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Optimal Parameters of Volt–Var Function in Smart Inverters for Improving System Performance

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Abstract: This paper proposes a method to improve the performance of a distribution system by optimizing volt–var function of a smart inverter to alleviate the voltage deviation problem due to distributed generation connection. In order to minimize voltage deviation and line losses which represent the performance of a distribution system, this paper proposes an algorithm that optimally sets the parameters of the volt–var function. In the process of optimizing the parameters of the volt–var function, the algorithm proposed in this paper considers minimizing the contribution of the reactive power in order not to affect the output of the distributed generation. In order to apply to the field, the distribution system in South Korea considering the configuration and operation regulation was selected as a test model for algorithm verification. As a result, the system performance was successfully improved by optimally setting the volt–var function of the smart inverter which is an effective way to solve the over-voltage problem caused by distributed generation connection. This paper verified the proposed method through OpenDSS, a quasi-static time-series simulation, for the test model considering the characteristics of the distribution system in South Korea.

Keywords: distribution system; smart inverter; photovoltaic (PV); volt–var function; optimization

1. Introduction

Distributed generation based on renewable energy sources is increasing all over the world, at the same time, distributed generation, such as photovoltaic (PV), are increasing rapidly in South Korea. According to the South Korean government’s plan, the total capacity of renewable energy sources to be supplied by 2030 will be 58.5 GW [1,2]. In particular, in South Korea, by encouraging the installation of the PV through an incentive program, the number of individual businesses is increasing, hence, connecting PV to the distribution system [3–5]. Therefore, distribution system operators (DSOs) need to improve system performance while maintaining the stability of the system even though the level of the PV penetration is increased.

When the PV penetration level of the distribution system increases, the problem of the over-voltage generally occurs before any thermal problem [6–9]. In order to solve the over-voltage problem, DSOs are considering tap control of main transformer (MTR) [7,8,10–12], installation of step voltage regulator (SVR) [7,10,13–16] and control of the distributed generation such as PV [7,8,17]. However, in South Korea, since tap control of the MTR is the authority of the transmission system operators (TSOs), it is difficult to apply tap control of the MTR as a way to solve the over-voltage problem caused by connecting distributed generation. In addition, even when over-voltage occurs in one of the multiple feeders, it is not

suitable for solving the problem. When the SVR is applied, one way to solve the over-voltage problem is to effectively solve the over-voltage problem for each feeder, but the disadvantage is that the cost increase as the number of installation increases depending on the number of feeders. Therefore, the function of controlling the output on the distributed generation in accordance with the distribution system condition is in the spotlight.

As mentioned above, in order to solve problems caused by increased penetration levels of the distributed generation and to improve the system performance, research has been done on the setting of the volt–var function. References [18,19] proposed a method to find optimal volt–var curves for grid-connected rooftop PV using a three-phase optimal power flow. However, these papers have limitations for performance improvement by optimizing only the set points of the volt–var curve. Reference [20] proposed the algorithm for volt–var curve selection with the integration of a high-level penetration of a PV smart inverter. However, it is practically difficult to change the optimal setting of the curve every hour. Reference [21] provided an option to optimize the volt–var and volt–watt function considering PV output and System losses. However, in this reference, reactive power command was fixed and voltage, which is an important factor, was not considered. References [22,23] evaluated the impact of a smart inverter volt–var function on voltage and power quality in electric power distribution system. These references consider many factors that could be considered in the system and classify the PV penetration rate as a scenario. However, there is a lack of explanation for the optimized volt–var curve and weights which significantly affect the results. Reference [24] reduced the energy losses by suggesting the optimal volt–var control method considering PV penetration rate and weather conditions. However, this reference does not consider the voltage factor which is an important factor in the system. Further, there is a realistic problem that it is difficult to update the volt–var control depending on the situation. Reference [25] described the function of a smart invert to improve the distribution system performance such as hosting capacity. However, this reference considered the factor of the system and did not consider the optimization process of the volt–var curves. Reference [26] evaluated the volt–var function and volt–watt function based on PV penetration level and PV curtailment. However, this reference was evaluated using a set-point of volt–var curve. Reference [27] analyzed the system factor according to volt–var function using a multi-objective function. However, the system factors were not considered at the same time by fixing the weight to 1. Further, this method causes a decrease in the PV output by not considering the effect on the active power for reactive power. Reference [28] analyzed the impact of the smart invert setting on the performance of a distribution feeder in the United States. However, this reference does not consider various factors of distribution systems. Further, the improvement of the proposed method was limited due to only using standard settings. References [29,30] analyzed five different inverter control strategies for differing objective functions. Further, these papers analyzed the output reduction effect of the active power due to the reactive power control. However, the improvement effect reached its limit because the inverter function such as volt–var had not been optimized.

This paper contributes the following parts to improve the shortcomings of existing studies.

