system loss, and (d) reactive power at PV system 5 for each case.

TABLE 6. Cases to evaluate VVC parameter update periods.

Case	Spring (h)	Summer (h)	Fall (h)	Winter (h)
A-1	Conventional method over 1 year			
A-3	Case A-3 over 1 year			
B	1418 to 3625	3626 to 5833	5834 to 8017	8018 to 8760, 1 to 1417
	Optimal VVC parameters from case A-3 optimized and updated every season			

TABLE 7. Performance results according to VVC update period.

Case	Season	Cumulative voltage deviation	Loss (MWh/season)	Peak of reactive power (kVAR)	Fitness value in (5)
A-1	Spring	67.97	2,776	454	3
	Summer	65.57	3,127	531	3
	Fall	69.05	2,615	488	3
	Winter	81.64	2,130	537	3
A-3	Spring	19.36	2,748	621	2.642
	Summer	19.48	3,076	705	2.609
	Fall	17.95	2,599	664	2.615
	Winter	20.12	2,161	707	2.578
B	Spring	30.92	2,725	534	2.611
	Summer	14.79	3,115	708	2.553
	Fall	17.08	2,622	645	2.573
	Winter	18.03	2,165	716	2.571

four optimal parameters. For cases A-1 and A-3, operation is shown over 1 year without updates. In addition, we consider case B with the four optimal VVC parameters obtained and implemented every season considering the changing characteristics.

Fig. 10(a) shows the VVCs for the cases listed in Table 6. Unlike yearly updates (cases A-1 and A-3), the seasonal update (case B) presents four different VVCs. Figs. 10(b)–(d) show the system performance for the VVC update cases, and Table 7 lists the performance results per season. The seasonal VVC update provides varied results. For example, case B provides higher peaks of the reactive power than case A-1 in all the seasons. In addition, case B provides higher voltage deviation than that of case A-3 during spring. However, the fitness value that reflects the overall system performance is the best in case B for every season.

In Fig. 10(a), the VVC for case B set during spring has a lower contribution than those for the other cases, resulting in a high voltage deviation. However, by improving the system loss and peak of reactive power, the fitness value in case B is improved than that in other cases. In summer, the VVC for case B has a higher contribution than those for the other cases in the low-voltage area, thus mitigating voltage deviations. In fall, the VVC for case B improves both the voltage deviation and peak of reactive power compared with the optimal setting for 1 year (case A-3). In winter, the VVC for case B reduces the voltage deviation compared with that for case A-3. Therefore, the seasonal VVC update in smart inverters is better than the yearly update.

As real-time update of the smart inverter is not feasible, an appropriate update period should be set according to the communication and control system capabilities. For example, if operation characteristics vary across seasons like in South Korea, the system performance may be improved by seasonal updates.

C. VVC SETTINGS APPLIED TO MULTIPLE PV SYSTEMS USING CLUSTERING

We evaluated the application of VVC settings for multiple PV systems grouped by clustering. In previous studies, various PV systems connected to a feeder shared the same VVC setting, thus limiting the VVC effectiveness. To improve the system performance, each PV system must have a specific VVC setting. However, individual VVCs for many small-capacity PV systems distributed in a feeder are difficult to obtain and implement. Therefore, we classify the PV systems connected to a feeder by clustering according to the optimal VVC. We used k-means clustering considering the tap setting trends of the distribution transformers. Thereafter, we evaluated the cases listed in Table 8.

TABLE 8. Cases to evaluate VVC settings in multiple PV systems grouped by clustering.

Case	Description
A-1	Multiple PV systems with the same VVC setting obtained from conventional method
A-3	Multiple PV systems with the same optimal VVC setting
C	PV systems grouped by clustering to use optimal VVC settings per group

Equation (6) represents the variance to perform k-means clustering. Various PV systems (S_l) with a minimum voltage deviation representing the variance (E) are clustered. The number of clusters (k) should be determined. Fig. 4 shows the setting $k = 3$ according to the three fixed taps of the distribution transformers in the South Korean distribution system.

