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Distributed Nodal Voltage Regulation Method for Low-Voltage Distribution Networks by Sharing PV System Reactive Power

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Abstract: With the intensive integration of photovoltaic (PV) sources into the low-voltage distribution networks (LVDN), the nodal voltage limit violations and fluctuation problem cause concerns on the safety operation of a power system. The intermittent, stochastic, and fluctuating characteristics of PV output power leads to the frequent and fast fluctuation of nodal voltages. To address the voltage limit violation and fluctuation problem, this paper proposes a distributed nodal voltage regulation method based on photovoltaic reactive power and on-load tap changer transformers (OLTC). Using the local Q/V (Volt/Var) feedback controller derived from the grid sensitivity matrix, the voltage magnitude information is adopted to adjust the output of PV systems. Moreover, in order to share the burden of voltage regulation among distributed PV systems, a weighted distributed reactive power sharing algorithm is designed to achieve the voltage regulation according to the rated reactive power. Theoretical analysis is provided to show the convergence of the proposed algorithm. Additionally, the coordination strategy for distributed PV systems and OLTC is provided to reduce the reactive power outputs of PV systems. Five simulation case studies are designed to show the effectiveness of the proposed voltage regulation strategy, where the voltage regulation and proportional reactive power sharing can be achieved simultaneously.

Keywords: distributed PV sources; low-voltage distribution network; reactive power sharing; voltage regulation

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1. Introduction

1.1. Motivation

A high proportion of renewable energy is connected to the low-voltage distribution network, making the distribution network change from a passive network to an active network. The intermittency, randomness, and volatility of renewable energy will affect the power flow and cause voltage problem in the low-voltage distribution network, such as limit violation, three-phase voltage unbalance, increased harmonic, and other power quality problems. The higher the penetration rate of renewable energy, the more significant the impact on the voltage of the low-voltage distribution network.

The traditional distribution network is a passive network, and the power flows from the substation to the load in one direction, which will not cause the voltage increase in the terminal node [1]. Traditional voltage control methods mainly use on-load tap changer regulator (OLTC), switched capacitor (SC), and step voltage regulator (SVR) [2]. The main purpose of these devices is to maintain the voltage of the distribution network within an acceptable range. The above voltage control methods play a great role in mitigating voltage fluctuations and maintaining stable system voltage operation [3]. With the integration of a high-penetration distributed generator (DG), OLTC and SC will not be able to respond to voltage changes in time. The intermittency, randomness, and fluctuation of DG bring power quality problems, such as voltage out-of-limit, three-phase unbalance, and increased harmonic content to the low-voltage distribution network. In the low-voltage distribution network with a high proportion of PV systems, the voltage regulation problem has become the focus of attention. A new suitable voltage regulation method using distributed resources are necessary to address the fast-changing nodal voltages caused by the PV integration.

1.2. Related Literature

Aiming at solving the problem of voltage violations in the low voltage distribution network, reference [3] pointed out that in the distribution network the relationship between the line resistance and the reactance determines the significant degree of the influence of the active and reactive power on the system nodal voltage. While references [4,5] investigated voltage regulation methods using reactive power in the low-voltage distribution network and concluded that reactive power is helpful to achieve voltage regulation in the distribution networks using the volt-var controller.

Adjusting the active and reactive power can effectively control the voltage of the distribution network when the resistance and reactance of the branch line are similar, which was concluded in references [6–8]. Additionally, control strategies based on voltage sensitivity matrix are gaining popularity [9–12]. In these methods, the sensitivity matrix is used to solve the problem of voltage regulation, where the voltage regulation resources include distributed generators [9–11], grid-connected converters [10], capacitors [9], and energy storage [10,11]. By controlling the output of renewable energy and the switching of capacitors, system nodal voltage can be regulated in the normal range [9]. Using the node voltage sensitivity matrix, reference [10] introduced a fuzzy prediction control strategy to adjust the output of renewable energy and energy storage to achieve voltage control. Reference [11] changes the control object into a grid-connected converter and proposes a voltage control method based on the voltage sensitivity matrix, which realizes the voltage regulation at photovoltaic grid-connected points. Reference [12] analyzed the problem of voltage fluctuations in short time scales, took distributed energy storage as the regulation resources, and proposed a voltage regulation method based on a sensitivity matrix to maintain voltage stability. The researchers considered the network loss in the control strategy and proposed a voltage regulation strategy based on voltage sensitivity [13]. Based on the research of balanced distribution systems, reference [14] considers different configurations and types of voltage regulators and studies the voltage control method of an unbalanced distribution system based on voltage sensitivity analysis. Therefore, in the above-mentioned strategies, the voltage sensitivity matrix, which is composed of line reactance and resistance information, is the main theory adopted in the voltage regulation. Normally, there are different resources (equipment) employed to achieve the nodal voltage regulation and voltage control.

Centralized voltage control methods are direct since the global information, network parameters, and global resources in a distribution network are known, which help to develop the voltage regulation model easily. Reference [15] proposes a centralized reactive power control model, which considers the coordination of centralized reactive power management and voltage-related characteristics. A centralized voltage regulation method based on robust optimization is proposed in [16] to minimize the economic cost of the distribution network by controlling the elastic load using demand response technology. Moreover, the reactive power regulation capability of distributed energy resources, combined with traditional voltage regulation methods, reduces the number of equipment adjustments, reduces network losses, and optimizes distribution network operation on the premise of ensuring system voltage safety. Reference [17] proposed a voltage control method based on the centralized control of the controllable dead-zone static synchronous compensator. The centralized control system measures the voltage of each compensator connected to the grid and modifies the voltage of all nodes through the target voltage. The voltage quality is improved so that all node voltages are regulated within the appropriate range. Reference [18] included the objective function of network loss on the basis of the coordinated centralized control of DG and OLTC and considered the economic benefits of system operation.

A framework to assess the performance of different OLTC-based control strategies in terms of voltage compliance with the standard BS EN50160 and the number of control actions was presented in [19] to show the advantages of remote monitoring-based strategies over the constant set-point and time-based control strategies in enhancing PV capacities and limiting operations of OLTC. A coordinated control strategy to control BESS along with OLTC is proposed in [20] to warrant acceptable voltage magnitudes at the distribution feeder, where an optimization strategy is designed to minimize the actions of OLTC and prolong the battery lifetime. A coordinating control strategy for an on-load tap changer (OLTC) of the main transformer in a distribution substation and PV smart inverters is proposed to maintain the voltage at the PCC fixed at the specified voltage level [21]. The alternative of exploiting distributed PV converters for voltage control is discussed in [22], which shows that PV inverters can help to stabilize the voltage in a PCC point also without coordination between inverters and/or with a centralized unit. To investigate how the setup of the voltage controllers inside PV inverters affects the operation of these controllers, the limits for reactive power injection is also considered. Reference [23] proposes an intelligent search algorithm, a voltage ranking search algorithm, to solve the optimization of flexible resource scheduling for voltage regulation. In [24], a coordination voltage control strategy using air conditioners and an OLTC is proposed to achieve voltage regulation without the occurrence of regulation lag caused by the OLTC.

Normally, as discussed, a centralized control method with the central controller collects the information of each node and sends a command to control the DG, OLTC and load, and other equipment after calculation. The principle is simple and easy to implement, but when considering that a large number of DGs are connected to the LVDN, the topology becomes complicated and communication restrictions need to be considered.