- Existing studies have the problem of analyzing only one of various factors such as power quality, losses, energy of the distribution system. So, in the setting process of the volt–var function, various factors such as voltage deviation, system loss and peak of reactive power were considered using a multi-objective function.
- The objective function was not properly utilized due to the weight that was not appropriate in the previous studies. Therefore, by using weights appropriately, the algorithm proposed in this paper could provide options to DSOs according to the situation of the distribution system.
- In previous studies, the volt–var function was proposed to update hourly or daily depending on the PV and load pattern. However, this method has encountered difficulties in real industry. To solve this problem, this paper verified the algorithm in a test model based on South Korea distribution system using real PV and load data (one-year).

Section 2.1 describes the test model that considers the characteristics of distribution system in South Korea for algorithm verification. Section 2.2 describes the volt-var function of smart inverter to alleviate the over-voltage due to connecting distributed generation. Section 2.3 describes the parameter optimization algorithm to improve the system performance while alleviating over-voltage problem. Section 3 shows the simulation configuration and results for verifying the proposed algorithm. Section 4 provides discussion about this paper. Section 5 is a conclusion.

2. Analysis Methodology

2.1. Test Model for Effect Verification

Section 2.1 describes the test model for verifying the effectiveness of the proposed algorithm. To consider South Korea's distribution system, the test model consisted of system configuration, operating regulation and field data. Figure 1 shows the test model considering the characteristics of distribution system in South Korea [7,13–15,31]. Table 1 shows the parameters used in the test model. Feeder #1 has a short range with urban, feeder #2 has a medium range and feeder #3 has a long range feeder with rural. The power conditioning system (PCS) capacity for modelling in the PV was set differently from case to case, but this model assumes a 10% margin [29,30,32]. The installation location of the PV was assumed to be the end of the long range feeder (Feeder #3) where the over-voltage problem occurs first before other location [9,33]. The reason for the assuming only one PV is to make it easier to analyze the system performance according to the parameter of the volt-var function.

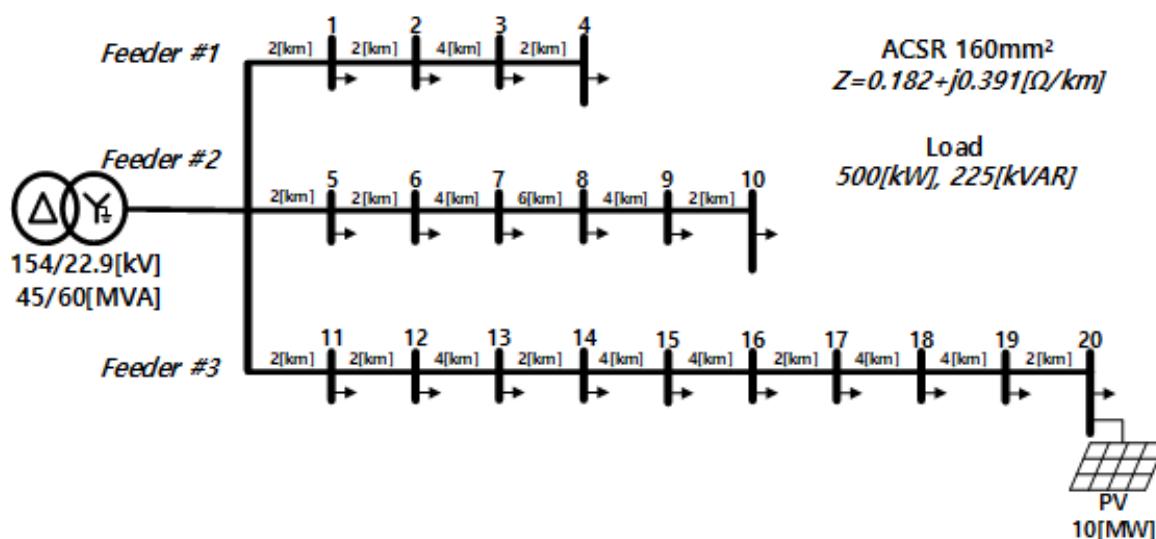


Figure 1. Test Model considering Characteristics of Distribution System in South Korea [7,13–15,31].

Table 1. Parameters of Test Model.

Classification	Parameter
Photovoltaic (PV) Capacity	10 [MW]
Power Conditioning System (PCS) Capacity	11 [MVA]
Each Load	500 [kW]/225 [kVAR]
Transformer	154/22.9 [kV], 45/60 [MVA]
Line Impedance (ACSR160 mm ²)	0.182 + j0.391 [Ω/km]

Figure 2 shows a one-year pattern that normalized the PV output and power usage of the load [34,35]. In the case of the PV output pattern which is South Korea's Yeong-Am PV data, the output is the highest in May due to the surrounding environment, such as temperature. Regarding the power usage of the load, the power usage is drastically reduced in the spring and autumn due to the holiday season (Korean

New Year's Day, Korean Thanksgiving Day). In addition, power usage increases due to heating and cooling loads in summer and winter.

As mentioned in the introduction, existing studies which are based on the daily pattern data are difficult to apply in the real industry due to the set parameters of the volt–var function. The updating method based on daily measurements will be applicable when communication performance is solved. In order to solve this problem, this paper proposes an algorithm to optimize the parameter of the volt–var function using a pattern of one year.

