AUT Journal of Electrical Engineering

AUT J. Electr. Eng., 55(1) (2023) 115-124
DOI: 10.22060/eej.2022.21735.5490

Reactive Power Management of PV Systems by Distributed Cooperative Control in Low Voltage Distribution Networks

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ABSTRACT: A distributed control strategy is proposed to enhance voltage regulation and reactive power sharing in Low Voltage (LV) distribution networks with high penetration of Photovoltaic (PV) systems. This paper investigates the disadvantages of the available methods that their aims are modifying the voltage profile levels of buses and managing the reactive power of PV inverters. Next, through the proposed method, PV systems reduce the deviation of voltage profile by absorbing or injecting reactive power. This paper eliminates the disadvantages of the available control method by the combination of distributed and local control approaches. Indeed, a local droop characteristic determines the reactive power ratio of the worst bus voltage deviation at a critical bus. Afterwards, the distributed control coordinates all PV systems to operate according to the PV system that locates at the critical bus. In addition, the proposed technique prevents PV systems from active power curtailment and manages reactive power sharing among PVs based on their reactive power ratings. A radial LV distribution system with seven PV systems is presented to analyze the proposed procedure. Simulation consequences are demonstrated to confirm the effectiveness of the control method for decreasing voltage deviation and precise reactive power sharing in the distribution network with PV systems.

Review History:

Received: Aug. 31, 2022
Revised: Nov. 15, 2022
Accepted: Nov. 30, 2022
Available Online: Mar. 01, 2023

Keywords:

Accurate Reactive Power Sharing
LV Distribution System
PV System
Reactive Power Management
Voltage Deviation

1- Introduction

In recent years, the growth of energy consumption in modern industrial society threatens the environment severely. Renewable Energy Sources (RESs) could extremely decrease the pollution of fossil fuels and preserve the environment as clean sources. For example, the power generation of PV systems has avoided 875 MW production of CO2. The installation of grid-connected Distributed Energy Resources (DERs) has been increased in power systems due to economic motivations, cutting pollution, and reducing transmission and distribution losses. Moreover, grid-connected PV systems have the most growth rate among RESs and play a crucial role in power systems [1]. Nevertheless, the high penetration of PV systems in LV distribution networks may bring about some challenges, such as reverse power flow and voltage deviations. In the radial LV distribution network, the PV systems generated abundant active power at about noon while loads consumed a little amount of active power, thus a reverse power flow may happen in the power system. As a result of this phenomenon, overvoltage occurs in the grid. Conversely, sun irradiation is less than its maximum limit during most of the day, so the load consumption might be further than the PVs' active power production. Thus, in this condition, the bus voltages fall due to the LV distribution network's relatively high resistance. To overcome these issues, several techniques have been presented in the literature. These strategies include installing fixed or switched Capacitor Banks (CBs) [2], control of On-Load Tap-Changer (OLTCs) transformers [3], PV power generation curtailment [4], Battery Energy Storage Systems (BESSs) [5], and reactive power control method [6]. There are some drawbacks to using CBs and OLTC transformers, such as slow response, producing large transients, generating high-frequency harmonics, and finite lifespans. Additionally, PV power generation curtailment strategy is not an efficient solution for the voltage deviation problem, especially when there is a voltage drop, and is not cost-effective in general. Pairing BESS with PV systems is an alternative approach for the PV power generation curtailment strategy. However, the lifetime of BESS decreases by frequent charging/discharging. Mreover, the installation of BESS equipment increases the cost of investment in PV power generation [5]. On the other hand, PV inverters can support voltage regulation if they can participate in reactive power management. The PV systems usually generate active power less than their nominal active power during the day, so the capacity of the PV systems can be used for reactive power compensation.

Generally, the control strategies in an LV distribution network include three main groups: centralized, decentralized, and local control approaches. Various techniques have been suggested in the literature to modify the voltage level in the distribution system. In [7] and [8], several decentralized constant Power Factor (PF) methods, the constant reactive