Therefore, distributed voltage control systems with the use of local information are widely investigated [25]. In reference [26], considering the reactive power absorption and compensation capabilities of distributed power sources, a distributed adaptive control method is proposed to solve the voltage violation problem caused by the mismatch between supply and demand. Similarly, reference [27] studied the voltage fluctuation problem of large-scale distributed generation connected to the distribution network and proposed a distributed control method to alleviate the voltage rise issues caused by active power injection. Reference [28] proposed a secondary voltage adaptive distributed control method based on the characteristics of distributed power inverters. To compensate for the uncertainty, each DG only needs its own information and the information of neighboring DGs in the communication network. Therefore, the method is only related to the communication network structure, does not require parameter information of distributed power sources, and is completely distributed and adaptive. The proposed distributed coordinated control strategy is of great significance for the realization of multiple time scales. Reference [29] performs real-time voltage control through the calculation of the optimal power flow. This method is suitable for dynamic distributed networks with multiple time scale requirements. Due to the difficulty of real-time power balancing, it lacks flexibility. Reference [30] takes the minimum cost as one of the control objectives and proposes a frequency and voltage control method based on distributed cooperative control, which ensures the balanced sharing of power reactive power. In [31], a decentralized control method for coordinated control (OLTC) transformers and PV inverters, is proposed for the voltage regulation of radial distribution networks, where the appropriate corrective actions are taken according to the predefined voltage zones.

Compared with the centralized methods, this paper proposes a distributed voltage regulation method for LVDN with high penetration of PV systems, only using the existing resources, namely, OLTC and PV sources, which are privacy-protected, flexible, and resilient to single-point failure. When it mentions to the existing distributed voltage regulation methods, the proposed coordination strategy of OLTC and PV can reduce the injection of reactive power while guaranteeing the voltage performance. Additionally, the proposed voltage regulation method is scalable since the parameters of the distribution network are not required.

To address the nodal voltage limit violation problems, this paper proposes a fully distributed voltage regulation method only using the existing resources, PV systems and OLTC, which avoids extra investments and maintains the system voltage safety. Moreover, to share the voltage regulation burden, a weighted distributed algorithm is designed to achieve the proportional reactive power sharing of PV systems. The coordination of OLTC reduces the reactive power injection. To conclude, the contributions in this paper include the following:

- The proposed voltage regulation method is scalable and simple since the parameters of the distribution network are not required.
- The proposed method is fully distributed, which only uses local information of voltage and reactive power, avoiding the possibility of single-point failure.
- The proposed reactive power sharing method ensures that the voltage regulation task is shared among PV sources according to the reactive power capacities.
- The distributed coordination strategy of PV and OLTC is proposed to improve voltage regulation efficiency.

The rest of the paper is organized as follows: Section 2 introduces the model of a distribution network with high-penetrated PV sources. Section 3 proposes the Var/Q local voltage control method and distributed proportional power-sharing strategy of PV sources. Section 4 is case studies, and the conclusion of the paper is in Section 5.

2. The Model of LVDN with Highly Penetrated PV Sources

This section proposes the multi-agent system (MAS)-based control model to solve the problem of over-voltage issues and introduces the composition of the physical network and the construction rules of the communication network G. The MAS-based two-layer control model is shown in Figure 1. The physical network of this model is composed of distributed PV sources and loads. In the LVDN (380 V), only photovoltaics is often considered. The control object proposed in this study is limited to PV sources and OLTC. In the LVDN, solar radiation determines the active power output of the PV sources, and each PV works in the maximum power point tracking (MPPT) control mode.

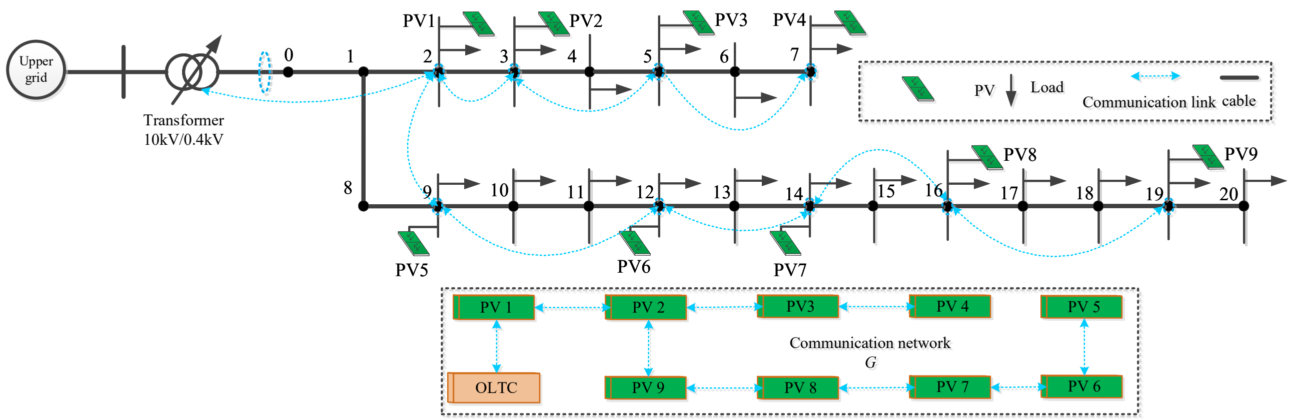


Figure 1. Node voltage regulation model of LVDN with a high proportion of distributed PV sources. The black arrow is the load of each node, while the dash blue lines with arrow are the communication links.

The corresponding communication network is composed of multiple agents, which have the ability to transmit and process information. Each PV and load corresponded to an agent in the communication network. For calculation convenience, it is necessary to ensure that the number of agents and the number of PV and loads are matched. In addition, there are communication links between the multi-agent system and the LVDN and links among agents. Therefore, the agent can collect information of PV and loads, such as power, voltage, and other information. Finally, each agent can obtain the output of each photovoltaic at the next moment according to the collected local information and the designed distributed control law so as to achieve the control purpose. The links (blue dashed lines) between the two layers show information flows. On the communication network G, in addition to collecting and transmitting information, each agent also needs to have the ability to calculate and process information. Graph G is a two-way connected network. Each agent is connected to at least two agents, and they not only have outgoing edges but also incoming edges. At the same time, each agent has a self-loop, which can not only collect the information of neighbor agents but also collect its own information. In addition, it is worth noting that the control object of the method proposed in this section is the reactive power of PV sources, so the PV agent belongs to the controllable agent, which is represented by a diamond. On the basis of the two-layer model, a distributed control strategy is designed to adjust the output of the PV reactive power to realize the voltage control.

3. Distributed Voltage Regulation Strategy Using PV Sources

3.1. The Design of the Local Voltage Controller

Combined with the district power flow model of the distribution network, the relationship between the node voltage amplitude and the branch power flow, shown in Figure 2, can be expressed by Equation (1) [32–34]. The analysis shows that the amplitude of the node voltage is related to the node load, the branch power flow, the line impedance parameter, and the voltage amplitude of the neighbor nodes. The adjustment of the power flow can indirectly adjust the node voltage. Additionally, the power flow can be adjusted by adjusting the injected power of the node, so the purpose of indirectly adjusting the node voltage can be achieved.

$$\begin{aligned} P_{\mathrm{L},i} &= P_{\mathrm{L},i-1} - L_{R,i-1}\frac{P_{\mathrm{L},i-1}^2+Q_{\mathrm{L},i-1}^2}{V_{i-1}^2} - P_i \\ Q_{\mathrm{L},i} &= Q_{\mathrm{L},i-1} - L_{X,i-1}\frac{P_{\mathrm{L},i-1}^2+Q_{\mathrm{L},i-1}^2}{V_{i-1}^2} - Q_i \\ V_i^2 &= V_{i-1}^2 - 2(L_{R,i-1}P_{\mathrm{L},i-1} + L_{X,i-1}Q_{\mathrm{L},i-1}) + \left(L_{R,i-1}^2 + L_{X,i-1}^2\right)\frac{P_{\mathrm{L},i-1}^2+Q_{\mathrm{L},i-1}^2}{V_{i-1}^2} \end{aligned} \quad (1)$$

