Study of Coordinated Reactive Power Control for Distribution Grid Voltage Regulation with Photovoltaic Systems

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Abstract - **Voltage rise and reverse power flow in the distribution grid with photovoltaic (PV) systems have caused new challenges of the reactive power control method. This paper presents a study of coordinated reactive power control for distribution grid voltage regulation with PV generation. The objectives of this research are to provide the reactive power to support the distribution grid and regulate the PV bus voltage of PV systems. The control method is based on centralized reactive power management in a high voltage (HV) distribution and coordination of voltage-dependent reactive power characteristics for allocating the reactive power to PV systems. The reverse power flow and voltage rise can be controlled by PV systems at the medium voltage (MV) level which contributes to controlling the reactive power exchange between HV and MV voltage levels. The system case consists of a PV system connected to the two radial feeders in the distributed grid. The simulated model of the proposed system is built through DIgSILENT PowerFactory software. Simulation results are presented to validate the effectiveness of the control method for mitigating voltage rise and reverse power flow in the distribution grid with the PV generation.**

Keywords - **Coordinated reactive power dependent voltage control, photovoltaic system, reactive power management, reactive power provision, voltage regulation**

I. INTRODUCTION

Thailand is provided with a rich solar energy resource across the country, experiencing high irradiance in the northeast and central parts of the country. By the end of 2017, large capacity photovoltaic (PV) power generation was installed in Thailand at about 3,200 MW [1]. Renewable energy distribution generation sources are becoming a growing significant factor in active power generation. The main source of the reactive power in power systems are synchronous generators. In the future, with growing renewable energy distributed generation sources connected to the distribution grid, these synchronous generators will be shut down one by one. Therefore, this growth requires stable electric power, and reactive power is significantly increasing. If one of the main sources of reactive power disappears, another source of reactive power is a require.

Currently, the high penetration of PV generation in the distribution grid is the motive for new challenges such as voltage rise, reverse power flow and insufficient reactive power in the grid systems [2]-[4]. In general, the distribution grid controls have three strategies such as centralized, decentralized, and local control strategies [5]. The reactive power control methods are able to be used to maintain the voltage level in the distribution grid. There are many reactive power control methods that are currently carried out in literature research, such as the constant power factor method [6], the variable displacement factor dependent active power method, $\cos\phi(P)$ [6], the active power dependent reactive power regulation method, $Q(P)$ [7], and the voltage-dependent reactive power regulation method, $Q(V)$ [8]. The development of the $Q(V)$ characteristic with a voltage-sensitive analysis was presented in [9]. In a designed simulation, it used the multi-objective method to make comparisions with the equal reactive power sharing method in order to find a voltage regulation technique to reduce the reactive power consumption and lines losses. This result showed that both methods could regulate the voltage to a limited state. However, the multi-objective method could consume less of the reactive power than the equal reactive power sharing method. In [10], weak point of various reactive power control method and a reactive power control technique with basic sensitivity analysis are proposed. The $\cos\phi(P,V)$ method is combined with the $\cos\phi(P)$ and the standard $Q(V)$ methods. In simulation results, the $\cos\phi(P,V)$ can regulated voltage the same as the others methods. It can be achieved PV capacity. However, it consumed less of the reactive power than the $\cos\phi(P)$ method but consumed more of the reactive power than the $Q(V)$ method. In [11], the central reactive power management strategy controlled reactive power changing between the HV and MV level by distribution system operators. The results found that central reactive power management provides stability and reliability to the system. The advantage of the local distribution grids controlled with the $Q(V)$ method is during the communication offline.

In this paper, analysis of reactive power management and coordinated reactive power dependent voltage regulation in the distribution grid with PV generation is presented. Section II presents the methods of reactive power control in the distribution grid. In Section III, the proposed coordination control method with voltage-dependent reactive power characteristic under study and a simulation platform is presented. Section IV presents the simulation results and discussion. Finally, Section V summarize, the conclusions of this paper.

