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EDITED BY
Chaolong Zhang,
Jinling Institute of Technology, China

REVIEWED BY
Nishant Kumar,
Indian Institute of Technology Jodhpur, India
Jie Shu,
Chinese Academy of Sciences (CAS), China

*CORRESPONDENCE
Fanyu Meng,
meng_fanyu@foxmail.com

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Voltage control strategy of a high-permeability photovoltaic distribution network based on cluster division

He Li[1], Kun Song[2], Fanyu Meng[3]*, Zhenhao Wang[3] and Chaobin Wang[3]

[1]State Grid East Inner Mongolia Electric Power Co., Ltd. Tongliao Power Supply, Tongliao, China, [2]State Grid East Inner Mongolia Electric Power Co., Ltd., Hohhot, China, [3]The Northeast Electric Power University, Jilin, China

The use of distributed photovoltaics (PVs) on a large scale often causes voltage over-limit problems in distribution networks. This paper proposes a distributed photovoltaic cluster collaborative optimization voltage control strategy based on an improved community algorithm to address the issue of centralized control being unable to respond quickly to the randomness of distributed photovoltaics and the difficulty of achieving overall coordination with local control. First, by improving the community algorithm, the division of reactive and active clusters, considering the power balance and node coupling degree, is realized. Then, the cluster-coordinated voltage control strategy is proposed by making full use of the power control ability of a photovoltaic inverter. Finally, a voltage regulation ability evaluation index is proposed to assess the node regulation ability within the cluster and select key nodes. This effectively reduces the number of control nodes. The simulation analysis of the improved IEEE 69 distribution network shows that the proposed voltage control strategy can mitigate the issue of voltage over-limit in high-permeability distributed photovoltaic access distribution and enhance the photovoltaic consumption capacity.

KEYWORDS

high-permeability distributed photovoltaic, distribution network, cluster division, key nodes, voltage regulation

1 Introduction

The National Photovoltaic Poverty Alleviation Policy has led to a significant increase in the number and capacity of grid-connected residential photovoltaic (PV) systems in the distribution network (Dong et al., 2021). In certain areas, the high penetration of distributed photovoltaic systems has resulted in power reversal, necessitating the transformation of the traditional passive distribution network into a complex multi-source distribution network. The distribution network often faces several risks, including voltage over-limit and harmonic pollution (Han et al., 2021). Voltage overloading, in particular, significantly affects the consumption of new energy in the distribution network and the safe and stable operation of cables.

There has been extensive research conducted by scholars both domestically and internationally on the issue of voltage over-limit caused by high-permeability photovoltaic access to distribution networks. Song et al. (2022) addressed the voltage issues of high-penetration PV installations by adjusting the tap of the load regulator

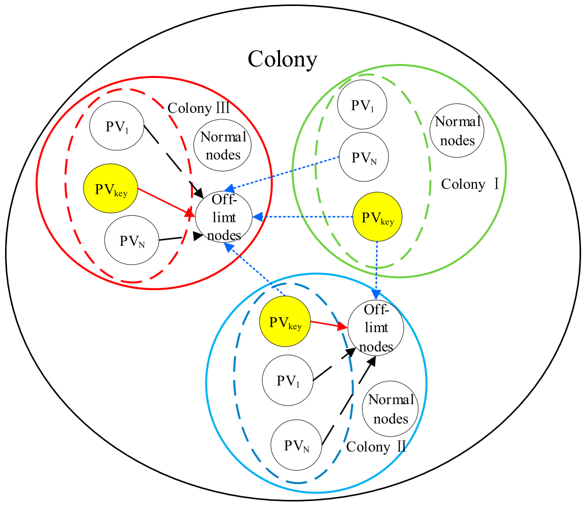

FIGURE 1
Reactive power coordination control.

transformer. Emiliano et al. (2019) established an active-reactive hierarchical zonal optimization model to optimize the reactive voltage loss and active network loss problems that exist in high-penetration PV distribution networks, and optimization calculations are performed using a control algorithm. Gao et al. (2019) proposed the voltage control strategy of a photovoltaic power station inverter and the calculation method of active/reactive power adjustment of the inverter, which solved the problem of voltage over-limit at the access point of the photovoltaic power station. Based on the consistency theory, Liu et al. (2021) proposed a strategy to allocate reactive power compensation based on photovoltaic capacity ratios to mitigate reactive power overshoot problems due to highly permeable distributed photovoltaic feeders. A local voltage control strategy for distribution networks with distributed PV systems is proposed by Chai et al. (2018). The aim of the strategy is to achieve cost-effective and efficient voltage control by reducing the coordination of the reactive power and optimizing the active power of the photovoltaic systems. Olivier et al. (2016) proposed a centralized control method for the access of distributed PVs to the distribution grid. The method employs equal proportions of reactive power compensation and active power curtailment for all distributed PVs. This approach significantly improves the distribution network voltage. When addressing the issue of voltage over-limit caused by high-permeability photovoltaic access to the distribution network, most of the literature adopts either a centralized control method or a local voltage control method to alleviate the situation. It is important to note that these methods can only alleviate the issue of voltage over-limit caused by high-permeability PV access to the distribution network. However, the centralized control method requires a large number of control nodes, which is not conducive to rapid control of voltage and will cause additional network losses. Local voltage control will lead to an excessive reduction of active power at some nodes. Voltage cluster control can be implemented to reduce the number of photovoltaic nodes that need to be effectively controlled, the additional network losses caused by power flow, and the light rejection rate of distributed photovoltaics.