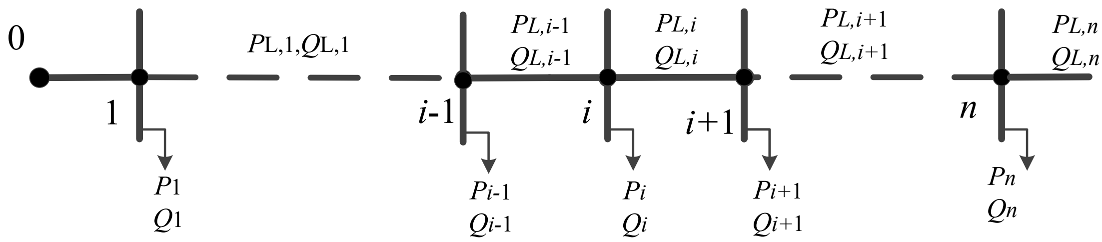


Figure 2. Network topology diagram of LVDN.

According to the district power flow model of the distribution network, the node voltage amplitude is related to the branch power flow and the branch line impedance. Therefore, the reactive power voltage regulation strategy of a photovoltaic power source can be designed, as shown in Equation (2)

$$Q(t+1) = Q(t) - k_q(U(t) - U_0) \quad (2)$$

where $Q(t + 1) = [q_i(t + 1)]_{n \times 1}$, $U(t) = [u_i(t)]_{n \times 1}$, respectively, represents the reactive power output of the PV at time instant $t + 1$ and time t, U_0 is the standard node voltage, and $k_q = [X_{ii}/U_0]_{n \times 1}$ represents the sensitivity coefficient. The sensitivity coefficient k_q can be determined by the network structure of the distribution network and the network parameters; that is, for the distribution network with known parameters of any parameter, the node voltage sensitivity coefficient corresponding to any node can be determined.

In order to realize the adjustment task of node voltage, the following local control strategy of node voltage is designed according to Equation (2).

$$\begin{cases} Q(t+1) = Q(t) - k_q(U(t) - 1.05U_0), & U(t) > 1.05U_0 \\ Q(t+1) = Q(t) - k_q(U(t) - 0.95U_0), & U(t) < 0.95U_0 \end{cases}, \tag{3}$$

Equation (3) shows that when the node voltage is greater than the upper limit of the node voltage, the photovoltaic power supply can absorb reactive power, thereby decreasing the node voltage amplitude. When the node voltage is less than the lower limit value, the photovoltaic power source can release reactive power to maintain the node voltage change within the normal range. By controlling the reactive power of the photovoltaic power supply, the node voltage can be adjusted.

The control objective is to achieve the nodal voltage regulation, namely, to achieve the following objectives:

- Inject reactive power from PV/OLTC when nodal voltage $U_i(t) \le U_{\min}$;
- Absorb reactive power from the grid when nodal voltage $U_i(t) \ge U_{\max}$;
- Proportional reactive power sharing when nodal voltage $U_{\min} \le U_i(t) \le U_{\max.}$

The proportional reactive power sharing control objective is to achieve the proportions of PV reactive power to maintain the same among different PV systems, i.e., to achieve $\left|B_i(t) - B_j(t)\right|_{t\to\infty} \to 0$, where $B_i(t) = Q_i(t)/Q_i^{\max}$ is the proportions of the PV reactive power. In order to achieve the proposed control objectives, following section is designed.

3.2. Distributed Power-Sharing of PV Reactive Power-Sharing

The node voltage feedback control law (3) can only ensure that the PV node voltage is controlled within the range of (0.95~1.05)U_0. In order to further improve the voltage regulation ability of the PV reactive power in the low-voltage distribution network and realize the balanced sharing of photovoltaic reactive power according to the rating PV reactive power, a MAS-based balanced reactive power sharing strategy of a PV source is designed.

Inspired by our previous research work [10,32], the distributed power sharing algorithm is designed to guarantee the proportional power sharing of PV reactive power. In order to make the PV reactive power distributed according to its reactive power capacity, the control law between controllable agents is designed according to the sub-network,

$$\dot{Q}(t) = -W \cdot Q(t), \tag{4}$$

In the formula, $Q(t) = [q_i(t)]_{n \times 1}$ is the reactive output column vector of the photovoltaic inverter, $W = aLC^{-1}$, where $L = D - A$ is the Laplace corresponding to the network topology G, and $a > 0$ is a constant, the diagonal matrix D is the out-degree matrix of the network G. Diagonal matrix C is composed of PV reactive power capacity, namely, the maximal reactive power matrix diag{$[Q_1^{\max}, \ldots, Q_i^{\max}, \ldots, Q_n^{\max}]$}.

Theorem 1. *On the communication network G, if the Agent adjusts the reactive power of the distributed PV sources according to the distributed control law (4), after serval iterations, the ratio of the reactive power of the PV to its capacity becomes* $\alpha = [\sum q_i(0)]/[\sum c_i]$*, and the sum of PV reactive power remains unchanged during the iterative process.*

Proof. First prove that the sum of reactive power remains unchanged.

$$\dot{B}(t) = -aC^{-1}L \cdot B(t), \tag{5}$$

Choose the following Lyapunov function,

$$V(t) = \frac{1}{2}B(t)^T LB(t) \tag{6}$$

Taking the derivative of Equation (6), it derives

$$\begin{aligned} \dot{V}(t) &= B(t)^T L\dot{B}(t) \\ &= -aB(t)^T LC^{-1}LB(t) \\ &= -aB(t)^T L_1 B(t) \\ &\leq -a\rho_2(L_1)\|B(t)\|^2 \\ &\leq 0. \end{aligned} \tag{7}$$

where $L_1 = LC^{-1}L$ is weighted control matrix, $\rho_2(L_1)$ is the minimal non-zero eigenvalue of matrix L_1. According to Formula (7), $V(t)$ gradually reaches zero, that is, when t goes to infinity, expression $|B_i(t) - B_j(t)| \to 0$. □

This section presents a distributed voltage control method for any balanced communication network, which can not only achieve distributed voltage control but also enable the photovoltaic inverter to generate power proportional to its capacity through iteration. Finally, it theoretically proved the effectiveness and convergence of the control laws.

3.3. Distributed Coordination of PV and OLTC for Voltage Regulation

In the actual operation process, due to the limitation of a power factor and an apparent power, the reactive power capacity of the photovoltaic power supply is usually limited, and its reactive power capacity can be expressed as,

$$Q^{\max} = \pm\sqrt{S_{PV}^2 - P_{PV}^2}, \tag{8}$$

In the formula, $Q^{\max}$ is the maximum reactive power output capacity of the photovoltaic inverter, S_{PV} is the apparent power capacity of the PV source, and P_{PV} is the active power output of PV.