II. METHODS OF REACTIVE POWER CONTROL IN DISTRIBUTION GRID

High penetration of PV distributed generations has caused effects on the distribution network such as voltage rise and reverse power flows. When PV systems are connected into the feeder, the power flow can be reversed. Therefore, the voltage can be higher at the end of the feeder than near the power transformer side.

The voltage rise caused by the PV systems can be expressed as the following:

$$\Delta V \approx \frac{R\left(P_L + P_{PV}\right) + X\left(Q_L + Q_{PV}\right)}{V_N} \tag{1}$$

where ΔV is the voltage change across the line, R and X are the resistance and reactance of the distribution line, P_L and Q_L are the active and reactive power consumption with the load, P_{PV} and Q_{PV} are the active and reactive power of the PV system, and V_N is the nominal voltage.

In equation (1), it can be noted that the reactive power of PV generation Q_{PV} can be used to control the voltage level. However, the benefit of voltage control by reactive power regulation is decided by the ratio of the system resistance to the system reactance (R/X ratio) in distribution system. Therefore, reactive power support is correlatively more beneficial in the MV distribution system than the low voltage (LV) distribution system due to having a lower R/X ratio. The reactive power control methods to support the voltage level can be achieved in various ways. Some of these methods are explained in this section.

A. Constant Power Factor Method

The constant power factor method is not consumed or injected by the reactive power when there is no active power of PV generation. However, this method causes unnecessary reactive power consumption and distribution line losses. It consumed or injected the reactive power which is not an interesting voltage parameter in the power system, thus, it can be adapted according to [6].

$$Q_{PV,ref} = \pm P_{PV}\tan\left[\cos^{-1}(\mathrm{pf})\right], \tag{2}$$

where $Q_{PV,ref}$ is the consuming or injecting the reactive power of PV generation, P_{PV} is the active power of the PV generation, and pf is a power factor.

B. Q(V) Characteristic Method

The reactive power capabilities of PV generations can be used to maintain the voltage level. The $Q(V)$ characteristic method directly spends the regional voltage information which is a consequence of the power consumption and injection.

For this method, the reactive power function by the PV generation is possibly developed in the following [10]:

$$Q_{PV,ref} = \begin{cases} Q_{PVi,\max}, & V < V_1 \\ \dfrac{Q_{PVi,\max}}{V_1 - V_{\min}}\left(V - V_1\right) + Q_{PVi,\max}, & V_1 \le V \le V_{\min} \\ 0, & V_{\min} \le V \le V_{\max} \\ \dfrac{Q_{PVi,\max}}{V_{\max} - V_2}\left(V + V_{\max}\right), & V_{\max} \le V \le V_2 \\ -Q_{PVi,\max}, & V > V_2 \end{cases} \tag{3}$$

where $Q_{PV,ref}$ is the reactive power for the local bus voltage regulation of PV generation, $Q_{PVi,\max}$ and $Q_{PVi,\min}$ are the maximum and minimum reactive power of PV generation, i is the number of PV system, V is the bus voltage, and V_1 and V_2 are the limited voltages.

From (3), it can be simply executed in the system controller and modified remotely to control the bus voltage by injecting reactive power from the PV generation even when there is no active power production. The general function of the reference reactive power generation and consumption for voltage regulation is shown in Fig. 1.

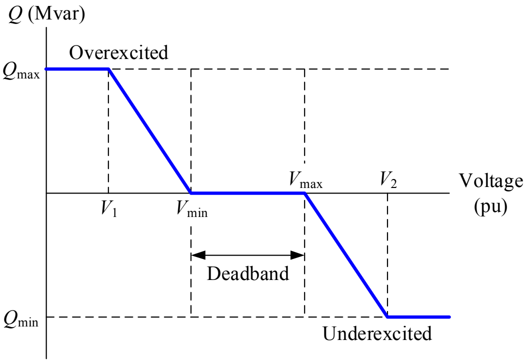


Fig. 1. Standard of $Q(V)$ characteristic.