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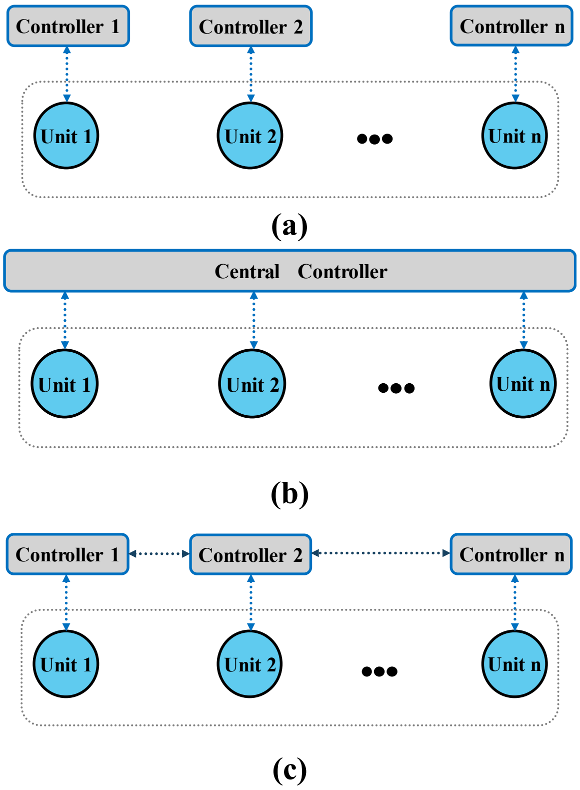

Fig. 1. Control schemes. (a) Decentralized method; (b) Centralized method; (c) Distributed method.

power method, PF control of active power output *cos(P)*, and voltage-dependent reactive power control *Q(V)* methods are discussed. An adaptive *Q(V)* method in which the droop parameters depend on grid impedance Z is proposed in [9]. The *Q(V)/P(V)* method has been proposed in [10] to further solve overvoltage compared to the approaches in which *Q(V)* control alone is inefficient. A study of coordinated reactive power control for distribution grid voltage regulation with PV generation is reported in [11]. The voltage sensitivity analysis is applied to compute droop settings of PV systems locally [12] and coordinate the relationship between reactive power and corresponding feed-in power of each PV system [13]. Nevertheless, voltage sensitivity matrix changes if network topology or connected element alter. Therefore, these two recent approaches need a centralized controller. In [14] and [15], a combination strategy of *cos(P)* and *Q(V)* is proposed to control the reactive power. A centralized method with volt-var control is proposed in [16] for reactive power management which depends on sensitivity to the critical bus. A study presents two reactive power centralized control methods to exploit the networked approach [17]. An optimal centralized control procedure whose objective is voltage deviation minimization is proposed in [18] to calculate the reactive power reference of PV systems. Several centralized [19-20] and distributed [21-22] voltage regulation techniques based on optimization control with diverse goals, such as minimizing voltage profile variations, active power curtailment, reactive power generation, and power losses have been suggested to generate optimized reactive power. In [23] and [24], the distributed method is activated only when the critical bus exceeds the allowable limit. Nevertheless, none of the above provides a fair reactive power-sharing.

This paper minimizes the voltage deviations by a distributed approach during high penetration of PV systems in an LV distribution network. With the proposed technique, all PV inverters function at their maximum active power point and engage in reactive power sharing based on the reactive power ratio of the critical bus PV inverter. The PV system located at the critical bus calculates the reactive power ratio reference considering the local measured voltage, and then conveys this reference to the next PV system by the communication link. Likewise, the other PV inverters get their reference reactive power ratio from their neighbor PV inverter. Thus, all PV inverters work at the identical reactive power ratio. Furthermore, this approach protects PVs from active power curtailment since PVs use the free capacity of inverters.

2- Reactive Power Control Scheme

2- 1- Control Schemes

The control schemes are separated into two main groups: 1) local and 2) communication-based links. According to the type of information exchange, the second group is categorized into centralized and distributed control [25].

In the local control, all units independently calculate the reference of the controllers. As depicted in Fig. 1(a), this scheme only utilizes local data. This method quickly reacts to variations in the environment which affect the operation of PV systems. Additionally, the local control tolerates the failure of units or communication links since it does not employ communication networks. However, in the local control, incoordination of units result in inaccurate reactive power sharing, voltage deviation, and frequency fluctuation. Furthermore, some PV systems might be saturated with reactive power while other PV inverters have empty capacity.

In centralized control, a central controller receives the units' information and determines accurately the reference amounts for every PV inverter according to Fig. 1(b). Nevertheless, this method is not reliable, and the effectiveness of this approach depends on expensive communication links and complex calculations. Hence, this control scheme is not suitable for large microgrids.

The distributed control strategy uses a sparse communication network without a central controller. Therefore, the distributed control is resistant and flexible. In this approach, each PV systems communicate with its neighbors, so all units use local data and their neighbors' information to work coordinately in microgrids. Fig. 1(c) indicates the distributed control scheme.