$$E = \min \sum_{l=1}^{k} \sum_{j \in S_l} |x_j - \mu_l|^2 \qquad (6)$$

Fig. 11 shows the clustering results of the test model according to the characteristics of the South Korean distribution system. As shown in Fig. 4, when the feeder is divided into three groups based on the voltage drops, three optimal VVCs can be obtained and assigned to the corresponding PV systems. Fig. 12(a) shows the VVCs for each PV system group in the feeder. As the PV systems are farther from the substation, the overvoltage reduces, and the VVC with the highest contribution of reactive power is obtained for region C (Fig. 11). Figs. 12(b)–(d) show the performance results according to the VVCs per case, and Table 9 lists the corresponding results. The voltage deviation for case C (with clustering) is lower than that of the conventional method (case A-1) but higher than the optimal VVC setting applied to all PV systems (Case A-3). In addition, for case C, the system loss is higher than that for cases A-1 and A-3, whereas the peak of reactive power is lower than that for case A-3. Nevertheless, the overall performance of VVC setting via clustering is higher than the settings for cases A-3 and A-1, thus confirming the benefit of implementing optimal VVCs for different groups of PV systems. Moreover, clustering allows to set optimal VVCs for small-capacity PV systems with similar operation conditions; in addition, other system and operation characteristics may be added to the clustering algorithm to further improve performance.

TABLE 9. Performance results according to the VVC implemented in multiple PV systems.

Case	Cumulative voltage deviation	Loss (MWh/year)	Peak of reactive power (kVAR)	Fitness value in (5)
A-1	283.89	10,649	537	3
A-3	76.91	10,586	707	2.582
C	111.62	11,799	561	2.546

D. VVC SETTINGS PRIORITIZING DIFFERENT FACTORS

Finally, we evaluated the prioritization of different factors by the DSOs to optimize the VVC. As the operation conditions of distribution systems vary, the VVC must be implemented in the smart inverter accordingly. Although the proposed algorithm facilitates performance improvement by a multi-objective optimization function (fitness value), the effect on each factor is different. Therefore, the proposed algorithm can be adjusted by the DSOs to implement optimal VVCs in the smart inverters by prioritizing factors that require more improvement.

Table 10 lists the cases to analyze factor prioritization for VVC optimization by adjusting the weights of each factor of the multiobjective optimization function in (2). A high weight prioritizes the corresponding factor, and the VVC parameters improve this factor over the others. Case A-1 represents the VVC setting with the conventional method, and case A-3 represents the VVC setting obtained from optimization, with equal weights for all the factors. Cases D-1 to D-3 prioritize minimization of the cumulative voltage deviation, system loss, and peak reactive power, respectively. However, no factor is disregarded in these cases (minimum weight of 1), and the prioritized factor has weight 3 because there are three factors for optimization. Nevertheless, the weights can be set by the DSO according to the operation requirements and conditions.

Fig. 13(a) shows the VVCs for the different factor weights. The VVC for case D-1 provides more reactive power while