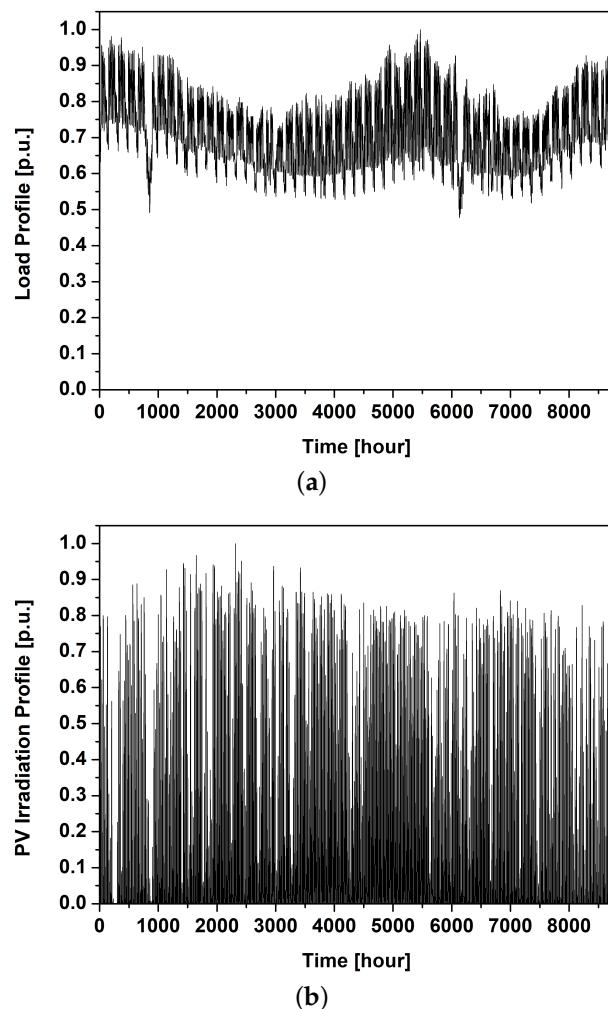


Figure 2. South Korea's One-Year PV Output and Power Usage Pattern of Load. (a) Power Usage Pattern of Load [34]. (b) PV Output Pattern [35].

2.2. Volt–Var Function of Smart Inverter

Section 2.2 describes the volt–var function of a smart inverter which is a solution to alleviate the over-voltage problem caused by the increase of connecting distributed generation. The volt–var function could help to maintain the power quality of the distribution system by controlling reactive power according to the point of common coupling (PCC) voltage. Figure 3a shows the common volt–var function curve [23,24,28]. The volt–var function is to control the absorption of reactive power if the voltage begins to exceed the upper level. On the contrary, when the voltage begins to fall below the lower level, the reactive power could be injected in the distribution system to help in maintaining the normal voltage. Figure 3b shows the standard default setting of volt–var function [25,33,36]. The standard setting is referred to as "Aggressive", "Moderate", or "Mild" depending on the slope. The volt–var function as a standard has a dead-band according to the nominal voltage (except "aggressive"). Except

for the dead-band, the region is linearly configured for the absorption or injection of the reactive power to help maintain the PCC voltage. The peak of the reactive power for these curves is affected by the inverter's capacity and operator's priority.

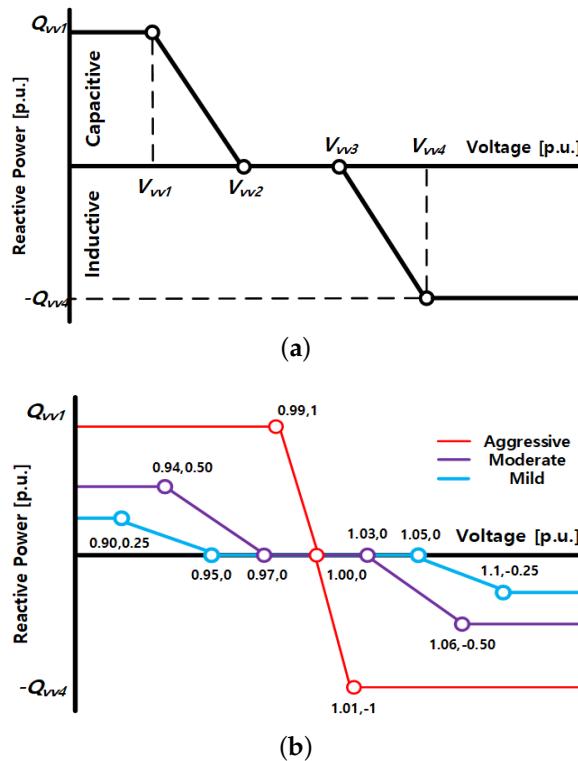


Figure 3. Volt–Var Function Curve. (a) Common Volt–Var Function Curve [23,24,28]. (b) Standard Default Setting of Volt–Var Function [25,33,36].

