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Coordinated control of PVs in medium and high voltage distribution network based on voltage partitioning and pilot nodes selection

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Abstract. High penetration of intermittent photovoltaic (PV) generation in medium and high voltage distribution network (DN) has caused uncertainty in power flow. Under this circumstance, great challenges have been put on reactive power control and voltage regulation in DN. In this paper, focusing on reactive power control of PVs and voltage regulation, a coordinated control of PVs in medium and high voltage DN is proposed based on voltage partitioning and pilot nodes selection. Firstly, three indices are introduced to evaluate performance of voltage partitioning, that is, redundancy rate of reactive power within a partition, strong coupling within a partition and weak coupling within partitions. Secondly, indices of observability and controllability are adapted to select pilot nodes. Then the control strategy of PVs in medium and high voltage DN is proposed according to results of voltage partitioning and pilot nodes selection. Case study results verified the feasibility and effectiveness of proposed control strategy.

1. Introduction

With the advance in renewable generation technology, more and more renewable generations such as photovoltaic (PV) generation are integrated to distribution network [1,2]. High penetration of PVs in distribution network (DN) brings great challenges on reactive power control and voltage regulation in a DN because of the uncertainties in power flow caused by intermittent and fluctuated PV power output [3,4]. Under the circumstance of two-way power flow in the DN, improper reactive power control and voltage regulation may even worsen network loss [5]. Therefore, effective coordinated control strategies of reactive power sources in the DN worth exploring.

The reactive power output of PVs can be controlled through inverters. Via coordinated control of PVs and other reactive power generation equipment, the reactive power control capacity of the distribution network can be remarkably improved [6]. However, the control and dispatch process become more complicated with more equipment involved. Faced with this problem, reasonable voltage partitioning and pilot nodes selection contributes to reduce the control variables and simplify computation, as well as achieve locally compensation of reactive power.

Much progress has been made on voltage partitioning and pilot nodes selection in the DN. For example, in [7] a novel methodology is presented to evaluate the QV interactions among buses and to partition the pilot voltage-reactive power coupling areas. In [8] a partitioning algorithm is proposed that minimizes both real and reactive power imbalance between generation and load within areas. In [9] spectral clustering method is adapted to partition Volt/Var control areas in bulk power systems. Generally, most voltage partitioning methods are based on electrical distance.

Reactive power control and voltage regulation methods are studied base on the principle of electrical distance with different objective functions, optimization model and solving algorithm. A double-layer voltage control strategy based on the distribution network partition is proposed aiming at jointly optimizing the active and reactive power outputs of PV units [10]. In [11], a secondary voltage control strategy is investigated based on a graph partitioning method which divides the power system into different regions to eventually prevent the propagation of disturbances and to minimize the interaction between these regions. A coordinated secondary voltage control strategy is presented based on partitioned power network and decentralized controllers designed for each region, to regulate voltage of buses and increase the security of the power network [12].

Based on the researches aforementioned, in this paper, focusing on reactive power control and voltage regulation in a medium and high voltage distribution network, a coordinated control strategy of PVs is proposed based on voltage partitioning and pilot nodes selection. Three indices are introduced to evaluate effect of voltage partitioning, that is, redundancy rate of reactive power within a partition, internal coupling within a partition and coupling between partitions. Besides, observability and controllability of node voltage are adapted as indices when selecting pilot nodes. Then, the coordinated control strategy of PVs is proposed with the objective of minimizing voltage amplitude off-set of pilot nodes.

The rest of this paper is organized as follows: Section 2 presents the voltage partitioning method in medium and high voltage DN with reactive power sources. Section 3 presents the pilot nodes selection methods. Section 4 proposes the coordinated control strategy of PVs in medium and high voltage DN based on voltage partitioning and pilot nodes selection. Section 5 presents a case study. Section 6 concludes main work.

2. Voltage partitioning in medium and high voltage DN with reactive power sources

The concept of voltage partitioning means that, the whole distribution network can be divided into several partitions, and nodes within a partition have strong coupling and nodes in different partitions have weak coupling. In this way, voltage regulation within a certain partition has little impacts on nodes in other partitions, thus separate voltage regulation in individual partitions can be implemented.