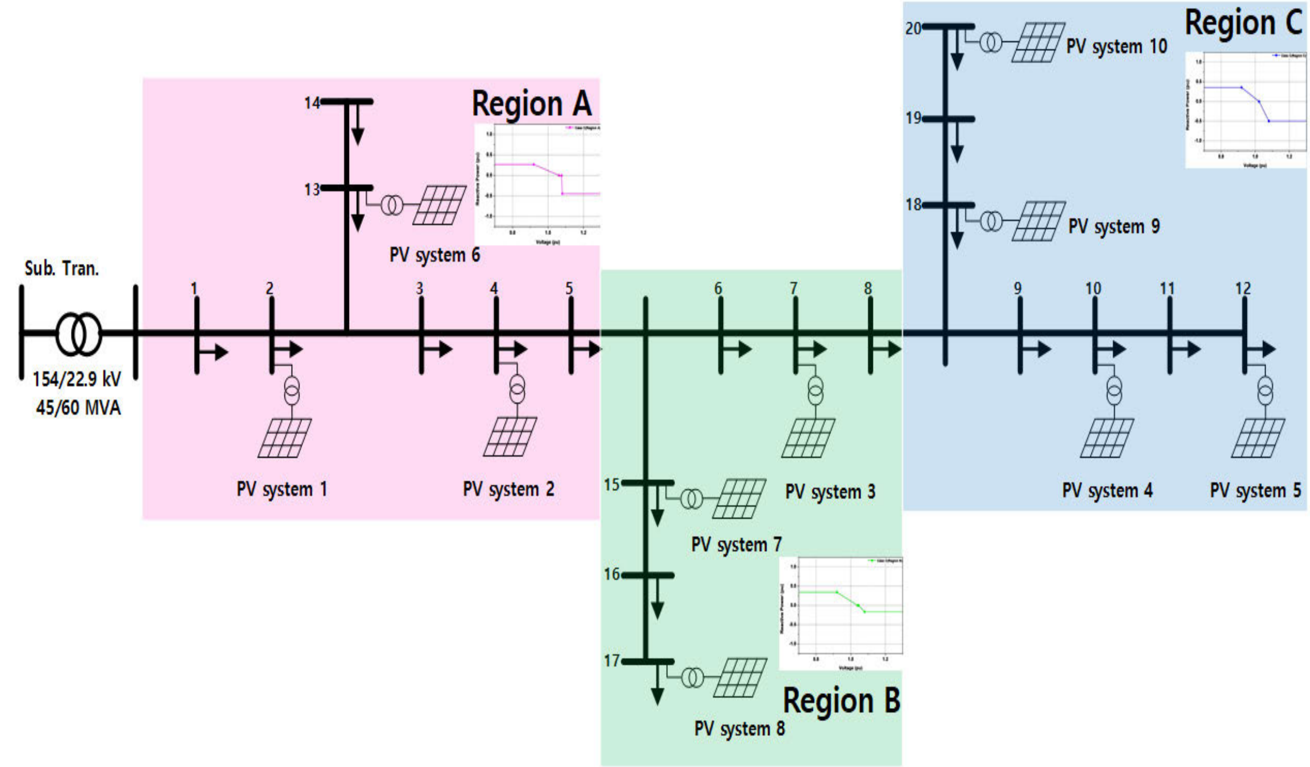


FIGURE 11. PV systems in the test model classified via clustering by considering the trends set for the distribution transformer.

TABLE 10. Cases to evaluate different prioritization of factors affecting the system performance.

Case	ω_1	ω_2	ω_3
A-1	Conventional method (default setting)		
A-3	1	1	1
D-1 (Priority to voltage deviation)	3	1	1
D-2 (Priority to system loss)	1	3	1
D-3 (Priority to peak of reactive power)	1	1	3

TABLE 11. Performance results by prioritizing factors for improvement.

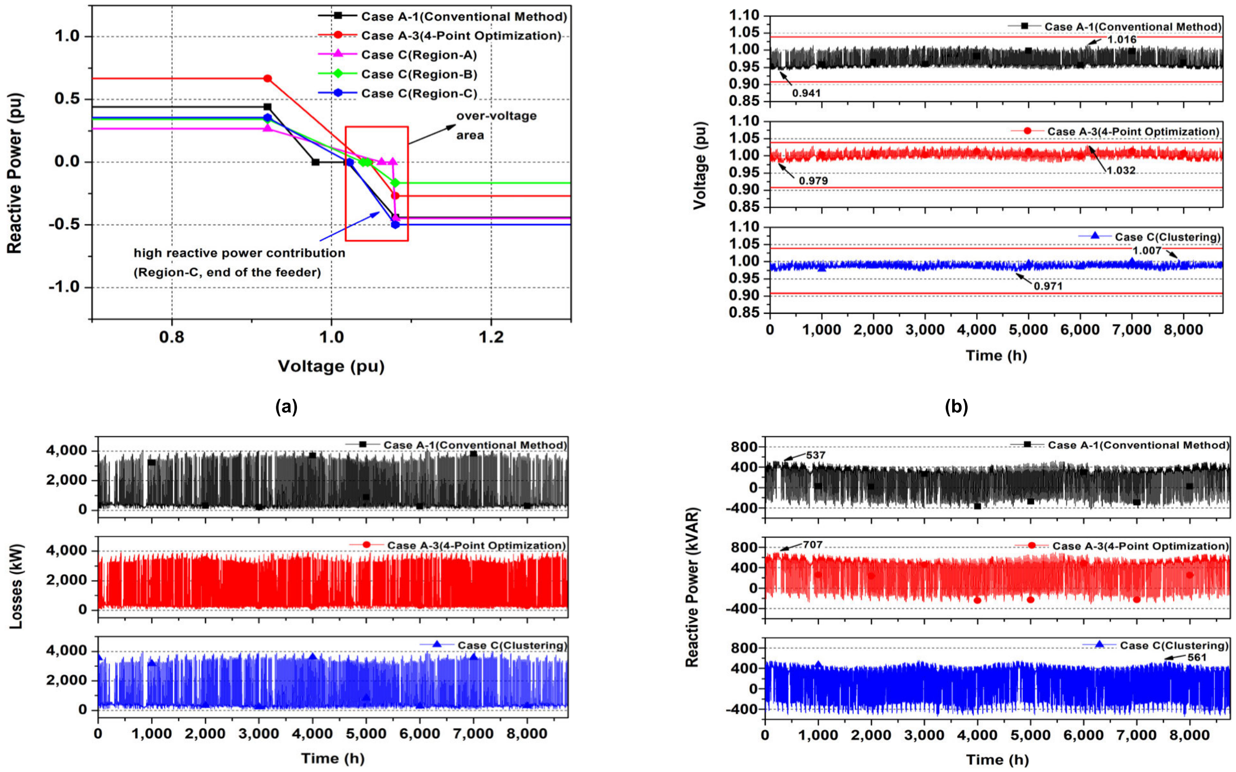
Case	Cumulative voltage deviation	Loss (MWh/year)	Peak of reactive power (kVAR)	Fitness value in (5)
A-1	283.89	10,649	537	3
A-3	76.91	10,586	707	2.582
D-1	46.91	10,808	733	2.877
D-2	89.89	10,221	680	4.464
D-3	316.22	10,517	344	4.023