Equation (1) shows the reactive power command ($Q_{s,i}(V(t))$) of the smart inverter according to the PCC voltage ($V(t)$) [24,26]. When the PCC voltage is lower than V_{vv1} , the smart inverter contributes to the reactive power (Q_{vv1}) to rise the PCC voltage. When the PCC voltage is between V_{vv1} and V_{vv2} , the smart inverter injects the reactive power corresponding to the slope to maintain the normal voltage. When the PCC voltage is between V_{vv2} and V_{vv3} in the setting curve where the dead-band exists, the smart inverter does not contribute the reactive power to the distribution system. On the contrary, when the PCC voltage rises between V_{vv3} and V_{vv4} , the smart inverter absorbs the reactive power to help limit the voltage rise. When the voltage rises above V_{vv4} , the smart inverter contributes to limit the voltage rise by absorbing the reactive power (Q_{vv4}).

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

Figure 4 shows the limit range of the inverter's reactive power. The PV system produces the energy depending on the PV panel (nameplate (kW)), irradiation and weather condition. Therefore, for economic reasons, individual business often prefers the PCS size smaller over the PV panel. However, when the reactive power needs to contribute a lot to the distribution system, the active power could be affected, such as limited output [18,23,29,37,38]. For this reason, the contribution of the reactive power should be minimized in order to guarantee the profits of individual businesses.

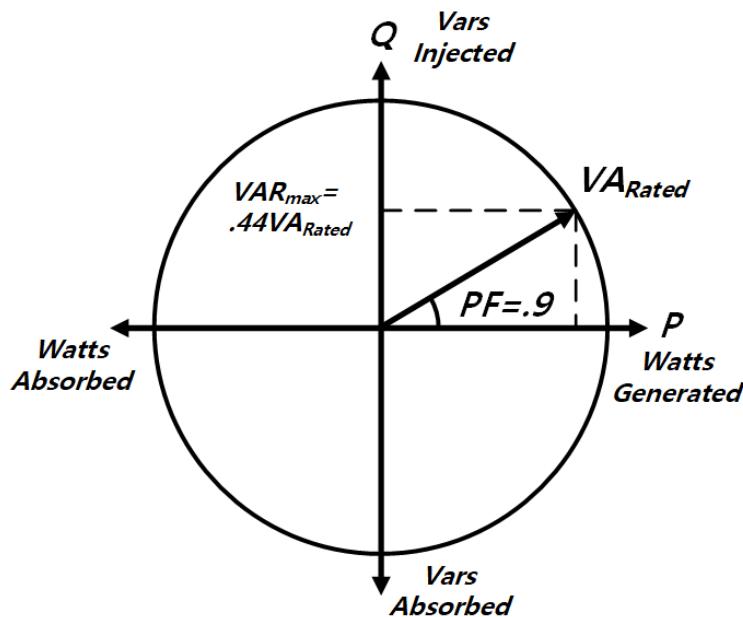


Figure 4. Determining Inverter’s Reactive Power Limit Range [18,23,29,37,38].

Figure 5 shows the voltage profile to confirm the improvement effect of the voltage quality when the volt-var function as “moderate” of Figure 3b was applied. The “moderate” setting is the most common of the standard settings. The quasi-static time-series PCC voltage was getting closer to the nominal voltage by applying the volt-var function. In other words, this means that the voltage deviation was reduced and the voltage quality was improved. Further, in terms of the grid code, an increase in voltage margin could be seen as an increase in hosting capacity.

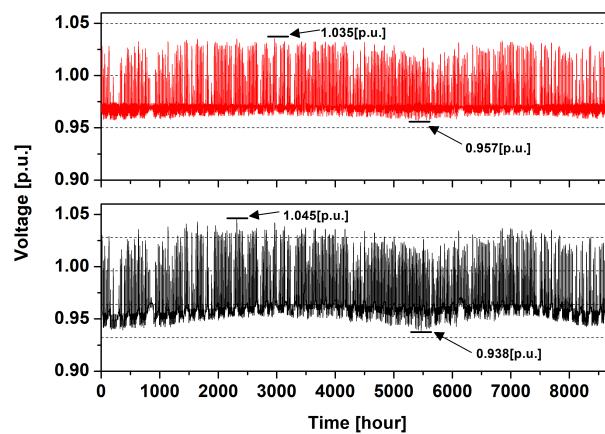


Figure 5. Voltage Profile when Volt–Var Function was applied or not.

2.3. Optimizing Parameter of Volt–Var Function Using Particle Swarm Optimization

Section 2.3 describes the process of optimizing the parameters of the volt–var function to improve the system performance using particle swarm optimization (PSO). The PSO is a computational method that optimizes the problem by iteratively improving the candidate solution by obtaining a motif from the movement of organisms in a bird flock or fish school. The PSO is very simple and fast because only the optimistic particles in different generations transmit information to other particles. By using PSO, one of the metaheuristics, as an optimization tool, algorithm proposed in this paper set a high iteration to avoid local solutions and reach a global solution. This method could increase the calculation time, but the setting of the smart inverter is not a big problem because it is a planning stage, not a real-time control stage or an operation stage. In addition, by using PSO as an optimization tool of the algorithm,

it can be flexibly applied to distribution systems with different configurations. In addition to the PSO, there are optimization methods such as genetic algorithms (GAs), and ant colony algorithms to solve the distribution system problem. However, the performance comparison of the optimization technique is not covered because it is beyond the scope of this paper [13–15,31,37–41].