In Fig. 1, it can be explained by the fact that if voltage rise over the maximum voltage range ($V_{\max}$) reactive power is consumed which decreases the voltage in an underexcited condition. When the voltage falls below the minimum voltage range ($V_{\min}$), the reactive power is injected to increase the voltage in an overexcited condition. The certain threshold between the maximum and minimum voltage ranges is the dead-band, which can be constant reactive power consumption or injection.

III. PROPOSED METHOD OF REACTIVE POWER CONTROL IN DISTRIBUTION GRID

This section describes the proposed method of reactive power control in the distribution grid with PV generations. Fig. 2 shows a single line diagram of the advised reactive power control method, which purposes to control the reactive power exchange at the HV level. The stepwise process of the proposed control algorithm is presented according to the following four steps.

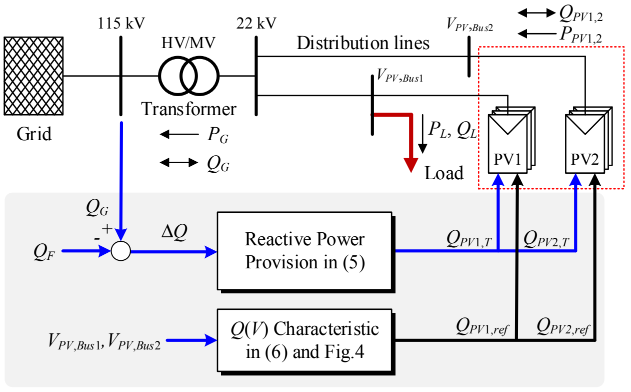


Fig. 2. Single line diagram of the reactive power control in the distribution grid with PV generations.

Step 1: Choose the target amount of the reactive power exchange at the HV/MV interconnection point by the grid operator. This method which is choosing the demand for reactive power exchange is zero ($Q_F = 0$).

Step 2: Calculate the reactive power deviation ΔQ at the HV/MV connection point, as follows

$$\Delta Q = Q_G - Q_F, \tag{4}$$

where Q_G is the reactive power exchange at HV grid, which means the summation of reactive power from load and distribution line losses, and Q_F is the fixed value for limit reactive power on the grid.

In (4), the reactive power exchange Q_G can be used the external measurement value.

Step 3: Reactive power provision process: The reactive power deviation ΔQ in (4) is utilized to compute the reactive power provision in PV generations at the MV level based on the characteristic curve as shown in Fig. 3.

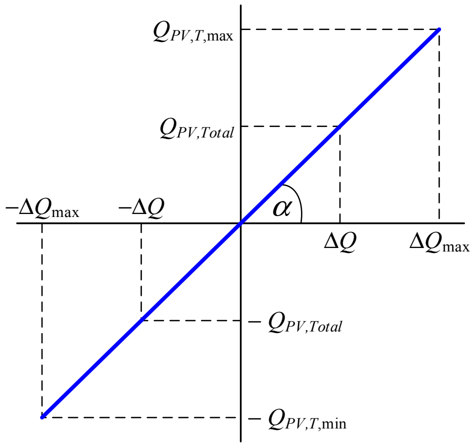


Fig. 3. The reactive power provision characteristic for central reactive power management.

In Fig. 3, the setpoint of the reactive power provision can be determined as follows

$$Q_{PVi,T} = Q_{PVi} + \left[\Delta Q \times \left(\frac{P_{PVi,IC}}{P_{PV,Total}} \right) \times \tan(\alpha) \right], \tag{5}$$

where $Q_{PVi,T}$ is the reactive power provision of PV generation (i = 1,2,…), Q_{PVi} is the current reactive power deployment, $P_{PVi,IC}$ is the installed active power of PV generation, $P_{PV,Total}$ is the total active power of the PV generation in the distribution grid, and α is the angle of the relationship between $Q_{PV,T}$ and ΔQ, which is substituting the value at 45°.

Therefore, the PV generations accept their reactive power provision from the central control system. The benefit of the reactive power provision is that it can provide a capacity of reactive power in each PV generation. However, it is an unsuitable value. The PV generations require a process in step 4 to regulate the bus voltage.