The distribution network cluster is to divide the distribution network into several clusters. The internal nodes of each cluster have strong coupling, and there is weak coupling between different clusters. When the power adjustment is carried out within the cluster, the voltage changes greatly. The voltage of the cluster experiences minimal fluctuations when voltage control is performed in other clusters. The methods for dividing power grids into clusters are generally categorized as cluster analysis, optimization algorithms, and complex community discovery. Madureira and Pecas (2009) proposed a power system hierarchical-partitioned voltage control framework in which partitions are defined as microgrids in each power system; controllers are installed in each partition to achieve partitioned control; each partition is weakly connected to each other to achieve partitioned decoupling; and finally, the whole is centrally coordinated and controlled. Pachanapan et al. (2012) proposed an adaptive technique for hierarchical zonal voltage control of the power system. The technique is based on dividing zones by the reactive power reserve of distributed reactive power controllers and the voltage sensitivity of each node to perform the reactive power exchange between zones. Ranamuka et al. (2014) proposed a voltage coordination control strategy based on an on-load voltage regulator and a distributed reactive power compensation device. The strategy first measures local data and then calculates the required voltage at the overrun node using a controller. In order to achieve voltage control within the sub-district, Fabio et al. (2008) used the particle swarm optimization algorithm, which is based on the ability of the PV inverter to compensate for a certain amount of reactive power. The goal is to absorb reactive power or active shear amount, depending on the degree of over-voltage and the degree of demand for voltage regulation and control. Zhao et al. (2018) suggested that photovoltaic inverters have reactive power compensation capacity based on the use of particle swarm optimization algorithms. The aim is to achieve minimum reactive power absorption or active shear as the target while prioritizing voltage regulation and control based on the degree of overvoltage and voltage demand within the sub-district. Mayank and Srinivasa (2019); Hossein et al. (2018) proposed a method of partitioning in terms of spatial scales and regulation of the voltage within the partition in terms of time scales. The literature above has achieved results in dividing system clusters. However, clustering analysis requires specifying the cluster center and number of clusters beforehand, and the results can be influenced by human factors. When utilizing the optimization algorithm to divide the cluster, the different coding methods can result in significantly varied partition results. Additionally, incomplete considerations when using complex community algorithms for cluster partitioning can also impact the partitioning outcomes.

In this paper, a distributed photovoltaic cluster collaborative optimization voltage control strategy based on an improved community algorithm is proposed to solve the problem of voltage overshoot caused by high-permeability distributed photovoltaic access in the distribution network. First, based on the traditional community detection algorithm, an improved community detection algorithm is proposed, which makes up for the shortcomings of the traditional algorithm's lack of global optimization ability. The optimal division

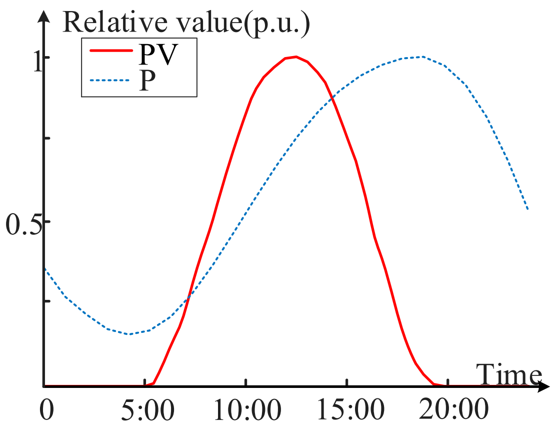

FIGURE 2
Daily curves of total PV generation and load.

results of the reactive power cluster and active power cluster are obtained using the community algorithm. Then, the voltage control method of reactive power cluster (first) and active power cluster (second) is proposed, which makes full use of the adjustment ability of the cluster. According to the difference in observability and controllability of nodes in the cluster, the selection index of key nodes in the cluster is proposed. Finally, according to the influence ability of different nodes in the cluster, the selection index of key nodes in the cluster is determined, and the key nodes are given priority. Through the simulation analysis of the improved IEEE 69-node distribution network, the results show that the proposed method can not only realize the voltage control in the cluster but also realize the coordinated control of the voltage between the clusters in emergency situations, reduce the number of control equipment, reduce the network loss, and effectively alleviate the problem of voltage overflow.

2 Cluster partition based on power sensitivity

In the complex power system operating environment, it is important to ensure that the partitioning of the power system effectively utilizes the control means of the reactive power compensation device. To achieve this, the sensitivity of active/reactive power voltage is calculated from the perspective of power system sensitivity. The cluster is then divided based on the power system's modularity function model.