2- 2- Reactive Power Control Approaches

Many papers are focusing on reactive power control of PV systems, and the control strategies are summarized in this section. The constant Power Factor method calculates the reference reactive power of the PVs based on Eq. (1). This approach is not involved in reactive power sharing when PV inverters do not generate active power. Furthermore, this

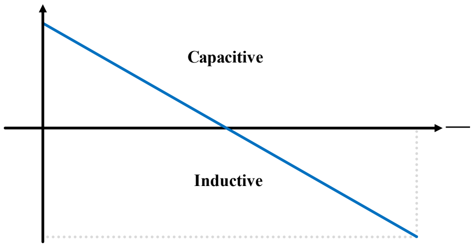

Fig. 2. ***cosφ(P)*** **control method.**

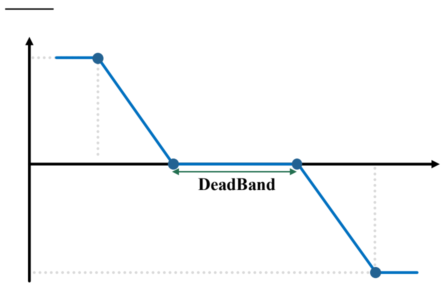

Fig. 3. Q(V) control strategy.

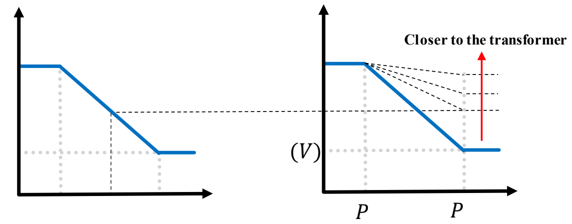

Fig. 4. ***cosφ(P,V)*** **control approach. (a) C2 is determined by voltage. (b) PF is determined by P and C2.**

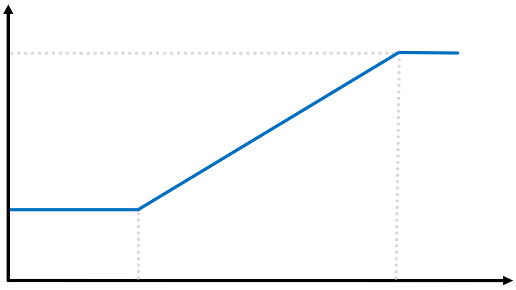

Fig. 5. Coefficient K

method determines reference reactive power irrespective of bus voltage, so it may absorb or inject unnecessary reactive power that causes power losses in the network [11].

$$Q_{PV,ref} = \pm P_{PV}\ tan(cos^{-1}(pf)) \tag{1}$$

where $Q_{PV,ref}$ is the consuming or injecting of the reactive power of the PV system, P_{PV} is the active power of the PV system, and *pf* is a Power Factor. Similar to the previous method, the constant reactive power technique determines the reactive power reference of PV inverters without respect to the bus voltage level. Therefore, it is not a suitable method for reactive power control.

cosφ(P) control strategy varies the inverter's Power Factor according to the active power production of PV inverters and obviates some of the disadvantages of the constant Power Factor method (e.g. unnecessary reactive power) [7]. As illustrated in Fig. 2, *cosφ(P)* control method reduces the Power Factor of PV inverters and operates in the inductive area when their active power generation rises. Conversely, as active power production decreases, this procedure diminishes the Power Factor in the capacitive area to inject reactive power. However, this method still absorbs or injects unnecessary reactive power regardless of voltage bus level. For instance, if both the active power of PV inverters and load demands are high, the inverter absorbs the reactive power, resulting in system losses increase.

In *Q(V)* control strategy depicted in Fig. 3, the amount of reactive power of the PV system is determined according to the voltage deviation of its bus [7-8]. Based on this method, PV systems near the critical bus sense the most voltage deviation, so they engage further to improve the bus voltage compared to other PVs. Therefore, these PV systems may saturate with reactive power while other PV inverters have free capacity for reactive power absorption/injection. On the other hand, voltages of PV systems located closer to the transformer usually are within the dead band, so they do not take part in voltage regulation.

Voltage sensitivity analysis can determine the most effective locations and amounts to serve reactive power for the grid voltage support from the PV systems [26]. Based on the voltage sensitivity matrix in Eq. (2), in a sample of radial LV distribution network illustrated in Fig. 8, the voltage of the farthest bus from the transformer is affected and deviated more than other buses, naming critical bus. That is, the active and reactive power variations of the PV systems and loads located farther from the transformer have more effect on critical bus voltage.