The setting of the volt–var function on the smart inverter affected the system losses and voltage deviation which represent the indicators of the system performance. The line losses are related to revenues from DSOs and customers. The voltage deviation is directly related to the power quality and planning of the system operation. Further, in some cases, as mentioned in Section 2.2, setting the volt–var function has an adverse effect like reducing the output of the PV. However, most PV operators in South Korea are managed by individual businesses. Therefore, since the PV output is directly related to the profit of the individual, it is difficult to mount the control which causes the output reduction in the smart inverter. For these reasons, this paper considered the elements of the multi-objective function to optimize the voltage deviation, the system losses and the peak of the reactive power.

Equation (2) represents the objective function that should be minimized to improve system performance.

$$\text{MinOF}(vv_{new}) = \text{Min} \sum_{t=1}^{8760} \left[\left(\frac{|\delta V_{i,t}(vv_{new})|}{|\delta V_{i,t}(vv_{con})|} \right)^{\omega_1} + \left(\frac{|P_t(vv_{new})|}{|P_t(vv_{con})|} \right)^{\omega_2} + \left(\frac{|Q_i(vv_{new})|}{|Q_i(vv_{con})|} \right)^{\omega_3} \right] \quad (2)$$

where,

i : Bus with distributed generation

t : Time [h]

vv_{new} : Parameter for newly updated volt–var function ($V_{vv1}, V_{vv2}, V_{vv3}, V_{vv4}, Q_{vv1}, Q_{vv4}$)

vv_{con} : Parameter of conventional volt–var function in Figure 3b (Moderate)

ω : Weight for each evaluation index (voltage deviation, line losses, peak of reactive power)

V_{ref} : 22.9 [kV]

$V_{i,t}$: Voltage of the bus (i) at time (t) according to parameters of the volt–var function

$\delta V_{i,t}(vv) = \frac{V_{ref} - V_{i,t}(vv)}{V_{ref}}$: Voltage deviation index of the bus (i) at time (t)

$P_t(vv)$: System losses at time (t) according to parameters of the volt–var function

$Q_i(vv)$: Peak of reactive power on smart inverter according to parameters of the volt–var function

Equation (3) represents the fitness value for improving system performance at each simulation iteration period (one year) by using Equation (2) and constraint. Particles (parameter, vv_{new}) with a minimum (optimum) fitness value represent the parameter of the volt–var function that can maximize the system performance.

$$\text{MinF}(vv_{new}) = \text{Min} \left[OF(vv_{new}) + \sum_{c \in N_{const}} \omega_c \cdot PF_c \right] \quad (3)$$

where

N_{const} : Set constraint

ω_c : Penalty coefficient

PF_c : Weight for each constraint

The following list describes the constraints that must be considered when setting the parameters of the volt–var function. In this paper, the penalty coefficient (10×10^{20}) is set to a very high value in order to find an optimized parameter that satisfies the constraints.

1. Voltage constraints

Table 2 shows the range in which the voltage of the distribution system regulated in South Korea should be maintained. Therefore, the voltage of the distribution system must be kept within the range as shown in Equation (4) during processing optimization of setting parameter [42].

Table 2. Voltage Operating Regulation Range of Distribution System in South Korea.

Nominal Voltage	Voltage Operating Regulation Range
22,900 [V] (1.0 [p.u.])	20,800 [V] (0.908 [p.u.]) ~ 23,800 [V] (1.039 [p.u.]) (−2100 ~ +900)

$$V_i^{\min} \leq V_{i,t} \leq V_i^{\max} \quad (4)$$

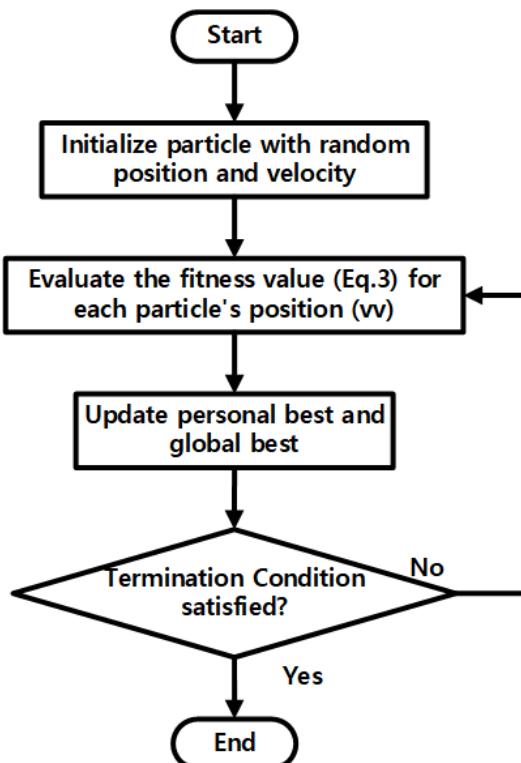
where, $V_i^{\min} = 0.908$ [p.u.], $V_i^{\max} = 1.039$ [p.u.]