In a medium and high voltage DN, power flow direction changes with active and reactive power output of PVs, which further causes changes in electrical distance of different nodes. Under this circumstance, difference between voltage partitioning with and without PVs and other reactive power sources should be well considered. In this paper, a multi-objective voltage partitioning method in DN with reactive power sources is presented based on electrical distances among nodes.

2.1. Electrical distance calculation considering reactive power sources

Electrical distance between node i and node j can be calculated as [13]:

$$D_{ij} = -\lg(\sigma_{ij} \times \sigma_{ji}) \tag{1}$$

where, D_{ij} is the electrical distance between node i and node j; σ_{ij} is the sensitivity of voltage of node i to voltage amplitude change of node j caused by reactive power injection change in node j. σ_{ij} can be expressed as:

$$\sigma_{ij} = \left[\frac{\partial V_i}{\partial Q_i}\right] \Big/ \left[\frac{\partial V_j}{\partial Q_j}\right] \tag{2}$$

where, V_i and V_j are the voltage amplitude of node i and node j, respectively; Q_i and Q_j are the reactive power in node i and node j, respectively.

In this paper, to better reflect impacts of reactive power sources in a DN, nodes with reactive power sources is treated as two individual nodes, that is, a load node and a reactive power source node. The reactive power source node can be simplified as a PQ node for power flow calculation. Therefore, the electrical distance matrix $\boldsymbol{D}$ contains information of all nodes, which can be expressed as:

$$\boldsymbol{D}=\begin{bmatrix}\boldsymbol{D}_{LL} & \boldsymbol{D}_{LG}\\ \boldsymbol{D}_{GL} & \boldsymbol{D}_{GG}\end{bmatrix} \tag{3}$$

where, $\boldsymbol{D}_{LL}$ is the electrical distance between two load nodes; $\boldsymbol{D}_{LG}$ and $\boldsymbol{D}_{GL}$ are the electrical distances between reactive power source nodes and load nodes, respectively, which reflect influence exerted on load nodes by reactive power source; $\boldsymbol{D}_{GG}$ is the electrical distance between reactive power source nodes.

2.2. Indices of voltage partitioning in DN with reactive power sources

2.2.1. Redundancy rate of reactive power within a partition. Ideally, reactive power load demands should be well satisfied by reactive power sources within a partition according to the principle of reactive power balance in a partition. Reactive power sources in a DN should be allocated into different partitions to satisfy different load demands. The redundancy rate of reactive power within a partition is used as an index to evaluate the performance of voltage partitioning schedule, which can be expressed as:

$$\varphi_1=\frac{\sqrt{\sum_{k=1}^{K}\left|\sum_{i_k=1}^{G_k}Q_{g\max,i_k}+\sum_{j_k=1}^{L_k}Q_{l,j_k}\right|}}{\left|\sum_{k=1}^{K}\sum_{i_k=1}^{G_k}Q_{g\max,i_k}+\sum_{k=1}^{K}\sum_{j_k=1}^{L_k}Q_{l,j_k}\right|}-\sum_{k=1}^{K}\frac{(u_k+l_k)}{2} \tag{4}$$

$$u_k=\frac{V_{k,P}^{u}-V_{k,P}^{s}}{V_{k,P}^{s}}\times 100\% \tag{5}$$

$$l_k=\frac{V_{k,P}^{s}-V_{k,P}^{l}}{V_{k,P}^{s}}\times 100\% \tag{6}$$

where, φ_1 is the redundancy rate of reactive power within a partition; K is the number of partitions, k=1,2,…,K; $Q_{g\max,i_k}$ and Q_{l,j_k} are respectively the upper limits of available reactive power and actual reactive power load in partition k; G_k and L_k are respectively the number of reactive power source nodes and reactive power load nodes; u_k and l_k are respectively the upper and lower limits of reserved reactive power in partition k; $V_{k,P}^{s}$ is the reference voltage of load nodes in partition k under current operation state; $V_{k,P}^{u}$ and $V_{k,P}^{l}$ are the node voltages when partition k operates under the upper and lower limits of its reactive power output.