2.1 Reactive/active voltage decoupling control

According to Yao et al. (2019), the calculation of power flux in the distribution is expressed in terms of the Jacobian matrix of the power system's load flow:

$$\begin{bmatrix} \Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q} \end{bmatrix} = \begin{bmatrix} \boldsymbol{J}_{\mathrm{P}\theta} & \boldsymbol{J}_{\mathrm{PU}} \\ \boldsymbol{J}_{\mathrm{Q}\theta} & \boldsymbol{J}_{\mathrm{QU}} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{\theta} \\ \Delta \boldsymbol{U} \end{bmatrix}. \tag{1}$$

In the above formula, $\Delta \boldsymbol{P}$ and $\Delta \boldsymbol{Q}$ are variations in the injected active power and reactive power of the node, respectively. $\Delta \boldsymbol{\theta}$ and $\Delta \boldsymbol{U}$ are the phase angle and voltage variation of the node, respectively. $\boldsymbol{J}_{\mathrm{P}\theta}$, $\boldsymbol{J}_{\mathrm{PU}}$, $\boldsymbol{J}_{\mathrm{Q}\theta}$, and $\boldsymbol{J}_{\mathrm{QU}}$ are sub-blocks in the middle of the Jacobi matrix.

Eq. 1 can be rewritten as

$$\begin{bmatrix} \Delta \boldsymbol{\theta} \\ \Delta \boldsymbol{U} \end{bmatrix} = \begin{bmatrix} \boldsymbol{S}_{\mathrm{P}\theta} & \boldsymbol{S}_{\mathrm{Q}\theta} \\ \boldsymbol{S}_{\mathrm{PU}} & \boldsymbol{S}_{\mathrm{QU}} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q} \end{bmatrix}. \tag{2}$$

In the above formula, $\boldsymbol{S}_{\mathrm{PU}}$ and $\boldsymbol{S}_{\mathrm{QU}}$ are the degrees of change in node voltage amplitude when the node injects unit active and reactive power, respectively. $\boldsymbol{S}_{\mathrm{P}\theta}$ and $\boldsymbol{S}_{\mathrm{Q}\theta}$ are the degrees of change in the node phase angle when the node injects a unit amount of active and reactive power, respectively.

From Eq. 2, the variation in voltage magnitude $\Delta \boldsymbol{U}$ with active and reactive power variations ($\Delta \boldsymbol{P}$ and $\Delta \boldsymbol{Q}$) at node i in an n-node distribution network can be expressed as follows:

$$\Delta \boldsymbol{U} = \boldsymbol{S}_{\mathrm{PU}} \Delta \boldsymbol{P} + \boldsymbol{S}_{\mathrm{QU}} \Delta \boldsymbol{Q} \tag{3}$$

In the above formula, $\Delta \boldsymbol{P} = [\Delta P_1 \cdots \Delta P_n]^T$, $[\Delta Q_1 \cdots \Delta Q_n]^T$.

The effect of accessing different capacity of PV at m nodes in the distribution network on the voltage at node i can be expressed as follows:

$$U_{i1} = U_{i0} + \sum_{j=1}^{m} S_{\mathrm{PU},ij} \Delta P_j + \sum_{j=1}^{m} S_{\mathrm{QU},ij} \Delta Q_j \tag{4}$$

where U_{i0} is the initial voltage at node i, $S_{\mathrm{PU},ij}$ is the active voltage sensitivity factor of node i to node j; and $S_{\mathrm{QU},ij}$ is the reactive voltage sensitivity factor of i to node j.

From Eqs 3, 4, it is evident that changing the reactive power of a node while keeping the active power constant only affects the voltage magnitude through the reactive sensitivity matrix. Similarly, changing the active power of a node while keeping the reactive power constant only affects the voltage magnitude through the active sensitivity matrix. Therefore, it is possible to achieve decoupling control of reactive power and active power (Chen and Shen, 2006).

2.2 Improved Louvain algorithm-based cluster partitioning

Louvain's algorithm (Feng et al., 2023) is a modularity function clustering algorithm proposed by Newman that quickly generates optimal clustering results and greatly reduces the intervention of human factors. The modularity function can be expressed as follows in Eq. 5:

$$\rho = \frac{1}{2m} \sum_i \sum_j \left[A_{ij} - \frac{k_i k_j}{2m} \right] \delta(i, j), \tag{5}$$

where A_{ij} is the edge weights of nodes i and j. $A_{ij} = 1$ when nodes i and j are directly connected. $A_{ij} = 0$ when they are not directly connected. k_i is the sum of all the edge weights connected to node i, k_j is the sum of all the edge weights connected to node j, and $m = (\sum_i \sum_j A_{ij})/2$ is the sum of all the edge weights in the network. If nodes i and j are in the same cluster, $\delta(i, j) = 1$; otherwise, $\delta(i, j) = 0$.

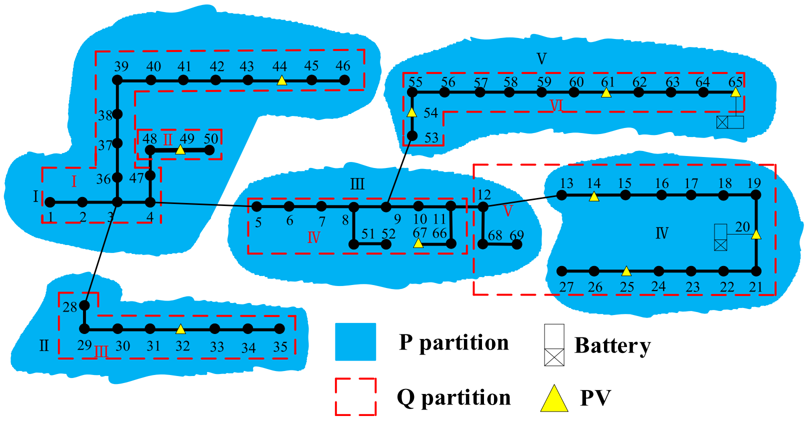

FIGURE 3
Active and reactive power partition diagram.