2. Parameter Setting Range of Volt–Var Function

In the process of setting optimal parameters, the parameter range is set as Equation (5) to enable the smart inverter to operate properly. The reason why V_{vv3} is set equal to or greater than V_{vv2} is to consider a dead-band through the optimization process. The proposed algorithm in this paper is similar to the existing volt–var function curve through these constraints, but could find the optimal parameters to improve the system performance.

$$V_{vv1} < V_{vv2} \leq V_{vv3} < V_{vv4} \quad 0 \leq |Q_{vv1}| \leq 1, 0 \leq |Q_{vv4}| \leq 1 \quad (5)$$

Figure 6 shows a flowchart that set the optimal parameters of the volt–var function for improving system performance using PSO. The minimum fitness value of Equation (3), which takes into account some constraints, could be calculated by iterating until the termination condition is satisfied.

**Figure 6.** Flowchart for Setting Optimal Parameter of Volt–Var Function.

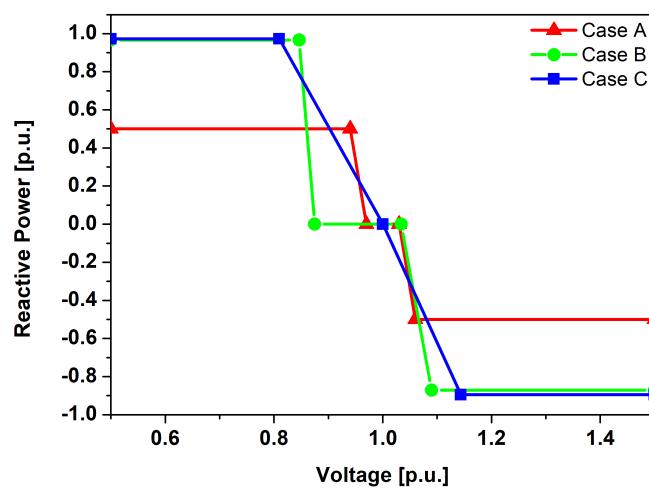
3. Simulation for Effect Verification

Section 3 verified the performance of the volt–var parameter optimization algorithm for the test model considering the distribution system characteristics of South Korea through simulation. To verify the contribution of this paper, the simulation tool was utilized by OpenDSS which is a quasi-static time-series simulation.

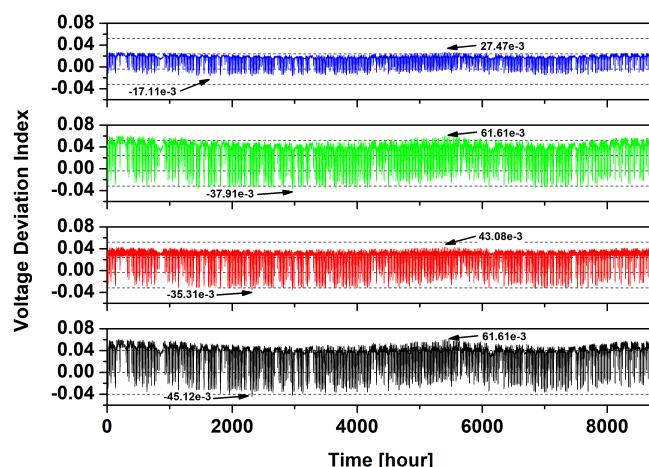
3.1. Simulation Configuration

Section 3.1 shows the simulation configuration for algorithm verification proposed in this paper. Table 3 shows the cases for comparison between the conventional method and proposed method to confirm the contribution of the proposed algorithm.

In order to confirm the effect of applying the volt–var function, the case where the volt–var function is not applied is named without a volt–var function (W/O V–V). Case A represents the default setting (“moderate”) by a standard volt–var function. Case B applies the same weight to each system performance and case C applies the most weight (ω_1) to prioritize the reduction of the voltage deviation. Case D applies the most weight (ω_2) to prioritize the improvement of the system losses. Case E sets high weight (ω_3) to prioritize the reduction of the peak of the reactive power so as not to affect the active power of the PV. When the fitness value of Equation (3) is optimal according to the weight, the parameter could be used to represent a volt–var curve as shown in the Figures 7a, 8a and 9a which could maximize the system performance.



(a) Volt–Var Function Curve according to Case.



(b) Hourly Voltage Deviation Index (Black, W/O V–V; Red, Case A; Green, Case B; Blue, Case C).

Figure 7. Case Comparison to verify the Improvement Effect on Voltage Deviation Index.