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \dfrac{\partial\delta}{\partial P} & \dfrac{\partial\delta}{\partial Q} \\ \dfrac{\partial V}{\partial P} & \dfrac{\partial V}{\partial Q} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{2}$$

To progress the operation of PV systems in reactive power management, *Q(V)* and *cosφ(P)* methods are combined. *cosφ(P,V)* strategy is one of the combinations of *Q(V)* and *cosφ(P)* methods to determine reactive power reference for the PV inverters for voltage rise conditions. Fig. 4 depicts *cosφ(P,V)* approach [14]. According to this method, in all

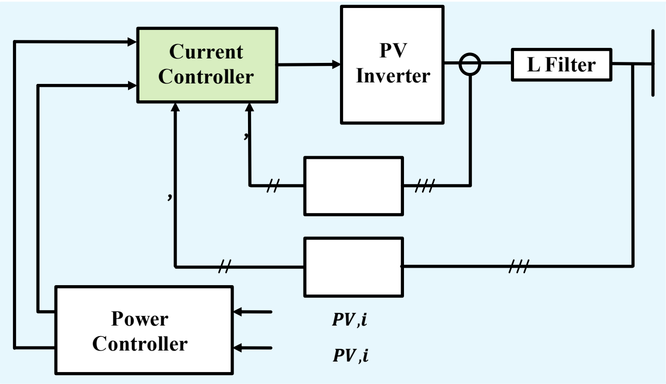

Fig. 6. The block diagram of a CCVSI

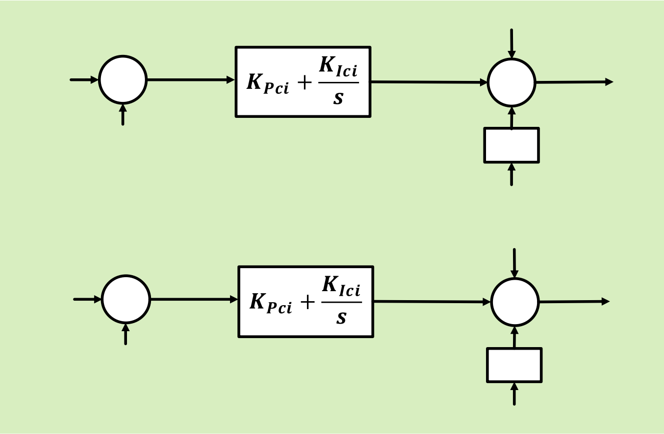

Fig. 7. The block diagram of the current controller

PV inverters, the above limitation of *cosφ(P)* characteristics are identical. However, the below limitation of *cosφ(P)* characteristics are selected based on the local voltage and *Q(V)* characteristic. Finally, the reactive power reference of PV inverters is determined according to the new *cosφ(P)* characteristic. In this strategy, the rest of PV inverters (except for the critical bus PV inverter) help the critical bus PV inverter to regulate bus voltage levels in the power network. However, during high penetration of the PV system, the critical bus PV inverter becomes saturated, while other PV inverters have unused reactive power capacity. A Central Reactive Power Management System (CRPMS) has been incorporated into *cosφ(P,V)* method to solve the saturating problem of the critical bus PV inverter. In this method, when the critical bus PV inverter is saturated, the CRPMS sends a signal to the closest PV inverter through communication links to operate at its lowest PF limit. If the closest inverter's reactive power is not sufficient, the CRPMS commands the next PV inverter, which has the highest sensitivity to operate at its lowest limit. The other PV inverters operate based on *cosφ(P,V)* method [16]. However, PV inverters do not operate in the same ratio of Q/Q_{max} according to this strategy.

Another approach of *Q(V)* and *cos(P)* combination calculates reactive power reference for the PV inverters according to Eq. (3) during voltage rise conditions [8].

$$Q_{PV,ref} = (1-K)\, Q_{ref,Q(V)} - (K)Q_{ref,PF(P)} \tag{3}$$

where $Q_{ref,Q(V)}$ is the reactive power by *Q(V)*, $Q_{ref,PF(P)}$ is the reactive power by *cos(P)*, and is the coefficient that is determined according to Fig. 5.

3- Graph Theory

A preliminary graph theory is briefly presented in this section as a fundamental for the proposed method. A graph is defined as $g = (V_g, E_g, A_g)$ where $V_g = \{v_1, \dots, v_N\}$ denotes the set of nodes, $E_g \subseteq V_g \times V_g$ is the set of edges or arcs between nodes, and an adjacency matrix $A_g = [a_{ij}] \in R^{N\times N}$. An edge from node *j* to node *i* is denoted by (v_j, v_i), meaning that node *j* sends information to node *i*. If $(v_j, v_i) \in E_g$, node *j* is called a neighbor of node *i*. The set of neighbors of the th node is defined as $N_i \triangleq \{v_j \in V_g : (v_j, v_i) \in E_g\}$. Next, the communication graph can be described through the following matrix: $A_g = [a_{ij}] \in R^{N\times N}$, where a_{ij} is the weight of the edge (v_j, v_i), and $a_{ij} > 0$ if $(v_j, v_i) \in E_g$, otherwise $a_{ij} = 0$. The degree matrix D_g has diagonal elements as $d_{ii} = \sum_{j=1}^{N} a_{ij}$ and $d_{ij} = 0$. when $i \neq j$. Afterwards, the Laplacian matrix can be expressed as $L_g = D_g - A_g$. A directed path from node *i* to node *j* is a sequence of edges expressed as $\{(v_i, v_k), (v_k, v_l), \dots, (v_p, v_j)\}$. A digraph is said to have a spanning tree if there is a node i_r (called the root), with a directed path to every other node in the graph [27].