TABLE 1 Table caption.

Cluster number	Reactive cluster node number	Active power cluster node number
Cluster I	44	44
Cluster II	49	32
Cluster III	32	67
Cluster IV	67	65
Cluster V	20	20
Cluster VI	65	None

2.2.1 Reactive power cluster division

In the distribution network, the reactive voltage sensitivity matrix is an important basis for reflecting the system voltage fluctuation. By comparing whether the side weights are connected or not, the reactive voltage sensitivity matrix can more accurately respond to the reactive coupling degree of different nodes, replacing the original side weight matrix by the mean value of different node sensitivities, and the improved side weights $\eta_{\mathrm{QU,ij}}$ can be expressed as follows in Eq. 6:

$$\eta_{\mathrm{QU},ij} = \frac{S_{\mathrm{QU},ij} + S_{\mathrm{QU},ji}}{2}. \tag{6}$$

The primary source of dynamic power factor correction on the grid is the power generators, whose power factor correction support is critical (VDE-AR-N4105, 2011). A distributed PV can change its output reactive power by regulating the inverter, thus providing support to the system voltage. The ability of distributed PV systems of different capacities to support voltage at other nodes varies, which not only affects the reactive power balance of the cluster but also affects the results of the cluster division. Adjusting the reactive power of node i to node j support capacity can be expressed as follows in Eq. 7:

$$\alpha_{\mathrm{QU},ij} = \frac{S_{\mathrm{QU},ij}}{S_{\mathrm{QU},jj}} \times Q_{\mathrm{QU},i}, \tag{7}$$

where $Q_{\mathrm{QU},i}$ is the adjustable reactive capacity of node i of the PV inverter.

The final improved weight matrix can be expressed as follows in Eq. 8:

$$A_{\mathrm{QU},ij} = \eta_{\mathrm{QU},ij} + \alpha_{\mathrm{QU},ij}. \tag{8}$$

The improved modularity can be expressed as follows in Eq. 9:

$$\rho_{\mathrm{QU,a}} = \frac{1}{2m}\sum_i \sum_j \left[A_{\mathrm{QU},ij} - \frac{k_i k_j}{2m}\right]\delta(i,j). \tag{9}$$

Considering the internal structural characteristics of the cluster, the aggregation index can be expressed as follows in Eq. 10:

$$\rho_{\mathrm{QU,b}} = \sum_{i,j=1}^{n} S_{\mathrm{QU},ij} \Bigg/ \left(m \times \sum_{c=1}^{m}\sum_{i,j=1}^{n} S_{\mathrm{QU},ij}\right), \tag{10}$$

where m is the number of total clusters and c is the label of the current cluster.

The integrated evaluation indicator can be expressed as follows in Eq. 11:

$$\rho_{\mathrm{QU}} = \rho_{\mathrm{QU,a}} + \rho_{\mathrm{QU,b}}. \tag{11}$$

2.2.2 Active power cluster division

The active sensitivity matrix accurately reflects the active coupling degree of different nodes. Therefore, by replacing the original edge

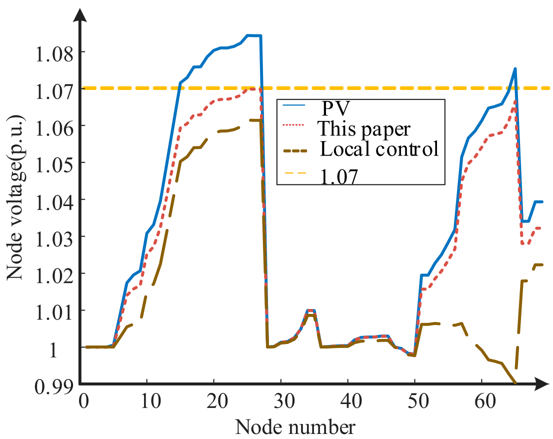

FIGURE 4
Different strategies of voltage regulation.

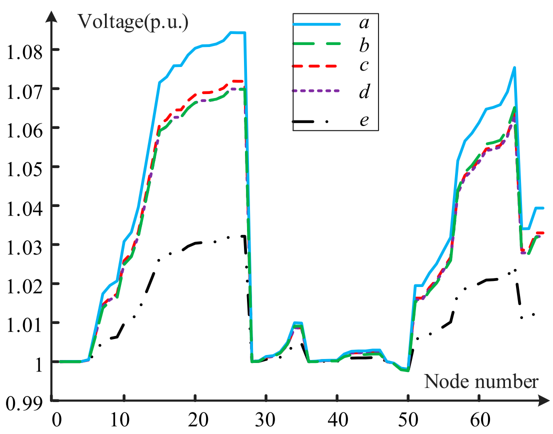

FIGURE 5
Voltage control of different permeabilities.