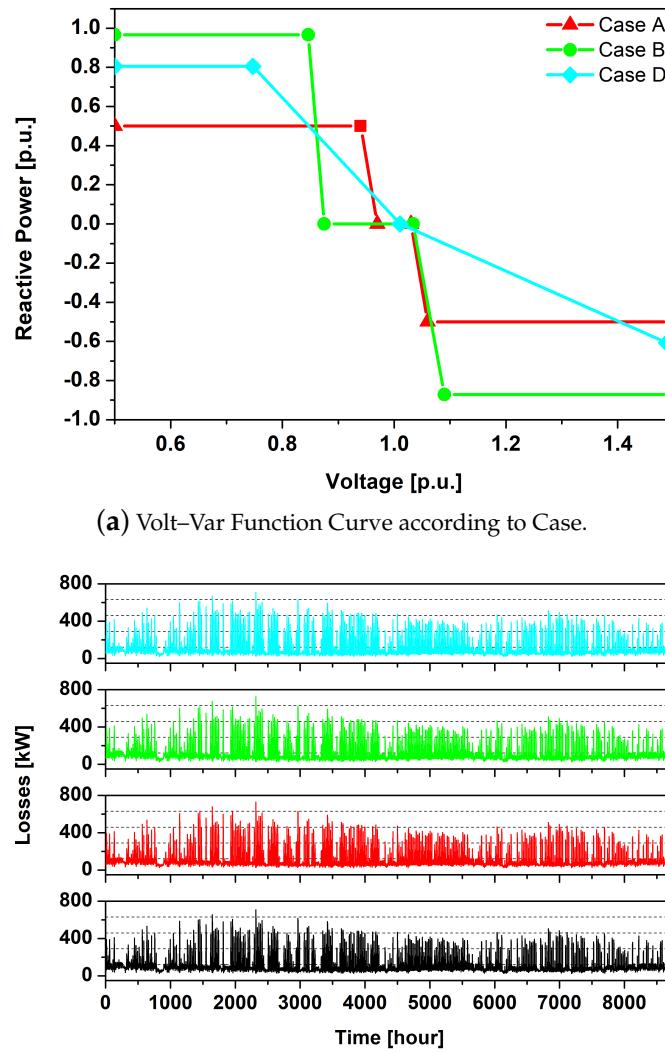


Figure 8. Case Comparison to verify the Improvement Effect on System Losses.

Table 3. Case Configuration.

Case	ω_1	ω_2	ω_3	Remark
W/O V-V	-	-	-	Without Volt-Var Function (Conventional Method without Function)
Case A	-	-	-	Standard Default Setting (Conventional Method with Function)
Case B	1	1	1	Equal Weight for All Elements
Case C	2	1	1	Priority to Voltage Deviation
Case D	1	2	1	Priority to System Losses
Case E	1	1	2	Priority to Reducing Peak of Reactive Power

3.2. Simulation Results

Section 3.2 describes the simulation results for verifying the proposed algorithm. Figure 7 compared the effects of the conventional method and proposed a method for voltage deviation. Figure 7a shows the volt-var curve according to the cases and Figure 7b shows the voltage deviation index according to the volt-var curve. Case C which sets the highest weight (ω_1) for voltage deviation was optimized for a curve with no dead-band, unlike other cases. Case C shows the most optimized result in terms

of voltage deviation through this curve. The voltage deviation index near zero indicates near nominal voltage, which means improved system performance.

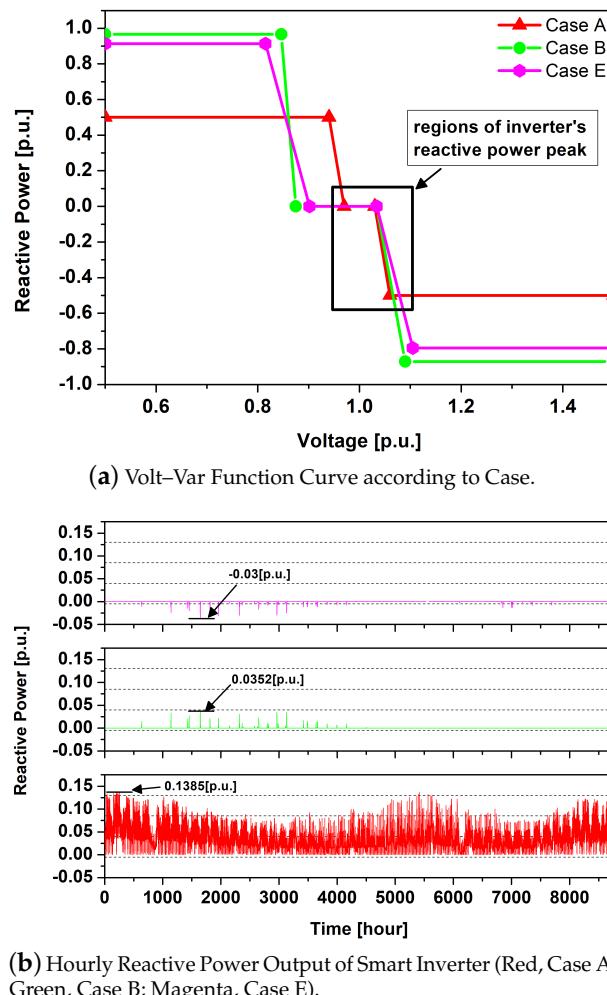


Figure 9. Case Comparison to verify the Improvement Effect on Limiting Reactive Power Peak.