4- Proposed Reactive Power Control

PV systems are Voltage Source Inverters (VSIs) that work as Current-Controlled VSIs (CCVSIs) to modify their power production in a grid-connected power network. The block diagram of a CCVSI is shown in Fig. 6. The direct and quadrature components of the CCVSI output current are controlled by an internal current controller. The block diagram of the current controller is shown in Fig. 7 [28].

In LV distribution networks, the usage of the traditional local methods based on the droop technique might cause the reactive power of PV systems to not share properly since the ratio of *X/R* of the lines is low. Hence, the goals of the proposed approach are enhancing the voltage profile of buses, protecting PV systems from active power curtailment, and accurate reactive power sharing among PVs considering their reactive power ratings. For such objectives, all PV inverters should follow the ratio of Q/Q_{max} of the PV system located at the critical bus. In this paper, the proposed method synthesizes the *Q(V)* droop characteristic with the distributed cooperative control to regulate voltage buses and share the reactive power accurately.

The proposed reactive power control method utilizes a *Q(V)* characteristic to calculate the local reactive power ratio reference for PV systems. Eq. (4) determines the reactive power ratio reference for PVs.

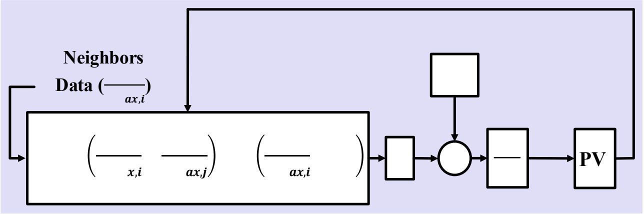

Fig. 8. The block diagram of the reactive power control in PV inverters.

$$\alpha_{Qi} = \begin{cases} +1, & V \le 0.9 \\ \dfrac{-(V_i - 0.95)}{0.05}, & 0.9 < V < 0.95 \\ 0, & 0.95 \le V \le 1.05 \\ \dfrac{-(V_i - 1.05)}{0.05}, & 1.05 < V < 1.1 \\ -1, & 1.1 \le V \end{cases} \tag{4}$$

where α_{Qi} is the local reactive power ratio reference of the ith PV inverter and V_i is the ith bus voltage. For PV inverters, $Q_{max,i}$ is defined as the maximum available reactive power and is calculated as:

$$Q_{\max,i} = \sqrt{S^2_{inveter,i} - P^2_{pv,i}} \tag{5}$$

where $S_{inverter}$ and P_{pv} are the rated PV inverter capacity and the generated active power of PV, respectively.

To decouple the reactive power sharing accuracy with the line impedance, distributed cooperative control is implemented to exchange PVs' data through communication links. It should be noted that the distributed control method only requires communication links between neighboring agents [27, 29].

The general form of the distributed cooperative control can be presented as follows [29]:

$$x_i = u_i = \sum_{j \in N_i} a_{ij}(x_j - x_i) + g_i(x_0 - x_i) \tag{6}$$

where i are the indexes of agent nodes, x_i is the information obtained from agent i, a_{ij} is the edge weight between node i and node j, and N_i is the set of indexes of the agents that are connected with agent i. The pinning gain g_i is nonzero for one agent.

The distributed cooperative control adjusts the control inputs of PV systems such that their output reactive powers are satisfied:

$$\frac{Q_1}{Q_{\max 1}} = \ldots = \frac{Q_{Nc}}{Q_{\max Nc}} = \alpha_{Qc} \tag{7}$$

where N_C, Q_i, $Q_{max\,i}$, and are the number of PV systems in the distributed system, the measured reactive power at the terminal of the PV system, the reactive power ratings of ith PV systems, and reactive power ratio reference of PV located at the critical bus, respectively. Therefore, the objective of the distributed cooperative control is to select PV system control inputs such that the error term $\sum_{j \in N_i \alpha_{ij}} \left(\frac{Q_i}{Q_{\max i}} - \frac{Q_j}{Q_{\max j}} \right) + \left(\frac{Q_i}{Q_{\max i}} - \alpha_{Qc} \right)$ synchronizes to zero [28]. is α_{Qc} set by the critical bus PV inverter in (4).