weight matrix with the mean value of the active sensitivity matrix, the improved edge weights can be expressed as follows in Eq. 12:

$$\partial_{PU,ij} = \frac{S_{PU,ij} + S_{PU,ji}}{2}. \tag{12}$$

In large grids, grid voltage variations are strongly correlated with reactive power variations, but in low- and medium-voltage distribution networks, active power variations can also cause voltage fluctuations. The ability to balance the active power in place within the active cluster should also be fully considered, and the ability of node i active power adjustment to support node j can be expressed as follows in Eq. 13:

$$\alpha_{PU,ij} = S_{PU,ij} \times \frac{P_{PU,i}}{S_{PU,jj}}. \tag{13}$$

The final improved edge weight matrix can be expressed as follows in Eq. 14:

$$A_{PU,ij} = S_{PU} + \alpha_{PU,ij}. \tag{14}$$

The degree of modularity can be expressed as follows in Eq. 15:

$$\rho_{PU,a} = \frac{1}{2m} \times \sum_i \sum_j \left[A_{PU,ij} - k_i k_j / 2m\right] \delta(i,j). \tag{15}$$

Finally, the aggregation metrics of the active clusters also need to be considered in Eq. 16:

$$\rho_{PU,b} = \frac{\sum_{i,j=1}^{n} S_{PU,ij}}{\sum_{c=1}^{m} \sum_{i,j=1}^{n} S_{PU,ij}}. \tag{16}$$

The integrated modularity evaluation indicator can be expressed as follows in Eq. 17:

$$\rho_{PU} = \rho_{PU,a} + \rho_{PU,b}. \tag{17}$$

2.3 Overall cluster division process

The example of reactive power clustering is used to illustrate how optimal clustering results can be obtained by improving the community algorithm in the distribution network. The following are the concrete steps we are taking:

Step 1: Obtain the relevant data on the distribution network, consider each node in the network as a cluster, and calculate the network modularity value ρ0 according to Eq. 11.

Step 2: Start with an initial node i, randomly select node j to form a new cluster, calculate the module degree ρ1, and calculate the network module degree increment. Combine nodes i and j into the same cluster if the module degree increment is positive.

Step 3: Treat the current cluster as a new cluster to continue combining with other clusters. Repeat Step 2, and after traversing all nodes in the entire distribution network, the first cluster division ends.

Step 4: Determine whether there is a cluster with only one node in the whole system. If so, repeat Step 2 and Step 3 for this cluster; if not, end the cluster division phase and output the result of the current cluster division.

3 Voltage-coordinated control of the cluster

To address the issue of voltage over-limit in the distribution network with high-permeability distributed photovoltaic access, the information processing center divides the network into multiple clusters based on the collected node voltage over-limit information.

This paper proposes a control strategy for several typical clusters, which is illustrated in Figure 1. In the event of voltage fluctuations, the system cluster can be divided into three categories: Cluster I, where the node voltage is normal and coordination ability is sufficient; Cluster II, where some node voltage exceeds the limit and coordination ability is sufficient; and Cluster III, where most

TABLE 2 Comparison of reactive power cluster division results of different calculations.

Algorithm	Number of clusters	Modularity
Fast Newman	7	0.6750
Louvain	5	0.6185
Proposed algorithm	6	0.7630

node voltage exceeds the limit and coordination ability is insufficient.

When the photovoltaic output of Cluster I fluctuates, the voltage remains at a normal level and the distributed photovoltaic continues to operate in a normal mode. In cases where Cluster II photovoltaic output fluctuates, some nodes may exceed the voltage limit. After the key nodes are compensated, the whole voltage level of the cluster returns to normal. When Cluster III's photovoltaic output fluctuates, some nodes' voltages overshoot the limit. In this case, the information processing center sends an action signal to Cluster III. Even after passing the reactive power compensation in Cluster III, the voltage remains in an over-limit state. The information processing center sends the action signal to Cluster I, which is more sensitive to the voltage change of Cluster III. After the action of Cluster I, Cluster III is still in the over-limit state of voltage. The information processing center sends the action signal to Cluster II. The compensation step is the same as the internal coordinated control of Cluster I.

In cases where there is no adjustable reactive power in any of the clusters, the active cluster coordination control and the reactive cluster coordination control are essentially identical during the active cluster coordination stage. The coordination control of cluster voltage can enhance the system's regulation ability, reduce the number of control nodes, improve voltage control efficiency, and decrease network loss.

3.1 Selection of key nodes for reactive power clustering

The selection of key nodes in the cluster must be both observable and controllable. First, the voltage of key nodes can reflect the general voltage level in the cluster, making it an observable factor. Second, the voltage control of key nodes can effectively impact the overall voltage level of the cluster while having minimal influence on the adjacent cluster, making it a controllable factor.

The key cluster node is selected based on the voltage/reactance sensitivity matrix, and the node's visibility index is expressed as follows in Eq. 18:

$$\omega_i = \frac{\sum_{j=1}^{N} S_{\mathrm{QU},ij}}{\left(\left(\sum_{i=1}^{n}\sum_{j=1}^{N} S_{\mathrm{QU},ij}\right)(N-1)\right)}, \tag{18}$$

where i is the node label in the cluster, j is the node number, N is the total number of nodes in the cluster, and n is the number of clusters.