Therefore, when considering the reactive power capacity constraints of distributed PV, the regulation of node voltages combined with OLTC is the focus of this section. The previous section expounds on the distributed PV reactive power sharing control strategy, which can realize the balanced sharing of PV reactive power while realizing nodal voltage regulation. In this section, the proportional value of PV reactive power is used to adjust the tap of OLTC. The specific strategy is as follows:

1. Photovoltaic reactive power ratio $|\alpha| > \alpha_1 > 0$, $\alpha < 0$, node voltage rises, OLTC tap position $u = u - 1$;
2. Photovoltaic reactive power ratio $|\alpha| > \alpha_1 > 0$, $\alpha > 0$, node voltage drops, OLTC tap position $u = u + 1$;
3. When $|\alpha| < \alpha 1$, the voltage violation problem of LVDN is regulated by PV reactive power with (3) and (4).

Moreover, the flowchart of the proposed voltage regulation method is shown in Figure 3.

3.4. System Structure and Parameter Setting

On the basis of the two-layer control model proposed in the above part, the simulation test is carried out by Matlab/Simulink. Different simulation cases are designed to test the effectiveness of the algorithm. The LVDN consists of nine groups of distributed PV and nine groups of loads, which is a radial network. The physical model consists of the main grid, transmission lines, PV sources, and loads. Nine groups of PV sources PV 1–PV 9 work in MPPT mode, and each group of PV produces active and reactive power. The capacity of

PV and load is shown in Table 1. The system reference voltage is set to 380 V, while the system frequency is 50 Hz, the line impedance parameter Z = 0.335 + j0.06 Ω/km, and the line length from the power common couple (PCC)node to each PV node is shown in Table 2. The communication network is shown in Figure 1. It is assumed that the reactive power of PV in the LV is controllable. In the initial state, the system runs in a stable state.

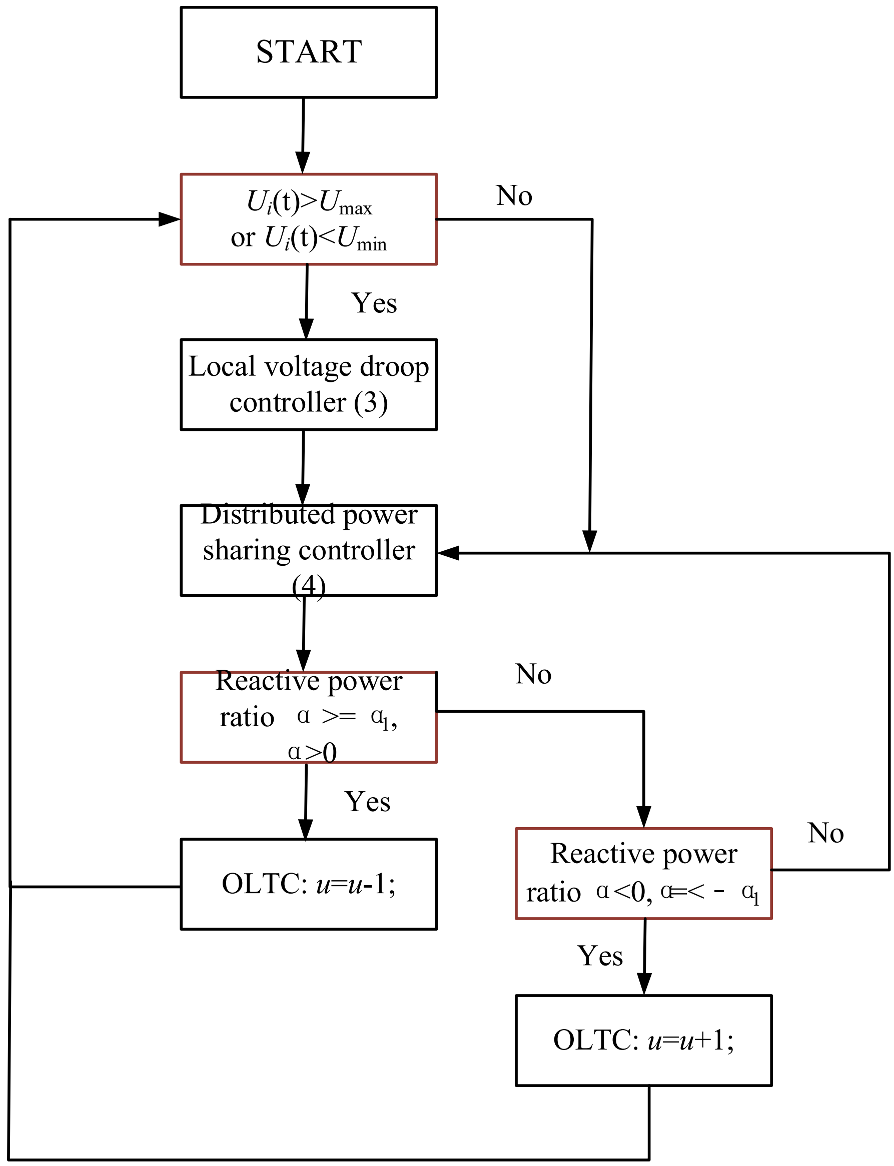


Figure 3. The flowchart of the proposed voltage regulation method.

Table 1. PV and load capacity parameters.

PV	P (kW)	Load	Max. Demand (kW)
PV_1	20	Load1	15
PV_2	15	Load2	10
PV_3	30	Load3	20
PV_4	25	Load4	20
PV_5	18	Load5	20
PV_6	12	Load6	15
PV_7	22	Load7	15
PV_8	16	Load8	15
PV_9	28	Load9	10

Table 2. The length of cables.

Cable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	17	18	19	20
Length (m)	335	502	670	167	134	201	168	168	168	168	402	168	201	234	335	268	335	670	335

4. Simulation Examples and Analysis

In this section, four different examples are designed to analyze and verify the performance and effectiveness of the distributed reactive voltage control strategy. In cases 1 and 2, the non-use and use of reactive voltage control are compared, and the effectiveness of the two-layer control strategy proposed in this paper for voltage control is analyzed. In case 3, the influence of reactive power-sharing control on nodal voltage regulation is considered. In case 4, the nodal voltage regulation strategy involving OLTC is considered. Cases 5 shows the differences between the proposed method when compared with the method only using OLTC. Table 3 shows the summary of the simulation case studies.

Table 3. Simulation Case Studies.

	V/Q Local Control	Power Sharing	OLTC
Case 1	×	×	×
Case 2	√	×	×
Case 3	√	√	×
Case 4	√	√	√
Case 5	×	×	√

×: not included, √: Included.

4.1. Case 1: Nodal Voltage Fluctuation without Local Voltage Controller

This case investigates the voltage fluctuation of nodal voltages without the proposed voltage regulation strategy. The distributed PV sources work in the maximal power point tracking (MPPT) control mode, and its capacity and parameters are shown in Table 1. The obtained simulation results are shown in Figure 4. As shown in Figure 4a, the total active power output of distributed PV sources varies from 0 kW to 140 kW, and the total load demand varies from 30 kW to 80 kW. This case is from the real distribution network in North China, where distributed PV sources are widely integrated into the low voltage distribution networks. Therefore, in the summer days, the distribution network with rich PV sources will inject power to the upper grid (middle voltage distribution network). The active power injection will cause the nodal voltage to rise in the PV integration nodes.

During daylight with rich solar radiation, the total power output of the distributed PV sources is greater than the load demand in the distribution network, which further increases the nodal voltage amplitude, causing the voltage amplitude of some nodes to exceed the upper limit, as shown in Figure 4b. In addition, when the solar radiation is insufficient and the PV power output is less than the load demand, the voltage amplitude of some nodes is less than the lower limit, and the voltage exceeds the lower limit. Therefore, in an LVDN with a high proportion of distributed PV sources, the problems of voltage rise, and a voltage drop will occur in some nodes at different times, making the task of voltage regulation more difficult. Moreover, from Figure 4b–d, the longer the cable length, the voltage magnitudes deviation from the normal values become larger. In other words, the fluctuation of voltage magnitudes becomes more severe with the increase in cable length (line impedance), which makes sense according to the power flow shown in Equation (1). The reactance and resistance of the branch line will increase when the length of cables increases.

