Voltage Control Strategy of Power Distribution Network with Schedulable Distributed Resources

Ling Wang[1,2](✉), Bo Fu[3], Youyong Lin[3], Chunming Tu[4], Fan Xiao[4], and Qi Guo[4]

[1] Electric Power Research Institute of Guangdong Power Grid Co., Ltd., Guangzhou, China
360409837@qq.com
[2] Key Laboratory of Power Quality of Guangdong Power Grid Co., Ltd., Guangzhou, China
[3] Guangdong Power Grid Corporation Zhuhai Power Supply Bureau, Zhuhai, China
[4] College of Electrical and Information Engineering, Hunan University, Changsha, China

Abstract. Wide use of schedulable distributed resources for flexible and effective power generation, combined with the actual situation of the country, has been valued by all countries of the world. Connecting schedulable distributed resources to power grid is an effective choice to solve the current energy shortage and improve energy utilization. When high proportion of schedulable distributed resources are connected to the power distribution network, power quality problems such as voltage fluctuation, flicker and off-limit will occur. Therefore, based on the distributed resource cluster, the power distribution network voltage control with a high proportion of distributed resource access is implemented. Through the calculation of the capacity utilization ratio of the leading nodes of the distributed resource cluster to the distributed power capacity, a quantitative relationship between the node voltage and the distributed resource output is established. And the corresponding parameter setting methods are given. Finally, the effectiveness of the proposed control strategy is verified by a numerical example in the IEEE 33-node system.

Keywords: Power Distribution Network · Distributed Resource · High Permeability · Distributed Control

1 Introduction

A high proportion of renewable resource is connected to the power grid in the way of Distributed Resource (DR), which is an effective choice to solve the contradictions between energy shortage and demand growth, energy utilization and environmental protection. The use of large-scale renewable resources to generate electricity will help make full use of the abundant, clean and diverse forms of energy available everywhere. And it can also provide customers with green electricity, so it is an important measure to achieve the goals of energy conservation and emission reduction [1]. Especially in the power distribution network in remote areas, with the further strengthening of the national new energy poverty alleviation policy, a large number of distributed renewable resource

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have been connected to the grid. And the penetration rate in some areas has been greater than 100% [2]. In the power distribution network, the power quality problems caused by the high proportion of distributed resource access are mainly reflected in voltage fluctuation, flicker and off-limit [3]. These problems not only limit the utilization rate of renewable energy, but also endanger the safe and stable operation of the system. At the same time, it brings great challenges to the planning, operation and control of the local power grid.

The control methods of power distribution network considering the access of distributed resource can be divided into two types: centralized coordinated control and decentralized autonomous control [4]. The centralized control mode is mainly based on the optimal power flow of the power distribution network, and relies on comprehensive data collection and reliable communication transmission to build and solve the optimal scheduling model [5]. Therefore, a high proportion of schedulable distributed resource connected to the power distribution network will cause a huge burden on the communication network and its computing capacity. The distributed control mode only uses local measurement information, which improves the response speed of the control system and reduces the investment cost. However, the distributed control mode uses limited information, so the utilization of adjustable resources is not sufficient [6].

In order to ensure the orderly, safe, reliable, flexible and efficient access to the power distribution network of high-proportion distributed resource, distributed control has been paid more and more attention in the power system. Compared with centralized and decentralized control, distributed control mode has better control robustness, communication flexibility and system scalability [7]. In recent years, distributed control mode has been partially studied in power system economic dispatch [8], virtual power plant [9] and the micro grid [10]. But the application in power quality control of power distribution network is less involved.

In this paper, the distributed control mode is adopted to realize the voltage control of power distribution network with a high proportion of distributed resource access based on distributed resource cluster. By calculating the dominant node of distributed resource cluster and the capacity utilization ratio of distributed resources, the quantitative relationship between the node voltage and the output of the distributed power supply is established. And the tuning method of the corresponding parameters is given. Finally, the effectiveness of the proposed control strategy is verified by an example of IEEE 33-node system.

2 Distributed Control Framework

The output of distributed resource is intermittent, volatile and uncertain under the influence of external environment. Its high proportion and large-scale access puts forward higher demand for the operation control of power distribution network. Cluster technology is an efficient technical means to achieve the security, stability and economic operation of power distribution network in the future [11, 12]. The power distribution network structure based on distributed resource cluster is shown in Fig. 1:

Several adjacent distributed resources in the dotted box form a distributed resource cluster with specific control objectives. By adopting the same distributed control strategy for each cluster, the output of distributed resource can be optimized to smooth the voltage deviation of power distribution network.