Step 4: Regulated the local bus voltage by using the reactive power control: The proposed characteristic curve is modified from the standard $Q(V)$ characteristic. The controller has calculated the reactive power setpoint and limits it within the operation area according to the extended $Q(V)$ characteristic. The proposed practice of the reference reactive power generation and absorption for different voltage limit infringement is shown in Fig. 4. The local reactive power controller has calculated the reference reactive power of the PV generations $Q_{PVi,ref}$ for regulating the local bus voltage.

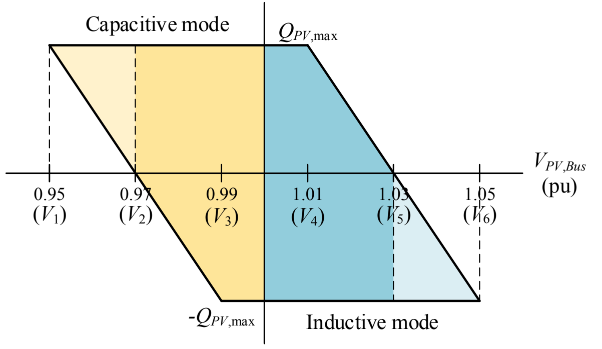


Fig. 4. $Q(V)$ characteristic of PV systems for local reactive power control.

The reactive power flow function by the PV generation is possibly developed in the following:

$$Q_{PVi,ref} = \begin{cases} +Q_{PVi,\max}, & V < V_1 \\ \dfrac{Q_{PVi,\max}(V - V_2)}{V_2 - V_3}, & V_1 \le V < V_3 \\ \dfrac{Q_{PVi,\max}(V - V_5)}{V_5 - V_6}, & V_4 < V \le V_5 \\ -Q_{PVi,\max}, & V > V_6 \end{cases} \tag{6}$$

where $Q_{PVi,ref}$ is the reference reactive power for the local bus voltage of PV generation and V_N is the nominal bus voltage (1 pu).

IV. RESULT AND DISCUSSION

For this reason, the DIgSILENT PowerFactory software was applied for the simulation. The single line diagram of the distribution system is illustrated in Fig. 2. It is the distribution grid at 115 kV connected by transformer 50 MVA, 115 kV/22 kV, which is the neglected operation of the on-load tap changer of the transformer and distribution line losses. The distribution lines used are the Space Aerial Cable (SAC) type, at a size of 185 sq.mm. and 30 km in length in both of the lines. In the case study, the PV systems have two units consisting of an installation power of 15 MW and 8 MW substituted by PV1 and PV2, respectively. A bus PV1 connects the load of the consumer. This method uses the centralized control strategy and neglected communication topic between different voltage levels, which modify $Q(V)$ characteristics of the local PV generations to compare them with the constant power factor method. The standard $Q(V)$ characteristics method was based on a 2% droop function.

The characteristics of the daily PV profile and daily load are illustrated in Fig. 5. The PV1 and PV2 are assumed to operate in the summer. Load profile was assumed to have a peak load of 5 MW at 21:00 and the lowest load of 2.5 MW at 5:00. The simulation results have three different methods, which were investigated and compared with the base case (without reactive power control).

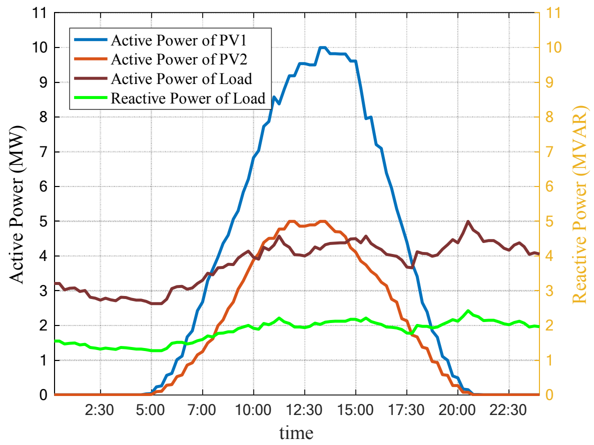


Fig. 5. Daily PV production and load profiles in the simulated distribution grid.