2.2.2. Internal coupling within a partition. Strong internal electrical coupling within a partition should be guaranteed after voltage partitioning, so that interactive influence between different partitions can be minimized. Index of internal coupling within a partition is used as an index evaluating performance of voltage partitioning, meaning the ratio of average electrical distance between load nodes to maximum electrical distance between load nodes. The index of internal coupling within a partition can be calculated as:

$$\varphi_2 = \frac{\sum_{j=1}^{L_k}\sum_{\substack{i=1\\ i\neq j}}^{L_k}(\boldsymbol{D}_{LL})_{ij}}{L_k\left(L_k-1\right)\cdot\max\left\{\boldsymbol{D}_{LL}\right\}} \tag{7}$$

where, φ_2 is the index of internal coupling within a partition. The lower φ_2 is, the stronger coupling of load nodes within partition k it means, which coincides within the principle of strong coupling within a partition.

2.2.3. Coupling between partitions. The index of coupling between partitions can be expressed as:

$$\varphi_3 = \frac{\frac{1}{G_k}\sum_{i=1}^{G_k}\sum_{j=1}^{L_k}\left(\boldsymbol{D}_{GL}\right)_{ij}}{\min_i\left\{\sum_{i\notin G_k}\sum_{j=1}^{L_k}\left(\boldsymbol{D}_{GL}\right)_{ij}\right\}} \tag{8}$$

where, φ_3 represents coupling between partition k and other partitions. The index of coupling between partitions reflects ratio of electrical distance between reactive power source nodes and load nodes in partition k to minimal electrical distance between reactive power source nodes in other partitions and load nodes in partition k. The index of coupling between partitions represents the influence exerted on load nodes in partition k by reactive power sources in other partitions.

2.3. Voltage partitioning model in DN with reactive power sources

To satisfy multiple requirement of voltage partitioning, a multi-objective optimization model is established to obtain optimal voltage partitioning results. The mathematical model is established as:

$$\min \quad F_1 = \alpha_1\cdot\varphi_1 + \alpha_2\cdot\varphi_2 + \alpha_3\cdot\varphi_3 \tag{9}$$

where, α_1, α_2 and α_3 are the weight coefficients of three indices, respectively, and they satisfy the constraint of:

$$\alpha_1 + \alpha_2 + \alpha_3 = 1 \tag{10}$$

The established voltage partitioning model can be solved through genetic algorithm (GA), where each branch in the DN is set a gene, and the gene has two statuses, 0-1, to represent connection and disconnection status of the branch. Usually, in IEEE standard test systems, the number of initial node of each branch is taken as the number of this branch.

3. Pilot nodes selection method in medium and high voltage DN with reactive power sources

The node voltage of pilot nodes should not only reflect overall voltage level in the voltage partition, but also can be regulated to achieve expected voltage level. These two characteristics of the pilot nodes are referred to as observability and controllability. The mathematical model of pilot nodes selection can be expressed as:

$$\min \quad F_2 = \beta_1\cdot\omega_{Oi} + \beta_2\cdot\omega_{Ci} \tag{11}$$

where, ω_{Oi} and ω_{Ci} are the indices of observability and controllability of node i, respectively; β_1 and β_2 are the weight coefficients, which satisfy the constraint of :

$$\beta_1 + \beta_2 = 1 \tag{12}$$

3.1. Observability of pilot nodes

The observability of pilot nodes means that, the pilot nodes voltage should be able to reflect overall voltage level of load nodes in the same partition and that the electrical distance between the pilot nodes and other load nodes within the partition should be able to reflect influence on pilot nodes voltage exerted by changes in voltage amplitude of other load nodes. Therefore, the observability of node *i* in partition *k* can be defined as:

$$\omega_{Oi} = \frac{1}{L_k - 1} \cdot \frac{\sum_{j=1, j\neq i}^{L_k} (\boldsymbol{D}_{LL})_{ij}}{\max_j \left\{ \boldsymbol{D}_{LL} \right\}} \tag{13}$$

The index of observability represents the ratio of average electrical distance between node *i* and other nodes in partition *k* to the maximum electrical distance between node *i* and other nodes in partition *k*. The lower ω_{Oi} is, the more sensitive the voltage of node *i* is to voltage changes in other nodes, meaning the better performance of observability of node *i*.