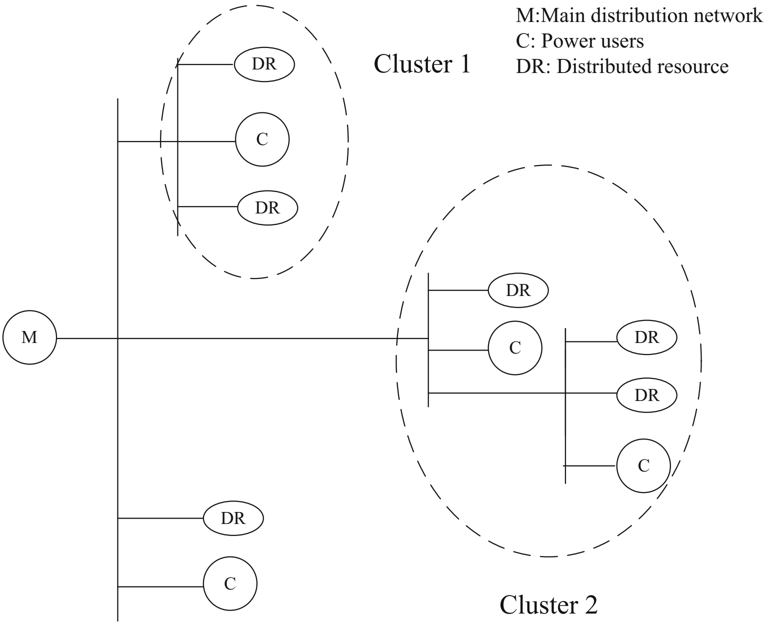

Fig. 1. Power distribution network structure based on distributed resource cluster

3 Distributed Control Strategy

3.1 Cluster Dominant Node

The selection of cluster dominant nodes is a key step in voltage control of power distribution network. The selection results have an important impact on the effect of organizing and coordinating controllable resources in power distribution network and maintaining the voltage level of power distribution network. Dominant nodes are defined as follows: there are a number of key nodes in a region, which are closely connected with other nodes in the region and can represent the voltage level of the region. By monitoring their voltage status, the voltage of other nodes nearby can be grasped [13].

The selected dominant node of the cluster should have both observability and controllability. On the one hand, the voltage of the dominant node can reflect the common voltage level in its region, which can be seen to have observability. On the other hand, when the controllable resources of the system are sufficient, the voltage control of the dominant node can effectively improve the overall voltage level of the region. But it has little influence on the neighboring region, which can be seen to have controllability [14]. Based on the observability and controllability of nodes, the comprehensive sensitivity S of all nodes in cluster i is calculated. The node with the highest comprehensive sensitivity is the dominant node:

$$\max S = \max(C + dD) \tag{1}$$

In the formula, C and D respectively represent the observability and controllability of nodes, and d is the weight coefficient.

The controllability of node l and its calculation equation can be expressed as:

$$\begin{cases} C_l = \sum\limits_{i \in M_a} \dfrac{\Delta V_l}{\Delta V_k} \\ D_l = \sum\limits_{h \in M_b} \dfrac{\Delta V_l}{\Delta Q_h} \end{cases} \tag{2}$$

In the formula, M_a represents the set of all nodes in the cluster; $\frac{\Delta V_l}{\Delta V_k}$ is the voltage sensitivity of node k to node l; M_b denotes the set of all controllable nodes in the cluster; $\frac{\Delta V_l}{\Delta Q_h}$ is the reactive voltage sensitivity of the voltage amplitude of node l to the reactive power injected into node h.

By locally linearizing the stable operation point of the power distribution network, the active voltage sensitivity and reactive voltage sensitivity can be obtained.

$$\begin{cases} \dfrac{\Delta V}{\Delta P} = \begin{bmatrix} (B+Q)(G-P)^{-1}(B-Q)+ \\ (G+P) \end{bmatrix}^{-1} \\ \dfrac{\Delta V}{\Delta Q} = \begin{bmatrix} (G-P)(B+Q)^{-1}(G+P)+ \\ (B-Q) \end{bmatrix}^{-1} \end{cases} \tag{3}$$

In the formula, B and G are the real and imaginary parts of the nodal admittance matrix respectively. P and Q are the diagonal matrices of the active and reactive power injected by the nodes.