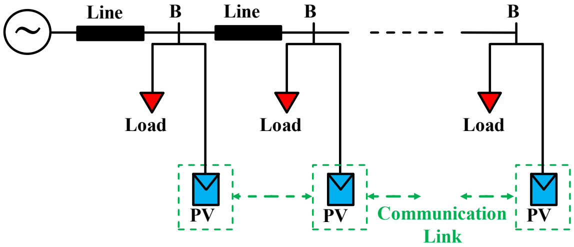

Fig. 9. The single-line diagram of the three-phase radial LV distribution system

Table 1. NETWORK PARAMETERS

Nominal voltage	380 V
Nominal Frequency	50 Hz
Line impedance (Line0)	0.16 Ω , 451 µH
Line impedance (Line1-6)	0.5 Ω , 1353.5 µH

According to [28], the reactive power Q_i can be tuned by controlling the quadrature term of the output current of PV inverters , i_{qi} and i_{qi} is controlled by i_{qrefi}. i_{qrefi} can be obtained as:

$$i_{qrefi} = (N_{Qi}(x_{cc_i}))^{-1}(-M_{Qi}(x_{cc_i}) + v_{Qi}) \tag{8}$$

And:

$$M_{Qi}(x_{cc_i}) = \frac{\dot{v}_{odi}\, i_{qi}}{Q_{\max i}} - \frac{v_{odi}}{Q_{\max i}} \left(\frac{-R_{fi}}{L_{fi}} i_{qi} - \omega i_{di} - \frac{1}{L_{fi}} v_{oqi} \right) \\ - \frac{v_{odi}}{Q_{\max i} L_{fi}} (v_{oqi} + \omega L_{fi} i_{di} - K_{PCi} i_{qi} + K_{ICi} y_{qi}) \tag{9}$$

And:

$$N_{Qi}(x_{cc_i}) = -\frac{v_{odi} K_{PCi}}{Q_{\max i} L_{fi}} \tag{10}$$

And:

$$v_{Qi} = -c_{Qi} \sum_{j \in Ni} a_{ij} \left(\frac{Q_i}{Q_{\max i}} - \frac{Q_j}{Q_{\max i}} \right) + g_i \left(\frac{Q_i}{Q_{\max i}} - \alpha_{Qc} \right) \tag{11}$$

where $c_{Qi} \in R$ is the coupling gain. It is assumed that the

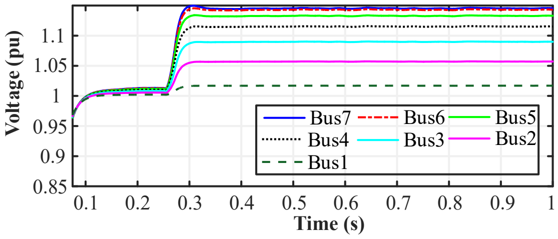

Fig. 10. Bus voltages based on *Q(V)* method in voltage rise condition.

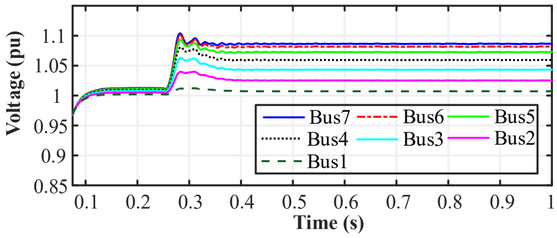

Fig. 11. Bus voltages based on the proposed method in voltage rise condition.

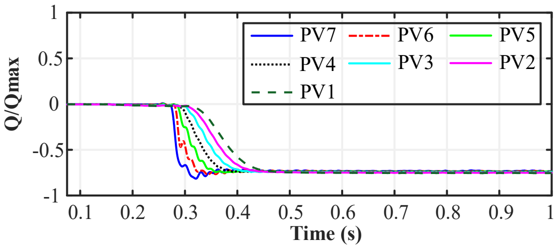

Fig. 12. Q/Qmax of PVs based on the proposed method in voltage rise condition.

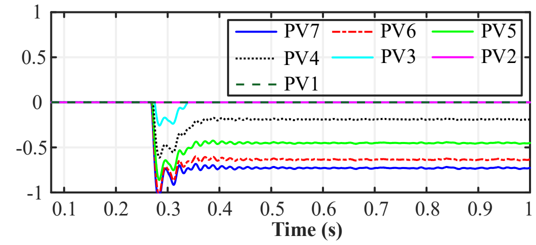

Fig. 13. Local reactive power ratio based on the proposed method in voltage rise condition.