Considering the influence of reactive power regulation of different distributed photovoltaics other nodes' voltage, the controllability index of the node can be expressed as follows in Eq. 19:

$$\sigma_i = \left(\sum_{I=1}^{m_Q}\sum_{J=1}^{n} S_{\mathrm{QU},ij} Q_I\right) \Big/ \left(m \times \sum_{I=1}^{N}\sum_{J=1}^{N} S_{\mathrm{QU},ij}\right), \tag{19}$$

where I is the node number with reactive power regulation ability in the cluster, J is the node number in the cluster, m_Q is the total number of nodes with reactive power regulation ability in the cluster, and Q_I is the adjustable active power of I nodes.

The comprehensive evaluation index of key node selection can be expressed as follows in Eq. 20:

$$\Gamma = \max\left((1-K_1)\omega + K_1\sigma\right). \tag{20}$$

In the formula, K_1 is the weight coefficient, and the selection of key nodes is mainly for voltage control, so $K_1 = 1$.

3.2 Voltage control in the reactive cluster

For the restricted clusters I and II, as shown in Figure 1, the primary nodes of each cluster act first. The voltage difference between b and the voltage limit ΔU_1 is then recorded. The amount of reactive power adjustment required for the over-limit node voltage to return to normal can be expressed as follows:

$$Q_c = \frac{\Delta U_1}{S_{\mathrm{QU},ab}}. \tag{21}$$

Let Q_a be the maximum reactive power adjustment amount that can be adjusted by the key node. If $Q_c < Q_a$, the key node provides Q_c voltage to return to normal. If $Q_a < Q_c$, the key node provides Q_a and performs power flow calculations. The difference between the voltage of the over-limit node and ΔU_2, and the network loss compensated by the key node is recorded. The reactive power coordination control is repeated according to the selection of key nodes. When the cluster has no reactive power adjustment, it enters the stage of reactive power coordination between clusters.

3.3 Voltage-coordinated control of different clusters

Beginning with the selection of the node that possesses the highest support capacity, we calculate the necessary reactive power adjustment to restore the voltage to its normal level using Eq. 21. If the required reactive power is less than what is provided by the current node, the voltage of the over-limit node will return to normal after performing reactive power compensation on the modified node. If the required reactive power exceeds what the current node can supply, the node will supply all the reactive power, perform power flow calculations, record the difference between the current voltage and the normal voltage, and compensate accordingly using the results of the impact capability.

When the adjustable reactive power of all clusters is insufficient, the control stage for active power clusters is initiated. The control mode for active power clusters follows the same steps as the reactive power clusters, without repetition.

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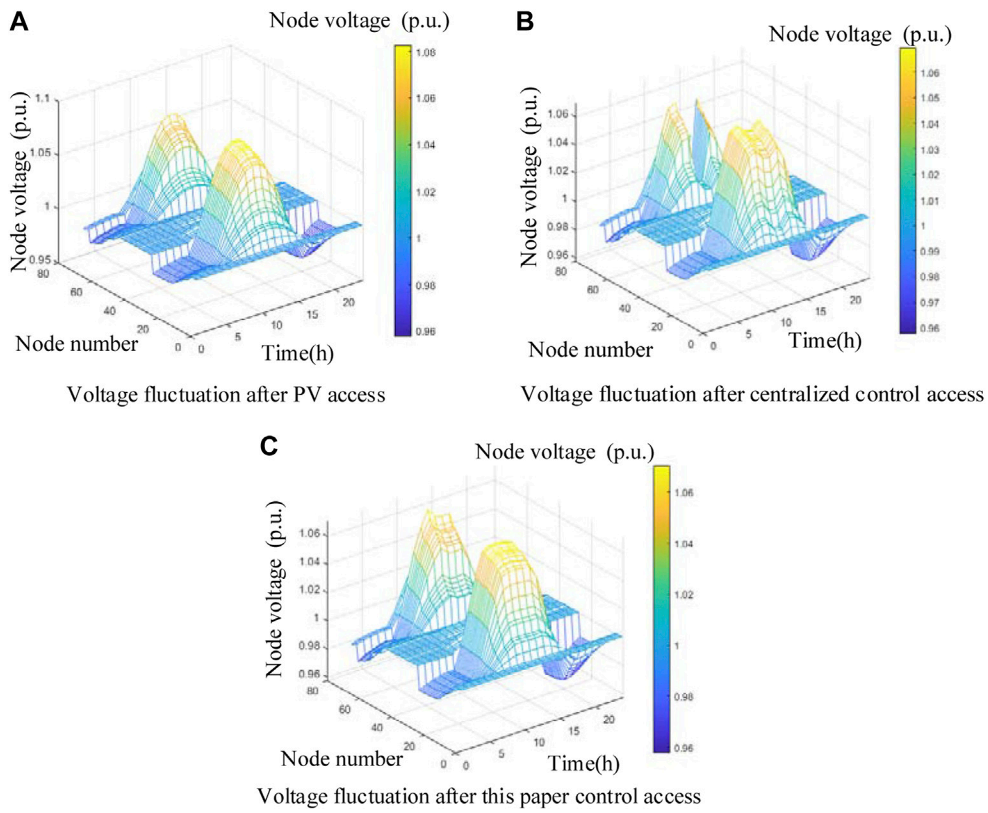

FIGURE 6
Voltage comparison chart for different situations.