A. Constant Power Factor Method

In this method, PV generations are operated in the inductive mode at 0.9 and the capacitive mode at 0.9 of power factor, according to the general grid code. Fig. 6 illustrates the voltage magnitude and reactive power of the study systems during the examined time period (0:00-24:00) with a constant power factor control method. Fig. 6 (a) shows that the voltage bus PV1 drops under the lower grid code during the time period (0:00-6:00) and (19:00-24:00), when both have a high load and no solar irradiance. Both PV systems exhibit overvoltage of an upper limit on the grid code during the time period (10:00-16:00) on the PV1 generation and (8:30-17:30) on the PV2 generation. It indicates that PV1 and PV2 generations inject over the reactive power requirement into distribution grid and these results are shown in Fig. 6 (b). It is observed that the reactive power on the distribution grid is a negative value and the reactive power on both PV generations are a positive value.

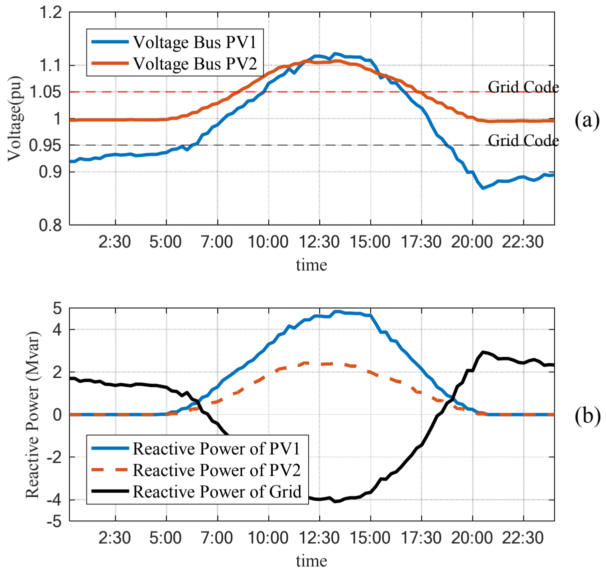


Fig. 6. Simulation results of the constant power factor method. (a) Daily voltage of PV generations, (b) Daily reactive power of PV generations and distribution grid.

B. $Q(V)$ Characteristic Method

In the $Q(V)$ characteristic method, the PV generations were simulated with a droop function of 2% with substitutes of $V_{\min} = 0.95$ pu. and $V_{\max} = 1.05$ pu. to compare with the proposed method. Fig. 8 shows the voltage magnitude and reactive power of the study systems during the examined time period (0:00-24:00) with the $Q(V)$ standard control method. Fig. 7 (a) represents the $Q(V)$ control method which can remedy the voltage rise on the both PV generations during the same time period of the fixed power factor control method. The bus voltage of the PV1 drops the same as when using the fixed power factor control method. It indicates that PV1 and PV2 can regulate voltage bus better than the fixed power factor control method. Fig. 7 (b) shows that the PV2 system does not support reactive power to the distribution grid. However, the PV1 system can support some reactive power to the distribution grid. It can be described that the $Q(V)$ standard control method can support less reactive power to the distribution grid.

C. Proposed Method

The proposed method is simulated with the centralized control strategy. The modifier Q(V) characteristics supports the reactive power on the distribution grid and regulates the bus voltage of PV generation. Fig. 8 illustrates the magnitude of voltage and reactive power with the study system during the examined time period (0:00-24:00) with the proposed control method.

Fig. 8 (a) indicates that the proposed control method can mitigate the voltage rise during the time period (8:30 - 17.30) which is comparable to the $Q(V)$ standard control method. Nevertheless, the proposed control method can control stability and lower voltage better than the $Q(V)$ control method. However, the characteristics of the voltage on bus PV1 drops the same as using the fixed power factor control method and standard $Q(V)$ control method. In Fig. 8 (b), results of the proposed control method can inject or consume the reactive power on a distribution grid. The PV1 injects the reactive power to support the distribution grid during the time period (6:00 - 19:30). The PV2 consumes reactive power to support the distribution grid at the same time period of the PV1.