reducing the voltage deviation compared with the other cases. Therefore, in Fig. 13(b), the voltage profile for case D-1 is the closest to the nominal voltage. The VVC for case D-2 reduces the system loss more than the VVCs for the other cases. Therefore, in Fig. 13(c), case D-2 shows the lowest system loss, as verified quantitatively in Table 11. The factors contributing to system loss are diverse, and thus, it is difficult to analyze the loss by considering only the VVC. The VVC for case D-3 suppresses the contribution of reactive power more notably than the VVCs for the other cases. In Fig. 13(d), the peak of reactive power is the lowest for this case.

Table 11 lists the performance results for each case. The fitness values for cases D-1 to D-3 increase compared with those for case A-3. In addition, the prioritized factor is successfully improved over the other factors. Therefore, prioritizing factors is convenient to set the VVC according to operation and system conditions. In general, case A-3, which sets the same weight for all the factors, is the best choice for overall system performance improvement.

IV. DISCUSSION

Table 12 summarizes all the evaluations of the proposed algorithm. Cases A (Section III-A) demonstrate the effects of the numbers of parameters optimized by the proposed algorithm. The best overall performance is achieved for case A-3, which optimizes four parameters determining the VVC. The optimization for case A-3 improves the performance by 12% compared with the conventional method



(a)

(b)

(c)

(d)

FIGURE 12. System performance according to VVC settings for all or groups of PV systems. (a) VVCs obtained from cases in Table 8. (b) Voltage at bus 12, (c) system loss, and (d) reactive power at PV system 5 for each case.