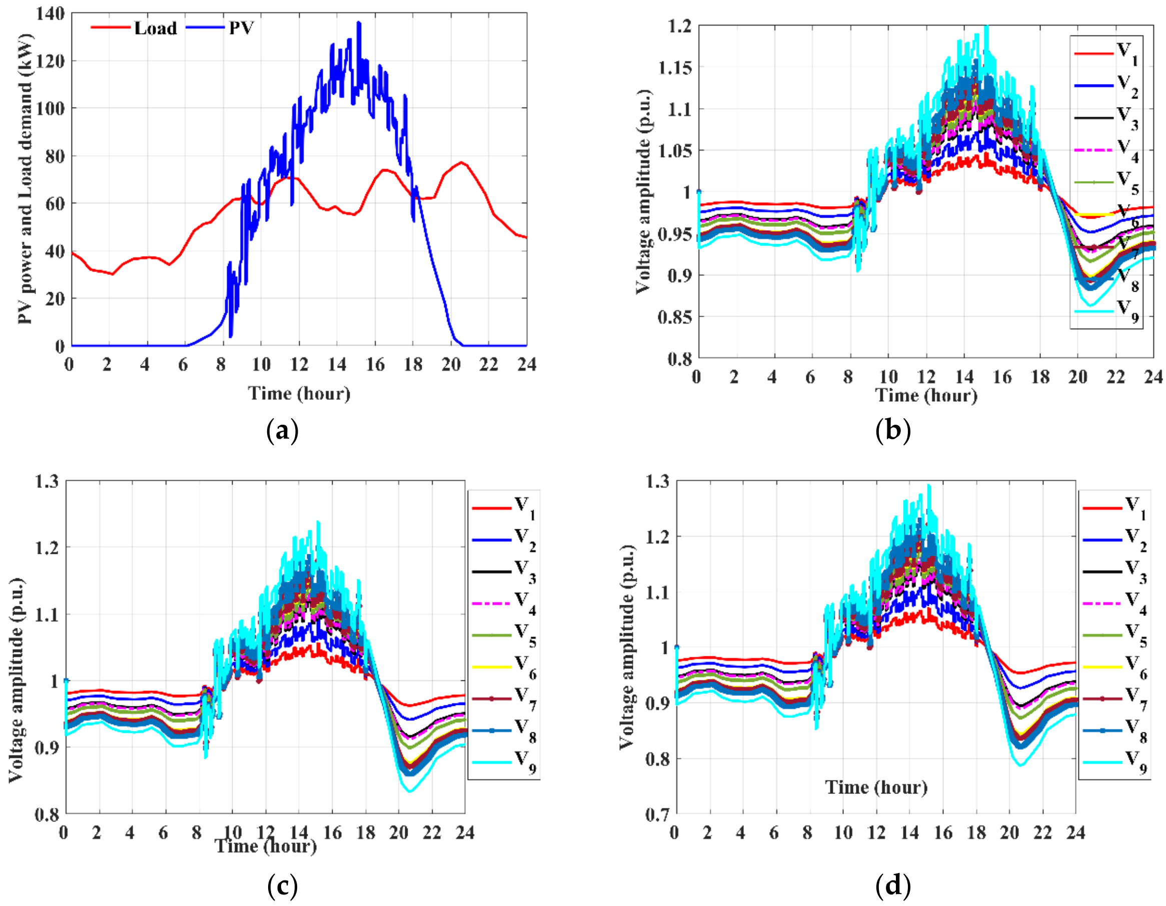


Figure 4. Node voltage fluctuation without regulation strategy: (**a**) Total PV power output and total load demand; (**b**) the fluctuation of node voltage amplitude; (**c**) the voltage amplitudes with 1.2 times the length of cables; (**d**) the voltage amplitudes with 1.5 times the length of cables.

4.2. Case 2: Voltage Fluctuation with Local Voltage Controller

This case is used to verify the effectiveness of the nodal voltage feedback control strategy (3). In this study, only the control strategy (3) without proportional power sharing strategy is used to adjust the nodal voltage amplitude. The simulation results are shown in Figure 5a,b. When the designed voltage local control strategy is adopted, the distributed PV sources can control the output of reactive power according to the node voltage amplitude, so that the nodal voltage is maintained within the normal range most of the time. Namely, the voltage-rise and the voltage-dip problems are alleviated. Using Var/Volt controller, if the voltage magnitude rises above the upper limit, the controller takes actions; then, PV systems will inject reactive power (negative). With the negative reactive power injection, nodal voltage will go back to the normal range, according to the power flow shown in Equation (1).

However, from Figure 5a, it can be seen that the voltage magnitude cannot drive into the normal range instantly when the PV output power is very drastic and fast. This is because the proposed voltage feedback controller is based on the voltage magnitude, only after nodal voltage is above the limit, the proposed controller works.

Figure 5c,d shows the simulation results when the capacity of PV reactive power is considered. Under this condition, PV with large capacity but light load demand nearby, the active power injection is larger than the local power consumption. Therefore, with the predefined rated reactive power, those PVs with larger capacities but relatively small reactive power ratings cannot inject sufficient reactive power to regulate the nodal voltages. In Figure 5c, the voltage cannot drive into the normal range when PV reactive power is constrained by the limits, as shown in Figure 5d. Therefore, the proposed local voltage regulation method is not efficient because of the limited reactive power injection of some nodes.