4 Example analysis

4.1 Parameter setting

In this paper, the effectiveness of the proposed cluster voltage control strategy for distribution networks with high penetration of distributed PV is validated using the IEEE 69-node distribution network as a sample. The system reference capacity $S_{\text{base}} = 10$ MVA, and the system reference voltage $U_{\text{base}} = 12.66$ kV. The system contains 69 nodes. The photovoltaic access nodes are 14, 20, 25, 32, 44, 49, 54, 61, 65, and 67, and the access capacity is 0.8, 1.2, 0.8, 0.53, 0.46, 0.32, 0.8, 0.53, 1.2, and 0.8 MVA, respectively. The minimum power factor is set to 0.95 by Song et al. (2023). The energy storage battery is installed at nodes 20 and 65, the installation capacity is 0.15 MW, and the level of energy storage in the battery is [0.15, 0.85]. The normal voltage level was set to [0.90, 1.07]. Based on the data from Author Anonymous (2024), the daily load curve of the distribution network in July, which includes both residential and commercial areas, conforms to the demand for residential, commercial, and industrial loads. The day with the highest light intensity in July was chosen for analysis. The total load and active power of the photovoltaic system over a 24 h period are shown in Figure 2. The reference values for the distributed photovoltaic and load are the maximum values of their respective all-day outputs.

4.2 Cluster voltage-coordinated control

The intensity of light increases steadily from 5:30 until it reaches its peak at 12:30 and then gradually decreases. The intensity of light increases steadily from 5:30 until it reaches its peak at 12:30 and then gradually decreases. The voltage fluctuation of the system over the course of the day after access to the photovoltaic system is shown in Figure 2. The node voltage at 12:30 even reaches 1.083 p.u., and the overall voltage change trend is consistent with the findings of Chai et al. (2018).

The results of clustering using the method proposed in the paper are shown in Figure 3. The entire system has an optimal number of six reactive clusters and a maximum modularity of 0.735. Additionally, the optimal number of active clusters in the system is 5, with a maximum modularity of 0.80. The coupling index used in cluster division in this paper reduces the number of individual cluster nodes too much or too little. For example, nodes 48, 49, and 50 in Cluster II are affected by the topology of the distribution network and the original parameters, so they are still in the same cluster.

The key nodes in different clusters are shown in Table 1. Among them, the reactive power cluster V is connected to multiple photovoltaics. Node 25, located at the back as far as the grid is concerned, is the most sensitive to voltage, but node 20 has more adjustable reactive power capacity. Node 20 has a greater impact on

TABLE 3 Comparison of different control methods.

Control mode	Reactive power absorption (MW)	Active power reduction (MW)	Network loss (MW)
Centralized control	4.5181	0.2051	1.7018
Cluster control	3.332	0.1648	1.9325

the voltage of the cluster. Finally, node 20 is the key node of cluster V.

The distributed photovoltaic system's low output causes a slight over-limit of voltage. To solve this issue, reactive power compensation can be applied to certain nodes within the cluster. Between 14:00 and 15:00, some nodes in the distribution network exceeded the voltage limit. Node 20 in cluster V compensated 0.34 kVar, resulting in a 57.1% decrease in the number of nodes with voltage exceeding the limit. Based on the calculation results of key node selection, node 25 in the cluster compensated 0.23 kVar, resulting in the restoration of normal voltage levels across all nodes.

Due to the increase in distributed photovoltaic output, reactive power coordination within a cluster alone is insufficient to meet voltage regulation requirements. Therefore, it is necessary to implement reactive power coordination control across different clusters to address the issue of voltage exceeding the limit. During the period of 10:00–11:00, there were more nodes in the distribution network with voltage exceeding the limit, and even after reactive power compensation for the internal nodes of Cluster V, the voltage remained over the limit. This led to the coordination stage of different clusters. Once the key nodes of Clusters IV and VI were compensated, the voltage of all nodes in Cluster V returned to normal.

When the photovoltaic system is close to full power, relying solely on reactive power cluster coordination may not be sufficient to meet the voltage regulation requirements. Therefore, the problem of voltage exceeding the limit is solved by controlling individual nodes in the active cluster. During the period of 11:00–12:00, the distributed photovoltaic system is close to full power, and the proportion of nodes with distribution voltage exceeding the limit continues to increase. After compensating the key node 65 in Cluster VI, the voltage in the cluster returns to normal. Despite compensating all the key nodes and other nodes with reactive power compensation ability in Cluster V, the voltage remains over the limit and enters the reactive power coordination stage of different clusters. Both Clusters IV and VI compensate for all the reactive power. Cluster V has nodes with voltages over the limit. After reactive power compensation in Clusters I, II, and III, the voltage remains unchanged, and the system enters the active power cluster control stage. Key node 20 in active Cluster IV reduces some of the active power, and the voltage returns to normal.

As shown in Figure 4, at a certain moment from 14:00 to 15:00, because the output of distributed photovoltaic leads to the system exceeding the limit, node 22 to node 27 of Cluster VI appears to exceed the voltage limit. The compensation strategy and the key node compensation strategy in the cluster are compensated, respectively. Through the curve comparison in Figure 4, it can be seen that the key node compensation strategy in the cluster is better than the local compensation strategy in the cluster, and the network loss controlled by the key node is reduced by 11.2% compared with the network loss controlled by the local control. With the increase in photovoltaic installation capacity and control number, this difference will be further expanded. Therefore, it is necessary to select key nodes in the cluster.