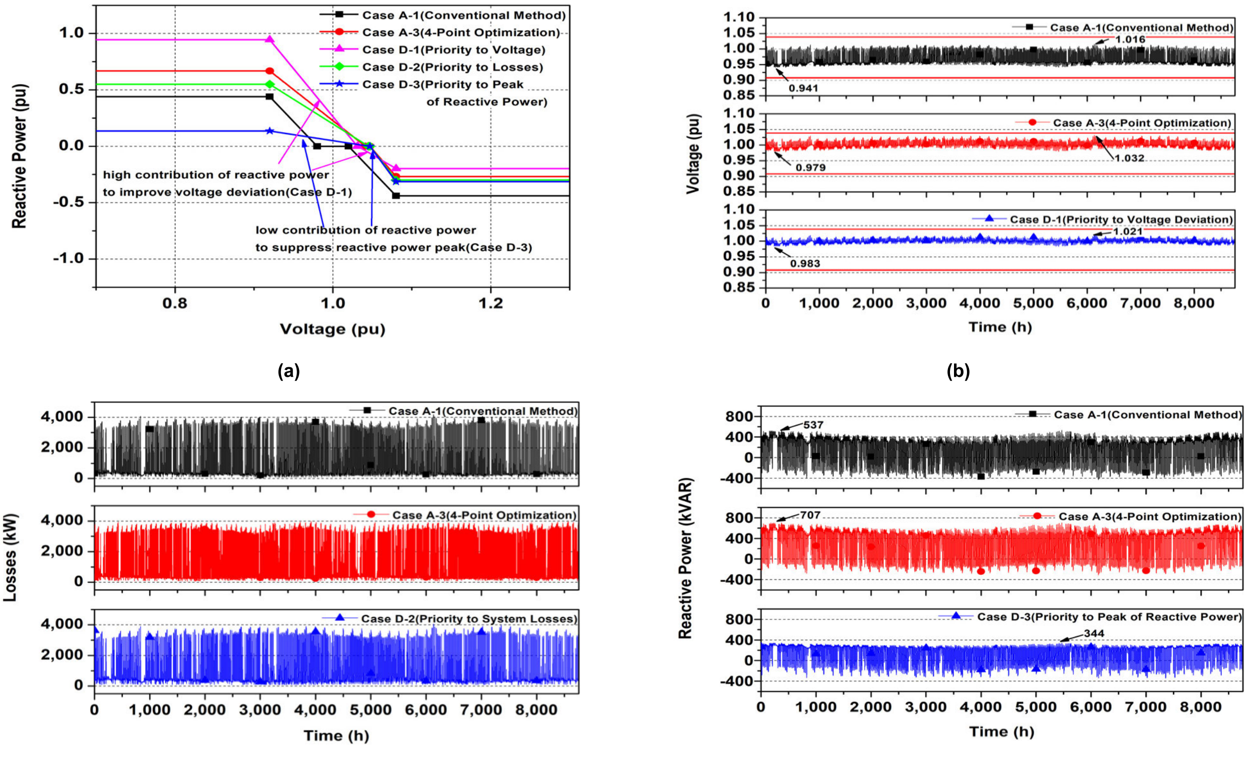
TABLE 12. Overall results obtained from evaluations of the proposed algorithm to improve performance in distribution systems.

Case	Cumulative voltage deviation	Loss	Peak of reactive power (kVAR)	Fitness value in (5)	Description
A-1	283.89	10,649 MWh/year	537	3	Conventional method (default setting)
A-2	151.73	10,468 MWh/year	602	2.640	Two-parameter optimization
A-3	76.91	10,586 MWh/year	707	2.582	Four-parameter optimization
B (A-3)	30.92 (19.36)	2725 (2,748) MWh/season	534 (621)	2.611 (2.642)	Seasonal VVC update (spring)
	14.79 (19.48)	3115 (3,076) MWh/season	708 (705)	2.553 (2.609)	Seasonal VVC update (summer)
	17.08 (17.95)	2622 (2,599) MWh/season	645 (664)	2.573 (2.615)	Seasonal VVC update (fall)
	18.03 (20.12)	2165 (2,161) MWh/season	716 (707)	2.571 (2.578)	Seasonal VVC update (winter)
C	111.62	11,799 MWh/year	561	2.546	VVC settings for multiple PV systems grouped by clustering
D-1	46.91	10,808 MWh/year	733	2.877	VVC settings prioritizing minimization of voltage deviation
D-2	89.89	10,221 MWh/year	680	4.464	VVC settings prioritizing minimization of system loss
D-3	316.22	10,517 MWh/year	344	4.023	VVC settings prioritizing minimization of peak of reactive power

(case A-1) and by 2% compared with the optimization of two parameters (case A-2).

Case B (Section III-B) was used to evaluate the effect of the VVC update period in the smart inverter. The daily or hourly update assumption depending on the surrounding conditions, such as weather or load, had several limitations. To overcome these problems, the effects of the annual and updated seasonal settings were compared, considering the seasonal characteristics of South Korea.

Compared with the conventional method (case A-1), the fitness value improves by 13% during summer and spring and by approximately 15% during autumn and winter when the VVC parameters are updated seasonally. Compared with the optimal annual update, the seasonal update improves the



(a)

(b)

(c)

(d)

FIGURE 13. System performance by prioritizing factors for optimization. (a) VVCs obtained from cases in Table 10. (b) Voltage at bus 12, (c) system loss, and (d) reactive power at PV system 5 for each case.

performance by 2% during spring and fall, 3% during summer, and 1% during winter. Therefore, we confirmed that the system performance can be improved by setting shorter VVC update periods with the corresponding optimal parameters.