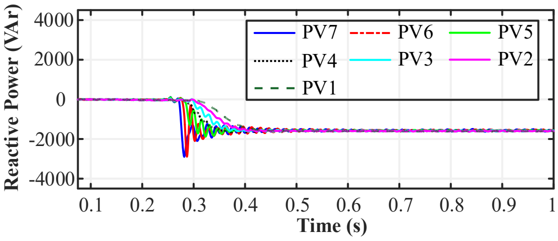

Fig. 14. Reactive power of PVs based on the proposed method in voltage rise condition.

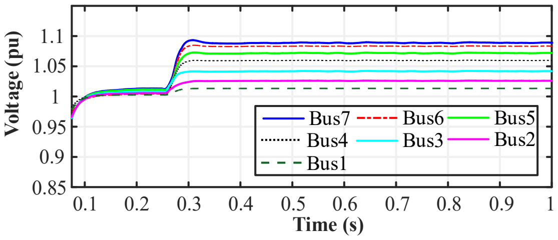

Fig. 15. Bus voltages based on the centralized method in voltage rise condition.

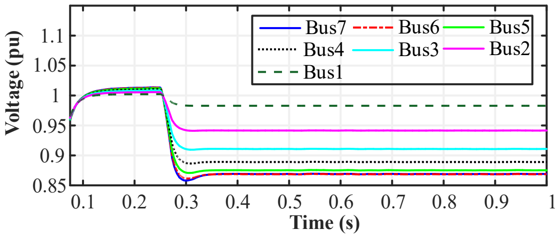

Fig. 16. Bus voltages based on *Q(V)* method in voltage drop condition.

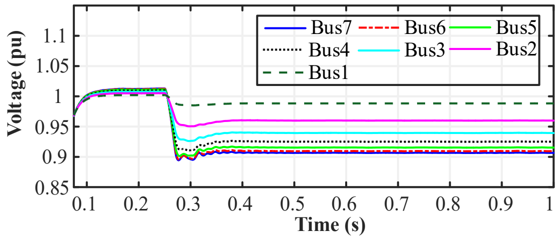

Fig. 17. Bus voltages based on the proposed method in voltage drop condition.

pinning gain $g_i \geq 0$ is nonzero for one PV that locates at the critical bus. ω is the base angular frequency of the LV radial distributed system. Other parameters are displayed in Figs. 6 and 7. Consequently, all PV inverters operate at the critical bus of the reactive power ratio of the PV inverter. The block diagram of the reactive power control in PV inverters is exhibited in Fig. 8 [28]. In addition, Maximum Power Point Tracking (MPPT) exploits the maximum active power of a PV array. Therefore, i_{drefi} determines based on the maximum active power of PV systems.

5- Simulation Results

The single line diagram of a radial LV distribution system is demonstrated in Fig. 9. The power system includes seven PV systems and seven loads that they divide into different bus locations of the feeder. The network parameters are mentioned in Table 1. In this power grid, Bus7 is the farthest bus from the main grid, so it is regarded as the critical bus. Therefore, in the proposed method, PV7 determines the reactive power ratio so that other PV inverters work at the reactive power ratio of PV7. In this section, two case studies, including voltage rise and the voltage drop condition, are evaluated to prove the advantages of the proposed method over *Q(V)* technique. It is regarded that all PV systems are similar, and their active power value is 4650 W during simulations. The rated PV inverter capacity is 5115 VA. In both cases, at t=0.15 sec, the reactive power controls are activated, and the load value is 4650 kW from

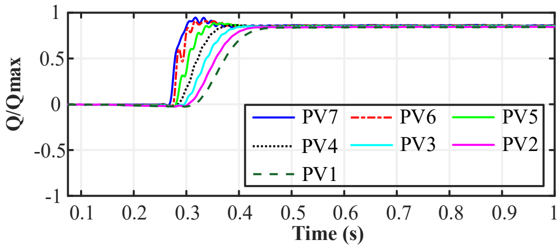

Fig. 18. Q/Qmax of PVs based on the proposed method in voltage drop condition.

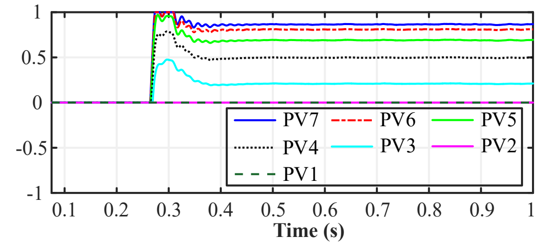

Fig. 19. Local reactive power ratio based on the proposed method in voltage drop condition.

t=0 s to *t*=0.25 s. It should be noted that the line impedance from each node to the PV inverter is neglected.