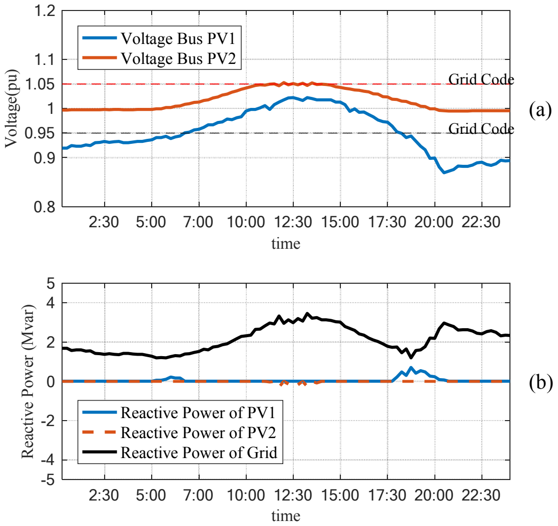


Fig. 7. Simulation results of the $Q(V)$ characteristic method. (a) Daily voltage of PV systems, (b) Daily reactive power of PV generations and distribution grid.

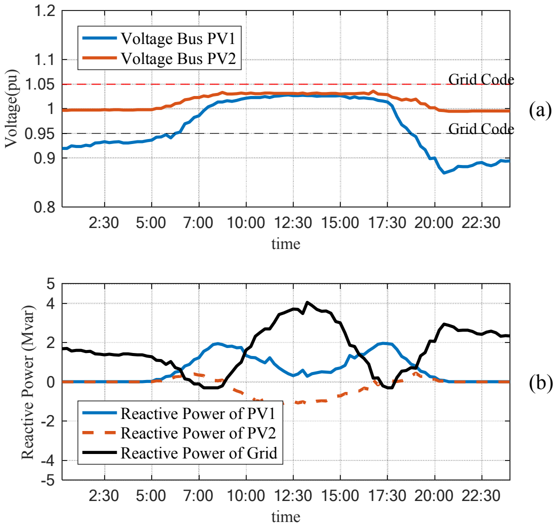


Fig. 8. Simulation results of the proposed method. (a) Daily voltage of PV systems, (b) Daily reactive power of PV generations and distribution grid.

D. The Error of Voltage Regulation in Distribution Grid

The simulation results of the reactive power control methods are utilized in this paper to regulate the voltage profile in the distribution grid. The mean magnitude of relative error (MMRE) and the root mean square error (RMSE) as shown below will be used to evaluate the accuracy of voltage regulation, as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(V_N - V_i\right)^2}{N}} \qquad (7)$$

$$\%\mathrm{MMRE} = \frac{\sum_{i=1}^{N}\left(\frac{\left|V_N - V_i\right|}{V_i}\right)}{N}\times 100 \qquad (8)$$