Case C (Section III-C) analyzed the optimal VVC settings for groups of PV systems obtained by clustering compared with the same setting for all the systems. In the distribution system, several small-capacity PVs were connected. In the conventional methods, the improvement in effect was limited because multiple PVs connected to the feeder were set to the same VVC. The proposed algorithm effectively sets multiple PVs through clustering, considering the setting trend of distribution transformers. Case C with VVC settings for PV system clusters improves the fitness value by 16% compared with the conventional method and by 2% compared with the optimal VVC for all the PV systems.

Finally, case D (Section III-D) evaluated the prioritization by the DSOs of different factors during optimization. Prioritization can be decided considering the conditions and requirements in the distribution system. In a previous study, the overall multiobjective function factor was not considered appropriately because its weight was not considered appropriately. For example, if the objective function factor weight is set at '0', there is no reason to use multiple-objective functions. Therefore, in addition to considering the overall factors, a curve suitable for the system situation was formed by selecting a higher weight for the factor that requires improvement. Case D-1 aimed to minimize the voltage deviation, obtaining improvements of 84% compared with the conventional method (case A-1) and 40% compared with the optimal VVC without prioritization (case A-3). Case D-2 aimed to minimize the system loss, obtaining improvements of 5% compared with the conventional method and 4% compared with the optimal VVC without prioritization. Likewise, case D-3 aimed to minimize the peak of reactive power, obtaining improvements of 36% compared with the conventional method and 52% compared with the optimal VVC without prioritization. Although the fitness values of cases D-1 to D-3 are higher than those of other cases, prioritization can considerably improve the highly weighted factors.

According to input data such as pv, load, and system configurations, the proposed algorithm optimally sets the smart inverter. Therefore, a trade-off relationship may produce different effects for each factor. However, the proposed algorithm optimally sets the smart inverter to the system condition according to the objective function and weight.

V. CONCLUSION

We proposed an algorithm to improve the performance of a distribution system by optimizing the VVC parameters implemented for smart inverters when several PV systems are connected to a common feeder. The proposed algorithm addressed the limitations of existing methods, as verified by simulations evaluating different approaches and scenarios.

The first limitation of the existing studies was that the overall system factors were not considered simultaneously, which was solved herein by considering the overall system through the multiobjective functions. The second drawback was that the VVC performance was evaluated without considering the service transformer; this was solved by verifying the algorithm for a test model by considering a transformer. The third shortcoming was that the VVC performance was evaluated with the default settings; this was solved by flexibly setting parameters through an optimization algorithm and analyzing the effects of the number of optimal parameters. The fourth limitation was that the VVC of the smart inverter was assumed to be updated hourly or daily in the field; this was solved by considering the weather characteristics based on the update period in the field. The fifth drawback was that multiple PVs were connected to the same VVC, and this was solved by setting the VVC after classifying the PVs via clustering and considering system trends. The sixth shortcoming was that the weights of the multiobjective functions were not used effectively; this was solved by allowing DSOs to set the weights such that the VVC suitable for the distribution system conditions could be mounted on the smart inverter. The proposed algorithm is thus suitable for deployment in the field, as detailed below.

- Operators can flexibly adjust the VVC. Depending on the computational resources available, increasing the number of optimized parameters can further improve system performance (Section III-A).
- The VVC can be set according to the viable update periods. When possible, shorter VVC update periods can be used to achieve higher system performance (Section III-B).
- Multiple PV systems connected to a common feeder may show different characteristics; thus, appropriate VVCs should be implemented. We used clustering to implement different VVCs for groups of PV systems. A more granular clustering may lead to further improvements in system performance provided the implementation complexity can be handled (Section III-C).
- By prioritizing different factors for improvement, DSOs can implement tailored VVCs in smart inverters according to operational and system requirements (Section III-D). For instance, overvoltage can be mitigated with higher priority under when several PV systems are connected (case D-1). When PV systems are connected via dedicated lines, system loss minimization is prioritized (case D-2). When the output power is affected by the small capacity of the smart inverter in the PV system, peak reactive power minimization can be prioritized (case D-3).

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