3.2 Node Voltage Control

After determining the dominant node of the distributed resource cluster, the voltage of the dominant node is controlled by adjusting the output of all distributed resources in the cluster. Firstly, the evaluation function of node voltage performance is defined, and the quantitative relationship between node voltage and distributed resource output is established through the capacity utilization ratio of distributed resource. Then, the reference value of the variation of the capacity utilization ratio of distributed resource in the cluster is calculated according to the voltage deviation of dominant nodes. Finally, the active power output of each distributed resource is calculated iteratively to achieve the goal of node voltage control.

Control Objectives

Take cluster *i* (*i* = *1, 2,…, N*) as an example. The optimization control objective is to control the voltage of the corresponding leading node to a rated value:

$$V_i = 1(p.u.) \tag{4}$$

In the formula, V_i is the voltage of the dominant node corresponding to cluster *i*.

In cluster *i*, the distributed resource *u* is responsible for node voltage measurement and voltage control performance evaluation. The voltage control performance evaluation function $f_{v,i}$ of the leading node of the cluster is defined as:

$$f_{v,i} = \frac{1}{2}(V_i - 1)^2 \tag{5}$$

Control Variables

The calculation equation of capacity utilization ratio at the *kth* iteration of distributed resource *j* in cluster *i* can be expressed as:

$$\gamma_{i,j}(k) = \frac{P_j(k)}{S_{i,j}\varphi_{i,j}} \tag{6}$$

In the formula, $\gamma_{i,j}(k)$ and $P_j(k)$ are respectively the capacity utilization ratio and active power output at the *kth* iteration of distributed resource *j*. $S_{i,j}$ and $\varphi_{i,j}$ are the capacity and power factor of distributed resource *j*.

The reference value calculation equation defining the capacity utilization ratio at the *kth* iteration of cluster *i* can be expressed as:

$$\Delta\gamma_i^{ref}(k) = -\left.\frac{\partial f_{v,i}}{\partial \gamma_{i,u}}\right|_{\gamma_{i,u}(k)} \tag{7}$$

$$\begin{aligned}\frac{\partial f_{v,i}}{\partial \gamma_{i,u}} &= \frac{\partial f_{v,i}}{\partial V_i}\cdot\frac{\partial V_i}{\partial P_u}\cdot\frac{\partial P_u}{\partial \gamma_{i,u}} \\ &= (V_i - 1)\frac{\partial V_i}{\partial P_u}S_{i,u}\varphi_{i,u}\end{aligned} \tag{8}$$

In the formula, $\Delta\gamma_i^{ref}(k)$ is the reference value of capacity utilization ratio at the *kth* iteration of cluster *i*; $\frac{\partial V_i}{\partial P_u}$ is the active voltage sensitivity of the dominant node voltage of cluster *i* relative to the active power injected by the distributed resource *u*.

The updated calculation equation of capacity utilization ratio of distributed resource *j* can be expressed as:

$$\gamma_{i,j}(k+1) = \sum_{n=1}^{N_i} d_{i,jn}\gamma_{i,n}(k) + d_{i,u}\varepsilon_i\Delta\gamma_i^{ref}(k) \quad (9)$$

In the formula, $\gamma_{i,j}(k+i)$ is the capacity utilization ratio at the $k + 1$ iteration of distributed resource *j* in cluster *i*; N_i is the total number of distributed resources in cluster *i*; $d_{i,jn}$ is the communication weight coefficient between distributed resource *j* and *n*; $\gamma_{i,n}(k)$ is the capacity utilization ratio at the *kth* iteration of distributed resource *j*; $d_{i,u}$ is the weight coefficient of node voltage measurement in cluster *i*; ε_i is the iteration step.

The calculation equation of the communication weight coefficient $d_{i,jn}$ can be expressed as:

$$d_{i,jn} = \frac{d_{jn}}{\sum_{n=1}^{N_i} d_{jn}} \quad (10)$$

In the formula, for the distributed resource *n* in cluster *i* that communicates with distributed resource *j*, there is $d_{jn} = 1$; For a distributed resource *n* with no communication connection, there is $d_{jn} = 0$.

For the distributed resource *u* responsible for node voltage measurement in cluster *i*, there is $d_{i,u} = 1$; For the rest of the distributed resource, there is $d_{i,u} = 0$.