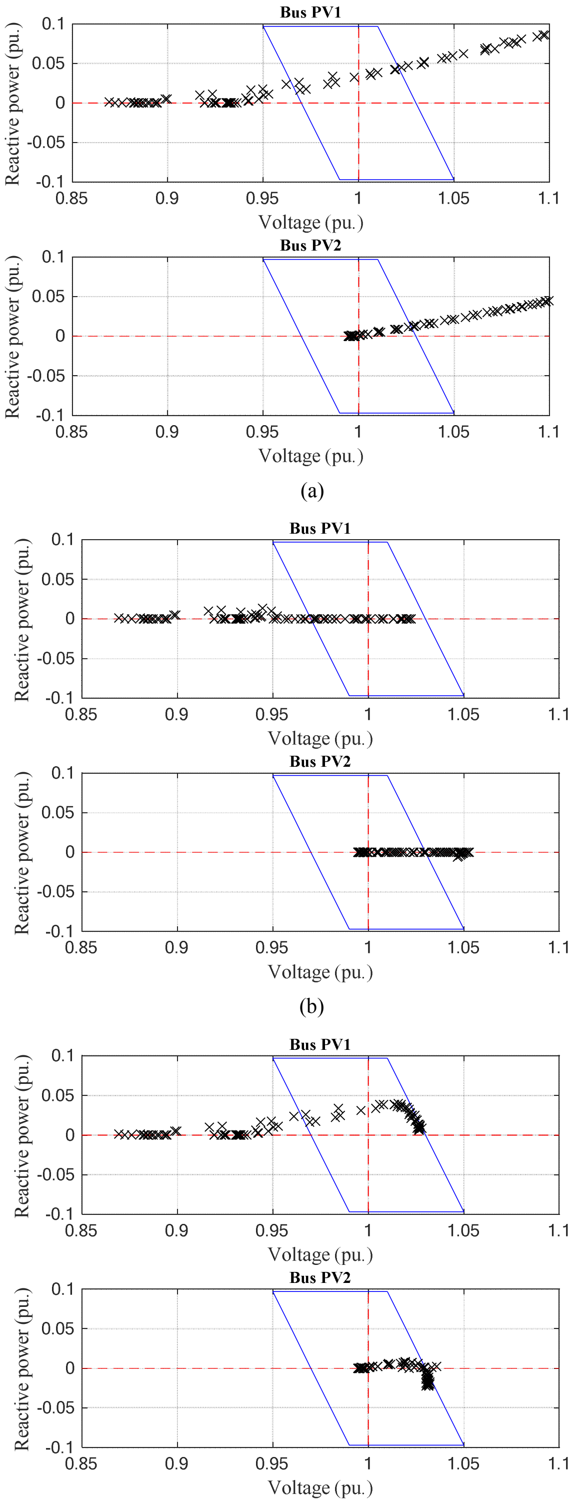
where V_N is the nominal bus voltage, V_i is the bus voltage, and N is the data sample time scale which the profile data is 15 minute intervals.

Fig. 9 shows the comparison of the boundary chart with the reactive power control methods. Fig. 9 (a) indicates the results with the constant power factor method. It is noted that the reactive power operation points are outside the boundary chart, which cannot limit the bus voltage. Fig. 9 (b) shows the operation points of reactive power based on the $Q(V)$ characteristic method. In this method, the PV generation consumes or injects a little reactive power into the distribution grid. The results of the proposed control method are shown in Fig. 9 (c). It is found that most of the reactive power operation points can still be in the boundary chart. Therefore, the proposed method can regulate voltage as the grid code. However, some operation points outside the boundary cannot support the reactive power because the power factor of the PV generation is fixed at 0.90, and there is not enough solar irradiance.

TABLE I
SUMMARY OF VOLTAGE REGULATION ERROR
IN DISTRIBUTION GRID

Method	RMSE		MMRE (%)	
	PV1	PV2	PV1	PV2
Without control	0.067	0.027	5.47	1.95
Constant pf at 0.90	0.083	0.056	7.50	3.91
$Q(V)$ characteristic	0.065	0.027	5.35	1.94
Proposed	0.064	0.021	5.31	1.68

Table I shows the summary of voltage regulation error in the distribution grid. It can be seen that the four different methods, particularly the proposed method, perform well in voltage regulating. The voltage regulating precision of the proposed method at bus voltage in PV1 and PV2 are 0.064 pu and 0.021 pu in RMSE and 5.31% and 1.68% in MMRE, respectively.



(a)

(b)

(c)

Fig. 9. Reactive power operation points of PV generations. (a) Constant power factor method, (b) $Q(V)$ characteristic method, (c) Proposed method.

V. CONCLUSION

This paper reviews the various reactive power control methods, which are advised by the grid code. The proposed method used the centralize reactive power management and modified the standard $Q(V)$ characteristic. In simulation results, the constant power factor method produces a voltage rise all bus voltage which consumes large of the reactive power from the distribution grid. The standard $Q(V)$ method can regulate the bus voltage within the grid code. However, it provides more reactive power to support the distribution grid than the constant power factor method. The proposed method could regulate the bus voltage better than the other control methods and provided reactive power similar to the standard $Q(V)$ method.

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