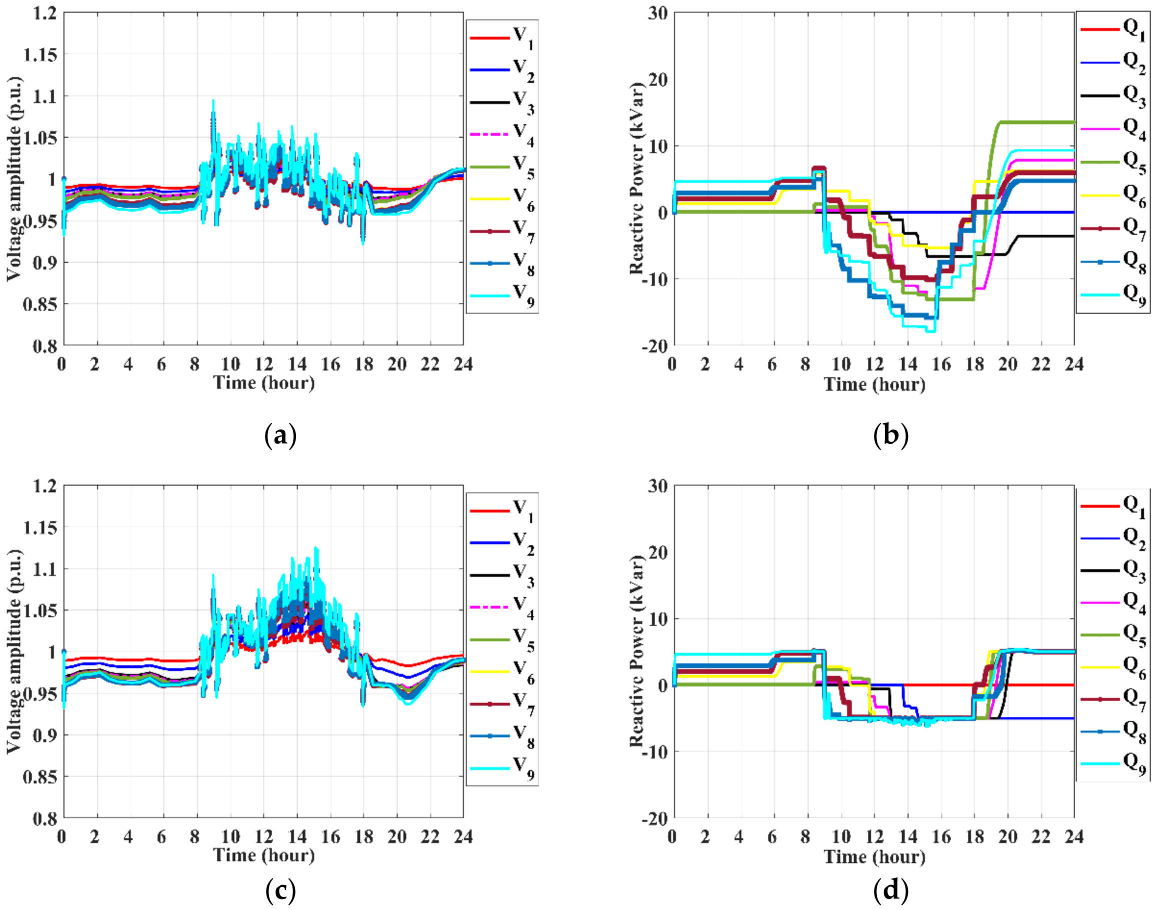
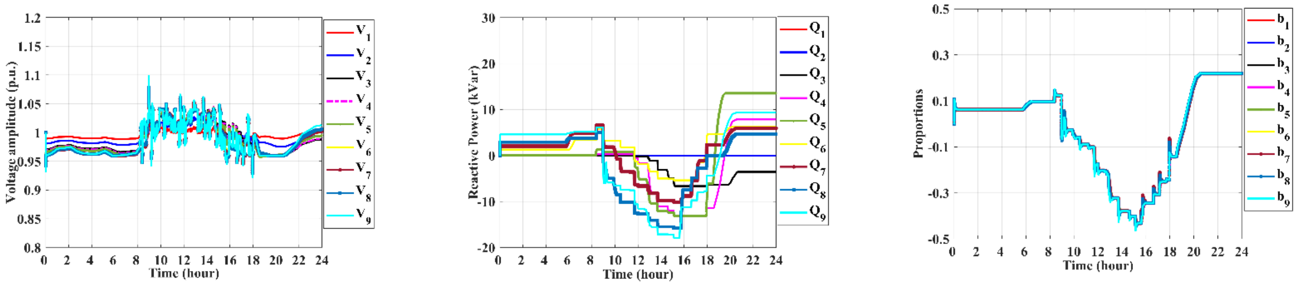


Figure 5. Voltage fluctuations: (**a**) Node voltage fluctuation; (**b**) photovoltaic reactive power output; (**c**) node voltage fluctuation with reactive power limits; (**d**) photovoltaic reactive power output with constraints.

4.3. Case 3: Proportional Sharing of PV Reactive Power

This section considers nodal voltage regulation for the balanced sharing of distributed PV reactive power. The proposed distributed reactive power sharing control strategy (4) and local node voltage feedback control strategy (3) are used to adjust the node voltage at the same time, and the obtained simulation results are shown in Figure 6. According to Figure 6a, it can be seen that under the regulation of the proposed strategy, the nodal voltage amplitude is maintained within the normal range even with highly fluctuated PV power outputs. When the PV active power output is greater than the system load demand, shown in Figure 4a, the node voltage rises beyond the upper limit. In order to achieve voltage regulation, PV sources absorb reactive power (negative reactive power) in terms of the controllers (3) and (4). Thus, with the proposed voltage regulator, the nodal voltage returns to the normal range. Therefore, between 10:00 a.m. and 18:00 p.m., the reactive power ratio value α is negative, while it can be seen that its absolute value reaches 0.48. When the load demand is higher than the PV output power, from 0:00 to 10:00 and 18:00 to 24:00, nodal voltages are lower than the bottom limit. Under this situation, PV produces reactive power (positive reactive power) proportionally to drive voltage into the normal range. With the proposed voltage regulation method, the over-voltage violation problems are tackled.

With the proposed controller, if the nodal voltage is beyond the upper limit, then PVs inject negative reactive power with the proposed Var/Volt controller to drive the voltage magnitude into the normal range. Thereafter, the proportional power sharing algorithm starts to adjust PV reactive power such that the voltage regulation burden can be shared among distributed PV systems. Therefore, none of voltage magnitudes goes beyond the limit. For the voltage dip problem, the same procedure will act. If the nodal voltages are all within the limits, PV systems will keep their reactive power output unchanged.

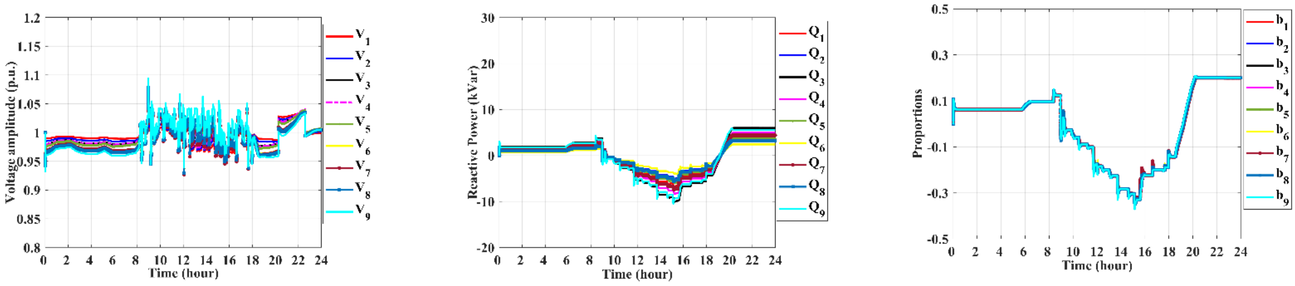


(**a**) (**b**) (**c**)

Figure 6. Nodal voltage magnitudes with reactive power sharing: (**a**) Nodal voltages; (**b**) reactive power of PV sources; (**c**) reactive power ratio of PV sources.

4.4. Case 4: Node Voltage Regulation with PV Reactive Power and OLTC

In order to reduce the reactive power injection to the upper grid, the OLTC is also a useful resource to regulate the nodal voltages. Therefore, this section considers the case where OLTC and distributed PV systems participate in the voltage regulation in the distribution network. Although using PV reactive power to achieve voltage regulation is effective, the rating power of PV reactive power is constrained by the PV apparent power, shown in (8). Therefore, the maximal reactive power to regulate nodal voltages is often limited. To improve the active power output as much as possible, the output of reactive power should be maintained at a low level, which is also constrained by its power factor angle. Therefore, the OLTC transformer is proposed to attend to voltage regulation aiming at reducing PV reactive power outputs. The simulation results are shown in Figure 7. According to the results, when the OLTC participates in the node voltage regulation, the reactive power output of the distributed PV sources is maintained between −10 k and 10 kVar, and the node voltage amplitude varies within the normal range. More importantly, the reactive power ratio value of PV sources varies from −0.3 to 0.2. Compared with the method without OLTC, the reactive power output of PV sources is reduced. When the reactive power is limited, the method that uses OLTC and PV reactive power can also achieve nodal voltage regulation effectively.