As shown in Figure 5, with the increase in the photovoltaic penetration rate, the node voltage of the whole distribution network also increases. The voltage situation of the distribution network is represented by curve e when the distributed photovoltaic penetration rate is 105%. The distribution voltage must not exceed the limit. It continues to operate normally. Curve c represents the distribution grid voltage when the penetration of distributed PV is 155%, and the voltage of some nodes in the distribution grid exceeds the limit. After the coordination of the reactive power in the cluster, the voltage returns to normal, as shown in curve d. Curve a illustrates the voltage situation in the distribution network when the penetration rate of distributed photovoltaics is 220%. There are voltage overshoot problems at some nodes in the distribution network. The coordination of reactive power clusters alone cannot meet the needs of voltage regulation. Active power cluster control is also needed, and finally, the voltage returns to normal, as shown in curve b.

4.3 Comparison of different control strategies

4.3.1 Voltage control within reactive power clusters

To determine the superiority of the Louvain algorithm-based improved cluster partitioning method, we compared it with the Fast Newman cluster partitioning algorithm, the Louvain algorithm, and the algorithm proposed in this paper for clustering the distribution network system. Table 2 provides the comparison results of modularity. The modularity metric can be used to evaluate the reasonableness of the cluster partition results presented in Table 2. The Fast Newman cluster partition algorithm reduces the number of individual cluster nodes to some extent by considering the coupling degree relationship, which improves the accuracy of the cluster partition. This paper combines the photovoltaic support capability with the sensitivity matrix to avoid an excessive number of adjustable distributed photovoltaics in the cluster when calculating the power balance index of the Louvain algorithm. The impact of distributed photovoltaics on the voltage and the coupling relationship of the cluster is also taken into account, in addition to the reactive power sensitivity matrix. As a result, the cluster division is more reasonable, leading to a higher reactive power cluster modularity value.

4.3.2 Comparison of pressure regulation effects of different methods

To determine the advantages of the proposed strategy, a comparison will be made between the use of the central control method for voltage regulation at the connection of high-permeability photovoltaic systems to the distribution system and the proposed cluster control method. The voltage fluctuation following all-day access to distributed PV is shown in Figure 6A. Due to the fluctuation of the distributed photovoltaic power, the voltage may exceed the limit value from time to time. Figure 6B shows the voltage fluctuation after centralized control throughout the day, while Figure 6C shows the voltage fluctuation throughout the day after implementing the strategy proposed here. Both centralized control and the strategy proposed in this paper maintain normal voltage levels. However, the voltage fluctuation is smaller with the proposed strategy, which is beneficial for ensuring the stable operation of the system.

Table 3 shows the reactive power compensation and active power reduction during the control process. The reactive power change in centralized control is 35.6% higher than that in cluster control. Even with coordinated control of reactive power clusters, there is still a problem of voltage exceeding the limit after Cluster V consumes all the reactive power. Reactive power Clusters 1, II, and III compensate reactive power Cluster V without affecting the system voltage before entering the active cluster control stage. During the active control stage, the active power reduction of cluster control is 19.65% lower than that of centralized control, despite a 0.2307-MW increase in network loss. However, all photovoltaic nodes participate in voltage regulation under centralized control rather than using fast responses to the volatility of distributed photovoltaics, even when the system error is within the allowable range.

5 Conclusion

The aim of this paper is to tackle the issue of voltage overshoot resulting from high-permeability distributed photovoltaic access in the distribution network. It proposes a distributed photovoltaic cluster collaborative optimization voltage control strategy based on an improved community algorithm, and the following conclusions are obtained:

1) The decoupling control of active and reactive power is achieved through the analysis of Newton–Raphson power flow computer theory. Additionally, we propose an improved cluster division index and obtain optimal results for reactive and active cluster division using the community algorithm.
2) The paper adopts a strategy of first reactive power cluster control, followed by active power cluster control for voltage regulation. Additionally, the paper proposes a selection index for key nodes in the cluster, taking into account the difference in voltage support ability among nodes. Using the improved IEEE 69 distribution network as an example, the simulation results demonstrate that the proposed method strengthens the coupling between nodes within the cluster, weakens the coupling between nodes in different clusters, and improves the power balance of the cluster. The proposed cluster control method prioritizes reactive power over active power, effectively resolving the issue of voltage over-limit. By adjusting the key nodes of the cluster, the search range is reduced, improving the calculation efficiency and reducing network loss in the system.

This work examines the impact of opening and closing various contact switches in the distribution network on cluster division. The objective is to enhance voltage control efficiency and PV consumption capacity.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

HL: writing–review and editing and writing–original draft. KS: writing–review and editing and writing–original draft. FM: writing–original draft and conceptualization. ZW: writing–review and editing and data curation. CW: writing–original draft.

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Conflict of interest

Author HL was employed by State Grid East Inner Mongolia Electric Power Co., Ltd. Tongliao Power Supply. Author KS was employed by State Grid East Inner Mongolia Electric Power Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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