3.2. Controllability of pilot nodes

The controllability of pilot nodes means that, the voltage of pilot nodes can be regulated to expected level. Therefore, strong coupling between pilot nodes and reactive power source nodes is required. The index of controllability of node *i* in partition *k* is defined as:

$$\omega_{Ci} = \frac{1}{G_k} \cdot \frac{\sum_{j=1}^{G_k} (\boldsymbol{D}_{LG})_{ij}}{\max_j \left\{ \boldsymbol{D}_{LG} \right\}} \tag{14}$$

The index of controllability of pilot nodes represents the ratio of average electrical distance between node *i* and reactive power source nodes in partition *k* to maximum electrical distance between node *i* and reactive power source nodes in partition *k*. Therefore, the lower ω_{Ci} is, the stronger coupling between node *i* and reactive power source nodes is, meaning the better regulation performance of voltage of node *i*.

The optimization model of pilot nodes selection can be solved through GA.

4. Coordinated control of PVs in medium and high voltage DN

With high penetration of PVs in distribution network, two-way power flow emerges. As active power output of PVs may cause increase in voltage of nodes to which PVs are connected, sometimes voltage violation in distribution network occurs too. On other hands, however, the reactive power output of PV systems can be controlled. Equipped with communication equipment, PV systems integrated to medium and high voltage distribution networks can be dispatched to achieve voltage regulation. However, coordinated control of all high penetration PVs in distribution network usually means large-scale variables and complicated computation. On this background, voltage partitioning and pilot nodes selection methods are adapted to simplify complex of coordinated control of PVs in DN. The main steps of coordinated control of PVs based on voltage partitioning and pilot nodes selection are depicted in figure 1.

Based on results of voltage partitioning and pilot nodes selection, the coordinated control strategy of PVs in medium and high voltage distribution network is formulated, with the objective of minimizing voltage offset value of pilot nodes. The controllable sources are PV systems in the distribution network. The established optimization model is:

$$\min \quad F_3 = \sum_{k=1}^{K} \frac{\left| V_{k,dom} - V_{k,set} \right|}{V_{k,set}} \tag{15}$$

where, $V_{k,dom}$ and $V_{k,set}$ are the actual and expected voltage amplitudes of the pilot nodes in partition k, respectively.

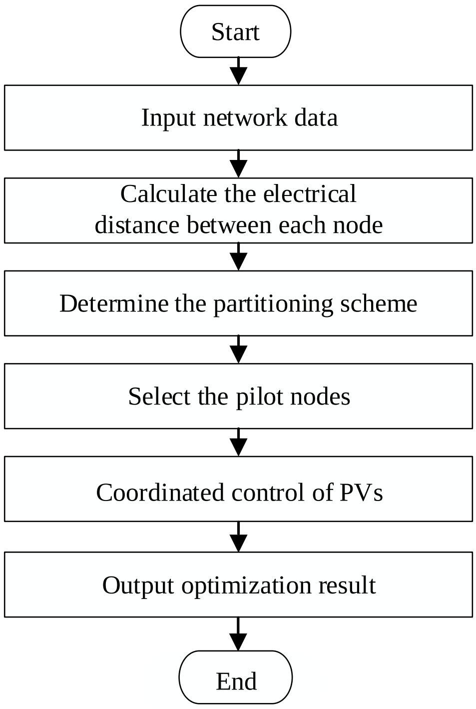

Figure 1. Flow chart of coordinated control of PVs.

The constraints are listed as follows:

- Constraint of power flow

$$\begin{cases} P_i = U_i \sum_{j\in i} U_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \\ Q_i = U_i \sum_{j\in i} U_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \end{cases} \tag{16}$$

where, P_i and Q_i are the active and reactive power injection in node i, respectively; U_i and U_j are the node voltage amplitudes of node i and nod j, respectively; θ_{ij} is the phase difference of voltage node between node i and node j; G_{ij} and B_{ij} are the conductance and susceptance of branch between node i and node j, respectively.