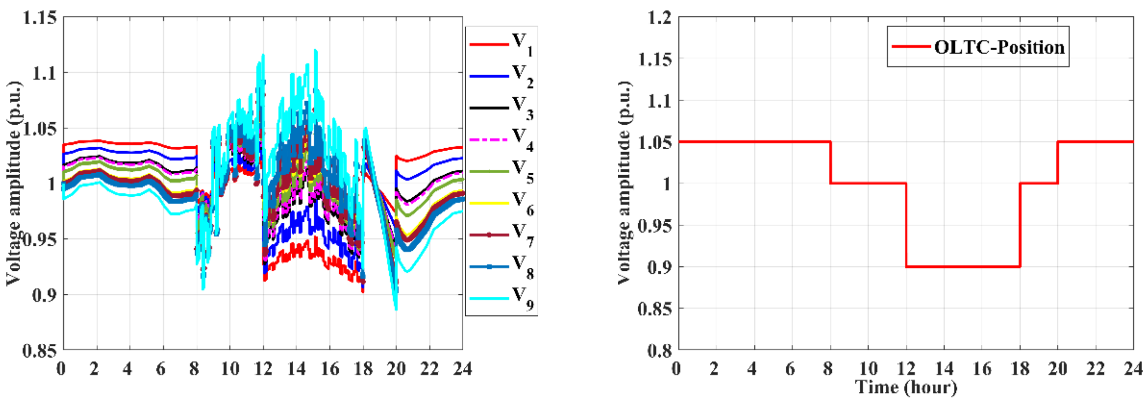
(**a**) (**b**) (**c**)

Figure 7. Node voltage fluctuation with OLTC and PV reactive power: (**a**) Nodal voltage fluctuation; (**b**) PV reactive power output; (**c**) proportions of reactive power.

As it can be seen, with the operation of OLTC, the PCC node voltage decreases when the system reactive power ratio is high. By adjusting the PCC node voltage and reference voltage, other nodal voltages also decrease, which can be calculated using the power flow shown in Equation (1). However, the operation condition is not suggested to change frequently because of lifetime degradation (economic cost) of OLTC. Therefore, OLTC is treated as an extra resource to achieve voltage regulatio, when PV reactive power is limited.

4.5. Case 5: Comparison with the Method Only Using OLTC

In order to show the effectiveness of the proposed voltage regulation method with PV reactive power and OLTC, simulation results only with OLTC are considered. Here, the tap position of the OLTC transformer is adjusted according to the time sequence. Normally, during the middle day with strong solar radiation, the PV output power is greater than the load demand, which causes a voltage rise problem. When load demand is greater than PV power, the nodal voltage dip problem shows up. Therefore, according to these scenarios, the tap positions are scheduled as shown in Figure 8b. Voltage magnitudes are shown in Figure 8a. It can be seen that the nodal voltages cannot be regulated into the normal range when the position of OLTC varies according to the PV output power, especially at the time instants when the tap position changes, namely, from 8:00 to 10:00, and from 18:00 to 20:00. This is because the voltage fluctuates very fast, and OLTC is not able to respond to the fast change in voltages. Moreover, from 10:00 to 18:00, nodal voltage of PV 9 still violates the upper limit, but voltage of PV 1 is below the lower limit when only using OLTC for voltage regulation. Therefore, compared with the results in Figure 7a, the proposed method has a better performance in voltage regulation.



(**a**) (**b**)

Figure 8. Node voltage fluctuation only with OLTC: (**a**) Nodal voltage fluctuation; (**b**) the tap position of OLTC.

From the comparison, one can see that voltage cannot be regulated into the normal range when only using OLTC since OLTC can only be used to adjust the voltage of PCC point effectively. The voltages of some nodes, that is, far from PCC point, heavily depend on the local PV power generation and power consumption. Therefore, these nodal voltages are not very sensitive to the OLTC operation, which can be explained by calculation power flow equation. Another point is that the nodal voltages are local. Additionally, OLTC operations have an impact on all nodal voltages. Some nodes with a heavy load demand have the possibility to endure the low voltage, as shown in Figure 8a.

5. Conclusions

Voltage limit violation problems have gained increasing attention in recent years, since green transition and CO_2 reduction enable renewable energy sources to integrate in the power system. Especially, the extensive integration of PV systems into the low-voltage distribution network causes severe voltage fluctuation problems. In this paper, aiming at solving the nodal voltage-limit violation problem of the low voltage distribution networks (0.4 kV) with a high proportion of distributed PV sources, a distributed nodal voltage regulation strategy based on distributed PV reactive power and OLTC transformer is proposed. Firstly, according to the nodal voltage sensitivity matrix analysis, the local feedback controller of the nodal voltage is obtained. Then, the weighted distributed reactive power sharing algorithm is designed to realize the proportional sharing of PV reactive power according to the reactive power capacity in order to enhance voltage regulation efficiency. Moreover, the convergence of the proposed power sharing algorithm is provided using Lyapunov analysis. For the limited PV reactive power capacity, OLTC is introduced to coordinate with PV sources to improve the node voltage regulation capability and reduce the reactive power output of PV sources. Finally, five sets of simulation studies are designed to verify the effectiveness of the proposed method.

For the phenomenon, nodal voltages, reaching 1.2 p.u, are beyond the upper limit (1.05 p.u) when PV active power is greater than the total load demand. Additionally, nodal voltages reaching 0.87 p.u, are below the lower limit (0.95 p.u) when PV power is lower than the load demand. To solve this problem, with the proposed voltage control method, voltage is restrained into the normal range, i.e., (0.95 1.05 p.u) with a lower reactive power ratio ($|\alpha| < 0.4$). Additionally, when compared to the method only using OLTC, the proposed method can achieve nodal voltage regulation more effectively, and PC reactive power output is reduced when collaborating with PV sources. Using the existing resources, such as PV systems, OLTC is a suitable way to achieve voltage regulation in LVDN with similar branch line reactance and resistance. However, for the network with high resistance, the voltage regulation method using PV reactive power is not very effective. Future work includes how to deal with voltage regulation problems in LVDN with a high R/X ratio.