Figure 8 compares the effects of the conventional method and proposed method on the system losses. Figure 8a shows the optimized curves by the cases and Figure 8b shows the hourly system losses by the case. Case D which has the highest weight (ω_2) for system loss shows that the system losses is the lowest. System losses are affected by various factors such as substation distance (transmission system), line impedance, PV output and load pattern.

Figure 9 compared the effects of the conventional method and proposed method for suppressing reactive power peak. Figure 9a shows the optimized curves for suppressing reactive power peak. Figure 9b shows hourly reactive power output of smart inverter according to the case. Because the W/O V-V case is not mounted with function, the reactive power does not contribute to the distribution system. The reactive power peak of case A is 0.1385 [p.u.], the reactive power peak of case B is 0.0352 [p.u.], the reactive power peak of case C is 0.03 [p.u.]. The best reason for the peak suppression effect is that the reactive power command is the smallest in the area where the curve of case C is generated from the peak.

4. Discussions

Section 4 discusses the results of the proposed algorithm. Table 4 shows the results of the simulation. The factors indicated per unit are shown to make it easier to analyze the improvement effect compared to the conventional method. The improvement effect on the maximum voltage and the minimum voltage

is most effective in case C which has a high weighting on the voltage deviation. Further, case C is the minimum value for the sum of voltage deviation for one year. In terms of system loss, it is confirmed that case D, which has the highest weight for system loss, improves by 6.2% when the function is not applied (W/O V-V) and by 2% compared to case A. In terms of suppressing the peak of reactive power, case E was found to be up to 75% of the limitation effect. In terms of the evaluation index (fitness value), case B, which applied the same weight to each system performance index, improved by 22% compared to case A. Although the fitness values of case B and case E are similar, case B considers the whole part of the system factors identically, and case E has an effect of suppressing reactive power because it applies a high weight to the reactive power suppression.

Table 4. Simulation Results.

Classification	W/O V-V	Case A	Case B	Case C	Case D	Case E
Maximum Voltage [p.u.]	1.045	1.035	1.038	1.017	1.038	1.038
Minimum Voltage [p.u.]	0.938	0.957	0.938	0.973	0.968	0.938
Sum of Voltage Deviation [Index]	307.26	236.11	306.97	134.89	155.23	307.01
Sum of Voltage Deviation [p.u.]	1.0313	1.0000	1.3001	0.5713	0.6574	1.3003
System Losses [MWh/Year]	975.39	933.39	975.89	940.75	914.60	975.81
System Losses [p.u.]	1.0450	1.0000	1.0455	1.0079	0.9799	1.0454
Peak of Reactive Power [kVAR]	-	1384.90	355.45	1407.78	1224.30	352.94
Peak of Reactive Power [p.u.]	-	1.0000	0.2567	1.0165	0.8840	0.2548
Fitness Value (Equation (3))	-	3	2.3456	2.5957	2.5358	2.3457

5. Conclusions

This paper proposed an algorithm that optimizes the volt-var function parameter of the smart inverter which is a method for mitigating over-voltage due to high penetration of the distributed generation. In order to improve the system performance, voltage deviation and system losses which are indicators of the distribution system, were minimized. Further, the peak of the reactive power was minimized in order to avoid affecting the output of the distributed generation. As a result, the system performance was effectively improved depending on how the weight is selected during the optimization process. Improving the system performance by weighting could provide various options to the DSOs.

The algorithm proposed in this paper has the following advantages:

- Through the test model considering the distribution system characteristics of South Korea, this paper verified that the over-voltage problem caused by the high penetration of the distributed generation was solved by the volt-var function (Check through Case A).
- The parameter settings of the volt-var function were optimally set through a multi-objective function considering the voltage deviation, the system losses and the suppression peak of the reactive power (Check Case B).
- Case C improved by setting more weight to the voltage deviation. This optimization case could be applied when hosting capacity increases and power quality improvements are needed.
- Case D validated the effect by setting more weight to improve the system losses. This optimization case could be applied to situations where system loss is to be minimized such as a long distance feeder and distributed generation line.
- Case E is an optimization to minimize the peak of the reactive power in order to not affect the output of the distributed generation. This optimization case is applicable to the state that needs to suppress the peak of the reactive power due to capacity limitation of the PCS and new installation of the smart inverter.

The algorithm proposed in this paper could improve the system performance such as voltage deviation and system losses for the DSOs. In addition, individual businesses could maximize profits by not affecting output of the distributed generation. According to the system condition, the system performance could be maximized through the algorithm proposed in this paper.

Author Contributions: methodology and Writing-original draft, H.-J.L.; software, K.-H.Y.; validation, J.-W.S., supervision, J.-C.K.; editing, S.-M.C. All authors have read and agreed to the published version of the manuscript.

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