- Constraint of pilot nodes voltage

$$V_{k\min} \le V_{k,dom} \le V_{k\max} \tag{17}$$

where, $V_{k\min}$ and $V_{k\max}$ are the allowable minimum and maximum node voltage amplitude of the pilot node in partition k, respectively.

- Constraint of reactive power output of PV inverters

$$Q_{Gi\min} \le Q_{Gi} \le Q_{Gi\max} \tag{18}$$

where, Q_{Gi} is the reactive power output of the PV inverter connected to node i; $Q_{Gi\min}$ and $Q_{Gi\max}$ are respectively the minimum and maximum reactive power output of the PV inverter in node i.

The established coordinated control model of PVs in distribution network can be solved through Particle Swarm Optimization (PSO) algorithm.

5. Case study

Take data from the 220kV Shuanglong substation, Huaian power supply company as an example. The substations distribution and connections in the regional distribution network is depicted in figure 2. We used MATLAB to solve the model on a PC with an Intel Core 5 CPU (2.6 GHz) and 4.0 GB RAM.

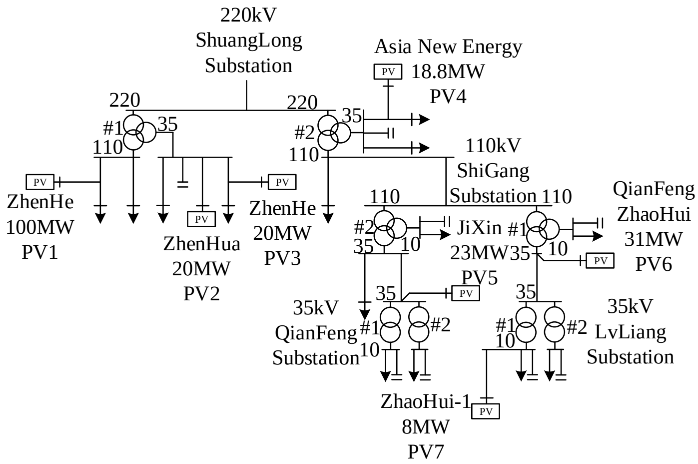

Figure 2. Regional substations distribution and connections.

Based on the regional substations distribution and connections, a 41 nodes equivalent topology of the distribution network can be obtained, as shown in figure 3.

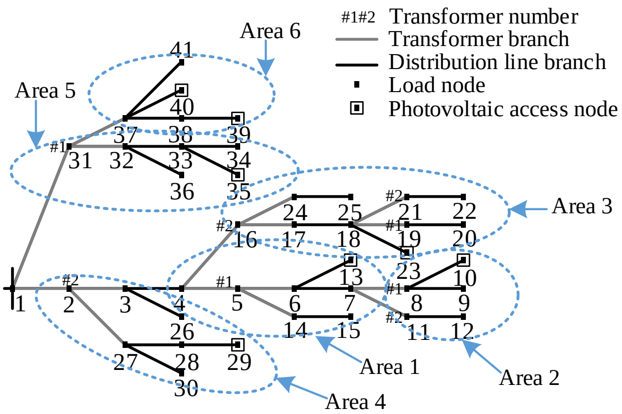

Figure 3. Equivalent topology of the 41 nodes distribution network.

There are four voltage levels in the 41 nodes distribution network, including 220kV, 110kV, 35kV and 10 kV. 7 PV systems are integrated to the whole distribution network. Specific information of the distribution network is presented in Appendix A1. The power output of each PV system at 12 am in a certain day is presented in table 1.

Table 1. Information of grid-connected PV systems.

Number	Voltage level	Nodes	Rated capacity/(MVA)	Active power output/(MW)
PV1	110kV	35	100	85.8889
PV2	35kV	40	20	14.7600
PV3	35kV	39	20	13.3112
PV4	35kV	29	18.8	11.6390
PV5	35kV	23	23	19.2672
PV6	35kV	13	31	24.9466
PV7	10kV	10	8	4.7246

Based on information of the distribution network and power output of PV systems, the electrical distance matrix $\boldsymbol{D}$ can be calculated. And the number of partitions K is set to 6 according to the distribution of PV systems. Then, the voltage partitioning results can be obtained according to indices of redundancy rate of reactive power source within a partition, internal coupling within a partition and coupling between partitions. The weight coefficients are set α_1 =0.5, α_2=0.25, α_3=0.25. The voltage partitioning results are shown in figure 3.