5- 1- Voltage Rise

This case study investigates the voltage rise which happens since load consumption is lower than the active power production of PVs. In case A, at *t*=0.25 s, the load value is adjusted to 1550 kW + j(0.2 * 1550) kVar. Figs. 10 and 11 show bus voltages while PV inverters operate based on *Q(V)* and the proposed approach, respectively. In the proposed method, all bus voltages are lower than 1.1 p.u. while in *Q(V)* method, some bus voltages are higher than 1.1 p.u. Therefore, such PV systems are saturated with reactive power while some PV inverters have free capacity. Fig. 12 illustrates the reactive power ratio of the PV inverters according to the proposed method. As illustrated in Fig. 12, all PV inverters operate at the reactive power ratio of PV7, which possesses the most local reactive power ratio according to Fig. 13. The output reactive of PV systems is displayed in Fig. 14. On the other hand, Fig. 15 indicates voltage buses while PV systems are provided with a centralized control method. In this method, every PV sends information to the central controller, then the center determines the reference reactive power ratio according to the most deviated voltage. As shown in Figs. 11 and 15, the proposed approach operates like the centralized strategy though the proposed method requires a sparse communication network and is more resilient.

5- 2- Voltage Drop

This subsection studies the voltage drop problem. Voltage drop occurs when the load demand is higher than the active power production. In this case, the load demand changes, and load values are equal to 7450 kW+j(0.2 * 7450) kVar at

t = 0.25s. Similar to the voltage rise case study, the consequences of this case prove that the functionality of the

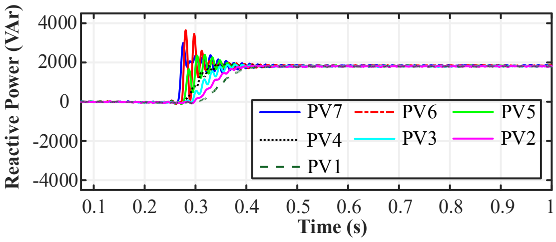

Fig. 20. Reactive power of PVs based on the proposed method in voltage drop condition.

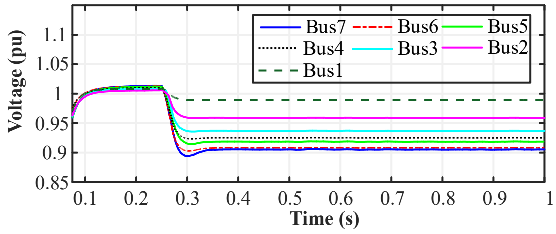

Fig. 21. Bus voltages based on the centralized method in voltage drop condition.

proposed strategy is more influential compared to the *Q(V)* approach. Figs. 16 and 17 show bus voltages based on the proposed method and *Q(V)* in the voltage drop condition, respectively. Employing the proposed method caused improved voltages, and are brought back to the acceptable region. Moreover, in the voltage drop condition, accurate reactive power sharing according to the proposed method is illustrated in Fig. 18. Indeed, PV7 placed at the critical bus experiences the greatest local reactive power ratio shown in Fig. 19, so all PV systems follow its command. Fig. 20 depicts the output reactive power of PV systems during the voltage drop situation. Finally, a centralized control method is applied to PV systems in voltage drop conditions. A central controller calculates the reference reactive power ratio according to the most deviated voltage, and then sends it to all PV systems. As illustrated in Figs. 17 and 21, the proposed approach succeeds to retain voltage buses between acceptable ranges similar to the centralized control technique.

6- Conclusion

This paper has first reviewed the existing reactive power control methods of the PV system in LV distribution network to show the drawbacks of previous reactive power control strategies for PV systems. Next, a new technique that combines decentralized and distributed control was proposed, which uses *Q(V)* characteristic to calculate the reactive power ratio reference for PV system located at the critical bus, and utilizes the distributed cooperative control to coordinate all PV systems. To verify the influence of the proposed strategy, a radial power network was simulated under rise and drop voltage situations in MATLAB/Simulink. Simulation results showed that all PV systems function at the same reactive power ratio. On the other hand, in contrast to *Q(V)* method, the free capacity of PV inverters closer to the transformer is used to decrease voltage deviation. Simulation results demonstrate that the proposed technique is more effective compared to *Q(V)* strategy in regulation voltage. As displayed in simulation results, in *Q(V)* approach, some PV systems are saturated with reactive power. Furthermore, the proposed procedure could protect active power curtailment through the useful use of the free capacity of the PV inverters.

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HOW TO CITE THIS ARTICLE

S. M. Rostami, M. Hamzeh, Reactive Power Management of PV Systems by Distributed Cooperative Control in Low Voltage Distribution Networks, AUT J Electr Eng, 55(1) (2023) 115-124.

DOI: 10.22060/eej.2022.21735.5490