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References

1. Zhang, B.; Lam, A.Y.; Domínguez-García, A.D.; Tse, D. An optimal and distributed method for voltage regulation in power distribution systems. *IEEE Trans. Power Syst.* **2014**, *30*, 1714–1726. [CrossRef]
2. Chaudhary, P.; Rizwan, M. Voltage regulation mitigation techniques in distribution system with high PV penetration: A review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3279–3287. [CrossRef]
3. Turitsyn, K.; Šulc, P.; Backhaus, S.; Chertkov, M. Distributed control of reactive power flow in a radial distribution circuit with high photovoltaic penetration. In Proceedings of the IEEE PES General Meeting, Minneapolis, MN, USA, 25–29 July 2010; pp. 1–6.
4. Almeida, D.; Pasupuleti, J.; Ekanayake, J. Comparison of Reactive Power Control Techniques for Solar PV Inverters to Mitigate Voltage Rise in Low-Voltage Grids. *Electronics* **2021**, *10*, 1569. [CrossRef]
5. Almeida, D.; Pasupuleti, J.; Raveendran, S.K.; Basir Khan, M.R. Performance Evaluation of Solar PV Inverter Controls for Overvoltage Mitigation in MV Distribution Networks. *Electronics* **2021**, *10*, 1456. [CrossRef]
6. Brenna, M.; De Berardinis, E.; Carpini, L.D.; Foiadelli, F.; Paulon, P.; Petroni, P.; Sapienza, G.; Scrosati, G.; Zaninelli, D. Automatic Distributed Voltage Control Algorithm in Smart Grids Applications. *IEEE Trans. Smart Grid* **2013**, *4*, 877–885. [CrossRef]
7. Bolognani, S.; Carli, R.; Cavraro, G.; Zampieri, S. Distributed reactive power feedback control for voltage regulation and loss minimization. *IEEE Trans. Autom. Control* **2014**, *60*, 966–981. [CrossRef]
8. Schiffer, J.; Seel, T.; Raisch, J.; Sezi, T. Voltage stability and reactive power sharing in inverter-based microgrids with consensus-based distributed voltage control. *IEEE Trans. Control Syst. Technol.* **2015**, *24*, 96–109. [CrossRef]
9. Fu, Y.; Wang, F.; Chen, C.; Yang, Z.; Liu, B.; Zhang, F.; College of Electrical and Information Engineering, Hunan University; Taiyuan Power Supply Company; South Power Supply Company. New Method of Voltage Control Considering Distribution Network Containing Distributed Generation. *Proc. CSU-EPSA* **2015**, *06*, 26–31.
10. Luo, Y.; Chen, M.; Kang, W.; Sun, X. Distributed Event-Triggered Voltage Control with Limited Re-Active Power in Low Voltage Distribution Networks. *Electronics* **2021**, *10*, 128. [CrossRef]
11. Wang, N.; Gao, P.; Jia, Q.-Q.; Sun, L.-L.; Bai, Y. Research on active and reactive power coordination control strategy of PV grid-connected system for voltage regulation. *Adv. Technol. Electr. Eng. Energy* **2017**, *36*, 23–29.
12. Zhang, J.; Zhuang, H.; Liu, J. Two-stage coordinated voltage control scheme of active distribution network with voltage support of distributed energy storage system. *Electr. Power Autom. Equip.* **2019**, *15*, 21–29.
13. Cai, Y.; Tang, W.; Zhang, B.; Li, T.; Wang, Z.; Gao, B. A Two-stage Volt-var Control in LV Distribution Networks with High Proportion of Residential PVs. *Power Syst. Technol.* **2019**, *04*, 1271–1280.

14. Bedawy, A.; Yorino, N.; Mahmoud, K. Management of Voltage Regulators in Unbalanced Distribution Networks Using Voltage/Tap Sensitivity Analysis. In Proceedings of the International Conference on Innovative Trends in Computer Engineering, Aswan, Egypt, 19–21 February 2018; pp. 363–367.
15. Xing, H.; Cheng, H.; Zhang, Y. Reactive Power Comprehensive Optimization in Distribution Network Based on Multiple Active Management Schemes. *Power Syst. Technol.* **2015**, *6*, 1504–1510.
16. Luo, C.; Tao, S.; Xiao, X. Multi-stage Robust Comprehensive Voltage Control in Active Distribution Network. *Mod. Electr. Power* **2016**, 44–51.
17. Viawan, F.A.; Karlsson, D. Voltage and Reactive Power Control in Systems with Synchronous Machine-Based Distributed Generation. *IEEE Trans. Power Deliv.* **2008**, *23*, 1079–1087. [CrossRef]
18. Caldon, R.; Spelta, S.; Prandoni, V.; Turri, R. Co-ordinated voltage regulation in distribution networks with embedded generation. In Proceedings of the International Conference & Exhibition on Electricity Distribution, Turin, Italy, 6–9 June 2005.
19. Long, C.; Ochoa, L.F. Voltage Control of PV-Rich LV Networks: OLTC-Fitted Transformer and Capacitor Banks. *IEEE Trans. Power Syst.* **2016**, *31*, 4016–4025. [CrossRef]
20. Tewari, T.; Mohapatra, A.; Anand, S. Coordinated Control of OLTC and Energy Storage for Voltage Regulation in Distribution Network with High PV Penetration. *IEEE Trans. Sustain. Energy* **2021**, *12*, 262–272. [CrossRef]
21. Ku, T.T.; Lin, C.H.; Chen, C.S.; Hsu, C.T. Coordination of Transformer on-Load Tap Changer and PV Smart Inverters for Voltage Control of Distribution Feeders. *IEEE Trans. Ind. Appl.* **2019**, *55*, 256–264. [CrossRef]
22. Ciocia, A.; Boicea, V.A.; Chicco, G.; Di Leo, P.; Mazza, A.; Pons, E.; Spertino, F.; Hadj-Said, N. Voltage Control in Low-Voltage Grids Using Distributed Photovoltaic Converters and Centralized Devices. *IEEE Trans. Ind. Appl.* **2019**, *55*, 225–237. [CrossRef]
23. Xie, Q.; Shentu, X.; Wu, X.; Ding, Y.; Hua, Y.; Cui, J. Coordinated voltage regulation by on-load tap changer operation and demand response based on voltage ranking search algorithm. *Energies* **2019**, *12*, 1902. [CrossRef]
24. Cui, J.; Liu, Y.; Qin, H.; Hua, Y.; Zheng, L. A Novel Voltage Regulation Strategy for Distribution Networks by Coordinating Control of OLTC and Air Conditioners. *Appl. Sci.* **2022**, *12*, 8104. [CrossRef]
25. Vovos, P.N.; Kiprakis, A.E.; Wallace, A.R.; Harrison, G.P. Centralized and Distributed Voltage Control: Impact on Distributed Generation Penetration. *IEEE Trans. Power Syst.* **2007**, *22*, 476–483. [CrossRef]
26. Carvalho, P.; Correia, P.; Ferreira, L. Distributed Reactive Power Generation Control for Voltage Rise Mitigation in Distribution Networks. *IEEE Trans. Power Syst.* **2008**, *23*, 766–772. [CrossRef]
27. Masters, C.L. Voltage rise: The big issue when connecting embedded generation to long 11 kV overhead lines. *Power Eng. J.* **2002**, *16*, 5–12. [CrossRef]
28. Fahimi, B.; Kwasinski, A.; Davoudi, A.; Balog, R.S.; Kiani, M. Charge It! *IEEE Power Energy Mag.* **2011**, *9*, 54–64. [CrossRef]
29. You, Y.; Liu, D.; Zhong, Q.; Pan, F.; Yu, N.H. Multi-time Scale Coordinated Control of Distributed Generators Based on Active Distribution Network. *Autom. Electr. Power Syst.* **2014**, *38*, 192–198+203.
30. Wu, X.; Shen, C.; Iravani, R. A distributed, cooperative frequency and voltage control for microgrids. *IEEE Trans. Smart Grid* **2016**, *9*, 2764–2776. [CrossRef]
31. Jafari, M.R.; Parniani, M.; Ravanji, M.H. Decentralized Control of OLTC and PV Inverters for Voltage Regulation in Radial Distribution Networks with High PV Penetration. *IEEE Trans. Power Deliv.* **2022**, *37*, 4827–4837. [CrossRef]
32. Kang, W.; Chen, M.; Guan, Y.; Wei, B.; Vasquez, Q.J.C.; Guerrero, J.M. Event-triggered distributed voltage regulation by heterogeneous BESS in low-voltage distribution networks. *Appl. Energy* **2022**, *312*, 118597. [CrossRef]
33. Farag, H.E.Z.; El-Saadany, E.F. A novel cooperative protocol for distributed voltage control in active distribution systems. *IEEE Trans. Power Syst.* **2013**, *28*, 1645–1656. [CrossRef]
34. Baran, M.; Wu, F. Network reconfiguration in distribution systems for loss reduction and load balancing. *IEEE Trans. Power Deliv.* **1989**, *4*, 1401–1407. [CrossRef]