According to figure 3, the whole distribution network is divided into 6 partitions. In each voltage partition, pilot nodes are selected according to the method in Section 3. With weight coefficients set as β_1=0.5 and β_2=0.5, the pilot node in each voltage partition is node 13, node 10, node 23, node 29, node 35 and node 40. We can see that the selected pilot nodes are exactly the nodes to which PV systems are connected, that is because the voltage of nodes with PVs is more observable and controllable.

Based on results of voltage partitioning and pilot nodes selection, with expected value of pilot node voltage set as 1.01 p.u., reactive power output of PVs is controlled to regulate voltage in each partition. The PSO algorithm parameters are set as follows: particle group size N=80, maximum iteration number T_{max}=200, particle dimension d=7, inertia weight w=0.729, learning factor c_1=c_2=1.49445. The calculation process of the PSO algorithm takes 140 seconds. The reactive power output of PVs after coordinated control is shown in table 2.

Table 2. Reactive power output of PVs after coordinated control.

Number	Nodes	Reactive power output/(MVar)
PV1	35	9.2329
PV2	40	-1.4716
PV3	39	1.1012
PV4	29	-2.6708
PV5	23	-1.4592
PV6	13	-9.9158
PV7	10	2.8038

According to table 2, PV1 and PV3 generate capacitive reactive power while the other PVs generate inductive reactive power. That is because reactive power demands near node 35 and node 39 are much larger than that near other nodes, hence much more local reactive power compensation is provided by PV1 and PV3.

The overall node voltage in distribution network before and after coordinated control of PVs are shown in figure 4, and comparison of voltage amplitude off-set of pilot nodes are shown in figure 5.

According to figures 4 and 5, we can obviously see that, through coordinated control of grid-integrated PVs' reactive power output, voltage of pilot nodes in each voltage partition tends to approach the expected voltage level. Meanwhile, no more voltage violation occurs after reactive power control and voltage regulation in the distribution network with PVs.

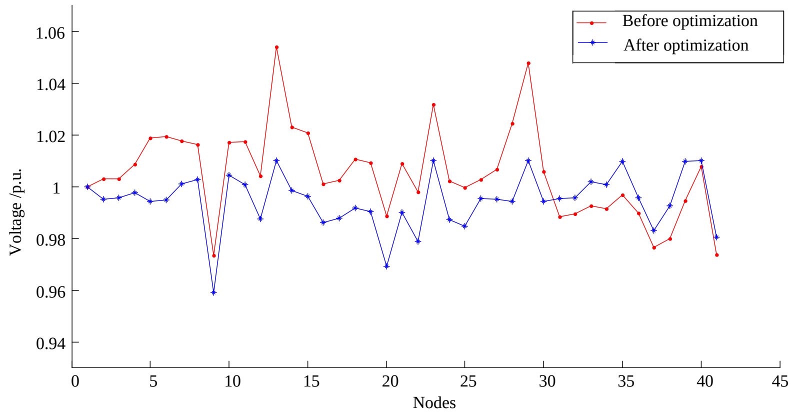

Figure 4. Node voltage before and after coordinated control of PVs.

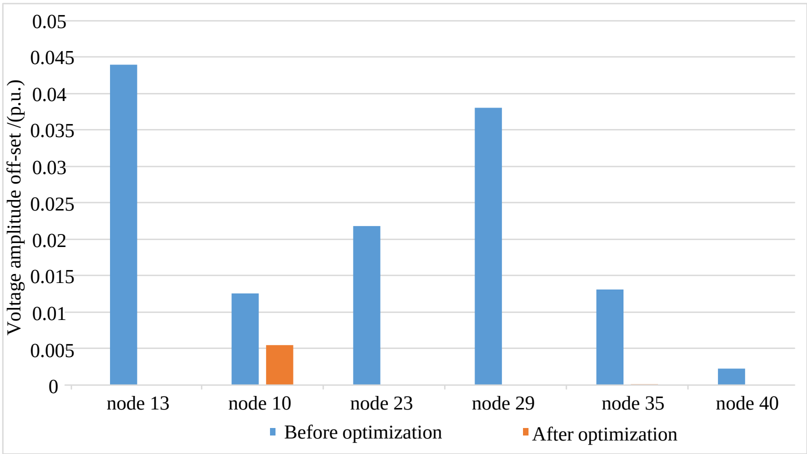

Figure 5. Node voltage amplitude off-set of pilot nodes.

6. Conclusions

With increasing penetration of photovoltaic generation in medium and high voltage distribution network, a coordinated control strategy of PVs to realize reactive power control and voltage regulation is proposed based on voltage partitioning and pilot nodes selection. Case study results demonstrated the feasibility and effectiveness of the proposed strategy. We can come to the conclusions that:

- Performance of voltage partitioning in a DN with reactive power sources can be well evaluated by indices of redundancy rate of reactive power, internal coupling within a partition and coupling between partitions.
- The voltage regulation performance can be improved through voltage regulation of pilot nodes where node voltage is observable and controllable in each partition.
- Through coordinated control of PVs after voltage partitioning and pilot nodes selection, the overall node voltage level in the distribution network is kept within an allowable range, and the whole computation process of reactive power control and voltage regulation is simplified to some extent.

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Generation Based Reactive Power Control Technology for Local Utilization of High Penetration PV).

Appendix

Table A1. Information of the 220kV distribution network.

Branches	Initial node	Endpoint node	*R*/ Ω	*X*/ Ω	Active load /(MW)	Reactive load /(MVar)	Voltage level /(kV)
1	1	2	0.2193	31.6079	0	0	220
2	2	3	0.3692	-2.4872	0	0	220
3	3	4	2.199	5.758	0	0	110
4	4	5	0.5916	26.07	0	0	110
5	5	6	0.394	0	0	0	110
6	6	7	2.36	4.496	0	0	35
7	7	8	1.69295	1.69295	0	0	35
8	8	9	1.308	1.67	3.152175	0.809869	10
9	8	10	0.0291	0.0484	1.739697	0.025195	10
10	7	11	1.58278	1.58278	0	0	35
11	11	12	0.573	1.296	1.672327	0.594649	10
12	6	13	1.957	3.17	0	0	35
13	5	14	0.4422	18.0972	0	0	110
14	14	15	0.2071	0.3261	0.93824	0.240576	10
15	4	16	0.798	32.9404	0	0	110
16	16	17	0.5152	-2.2041	0	0	110
17	17	18	1.912	4.495	0	0	35
18	18	19	1.69295	1.69295	0	0	35
19	19	20	1.778	3.39	1.126384	0.215152	10
20	18	21	1.58278	1.58278	0	0	35
21	21	22	0.7047	1.4502	1.177008	0.461944	10
22	18	23	2.277	3.542	0.55702	0.9476	35
23	16	24	0.5789	21.2256	0	0	110
24	24	25	0.2089	0.3306	0.952656	0.290176	10
25	3	26	0.2643	1.274	21.67236	-1.98239	110
26	2	27	1.506	62.9872	0	0	220
27	27	28	7.43	9.561	2.779665	3.056484	35
28	28	29	3.24	4.8	0	0	35
29	27	30	0.7236	1.435	0.882244	0.383922	35
30	1	31	0.332	36.3	0	0	220
31	31	32	0.5486	-4.0333	0	0	220
32	32	33	1.2721	4.7236	0	0	110
33	33	34	0.8229	3.0554	1.342585	4.453938	110
34	33	35	1.109	5.214	0	0	110
35	32	36	0.1099	0.4374	25.29051	-9.14172	110
36	31	37	2.5209	84.7	0	0	220
37	37	38	4.091	7.072	5.026044	2.740972	35
38	38	39	1.7	4	0	0	35
39	37	40	3.032	3.842	-0.44269	0.526281	35
40	37	41	0.5609	1.0565	3.959818	1.445063	35

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