According to the updated capacity of the distributed resource *j*, the active power output at the $k + 1$ iteration can be deduced by using the ratio:

$$P_j(k+1) = \gamma_{i,j}(k+1)S_{i,j}\phi_{i,j} \quad (11)$$

Control Process

The voltage control flow of power distribution network with high proportion of distributed resource access based on distributed resource cluster is shown in Fig. 2:

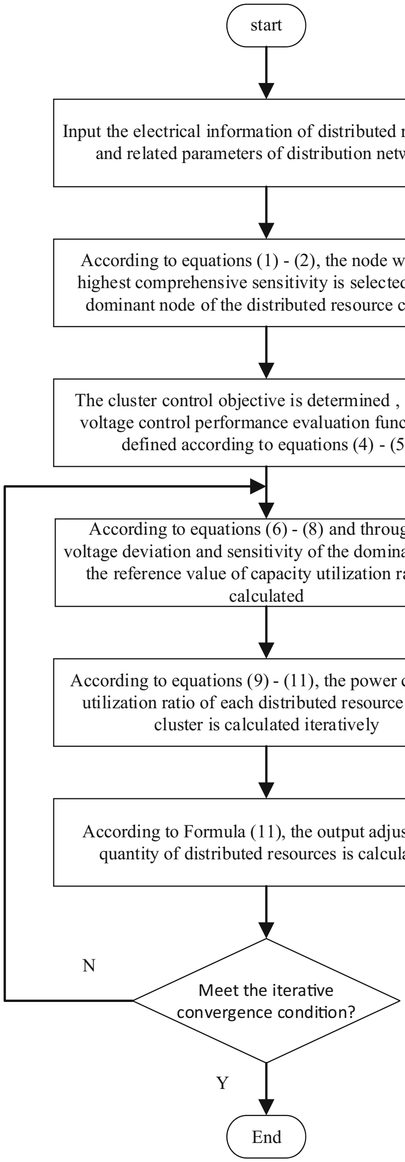

Fig. 2. Power distribution network voltage control flow based on distributed resource cluster

4 Simulation Examples

In this paper, the standard IEEE 33-node power distribution network system is used for simulation calculation, and the proposed voltage control strategy is analyzed by example. The system structure is shown in Fig. 3.

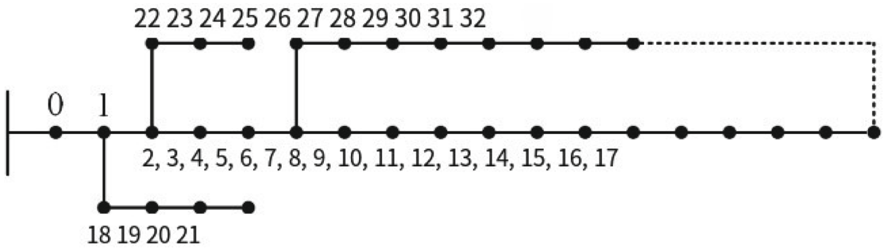

Fig. 3. IEEE 33 node network structure

The system has 32 branches, one contact switch branch, and node 0 is the balance node of the system. The reference voltage of the system is 12.66 kV. The reference power is 10 MVA. The total active load is 3715 kW. The total reactive load is 2300 kVar. The line impedance, node load and other parameters are detailed in the reference. The access capacity of the distributed resource is 1500 kVA. The minimum power factor is set as 0.9, and the maximum number of simulation iterations is 1500. In each example, the permeability of distributed resource is 50%. In other words, the total output power of distributed resource is 1857.5 kW.

In order to verify the effectiveness of the control strategy proposed in this paper, different load capacities and different wiring modes of the power distribution network system are selected. The effect of node voltage control in power distribution network is compared and analyzed.

4.1 Example 1 (Radial Connection Mode)

When the contact switch of the system is unlocked, the system is in radial connection mode. Four distributed resources are connected to the system, which are located at nodes 23, 31, 31 and 31 respectively. The three distributed resources connected to node 31 constitute a distributed resource cluster, and the dominant node is 31. The distributed resources connected to node 23 constitute the distributed resource cluster, and the dominant node is 23.

In this example, Fig. 4 shows the node voltage distribution after iteration when the system is at rated load in the radiant wiring mode. Figure 5 shows the node voltage distribution after iteration when the system is at low load (10% load rate) in the radiant wiring mode.

According to the voltage distribution under different conditions, when the system load is high and voltage control is not carried out, the lower limit of node voltage at the end of the line is prone to occur. For example, the voltage deviation of node 17 at the end of the power distribution network in Fig. 4 reaches 0.05924 (p.u.). At the same time, there are several nodes with voltage deviations ranging from 0.03 to 0.06 (p.u.), which have exceeded the lower limit of node voltage for normal operation of the power distribution network system. When the output of the distributed power supply in the system is large and voltage control is not carried out, the power distribution network will generate reverse power flow to make the node voltage exceed the upper limit. For example, the voltage deviation of node 31 in Fig. 5 reaches 0.04873 (p.u.). At the same

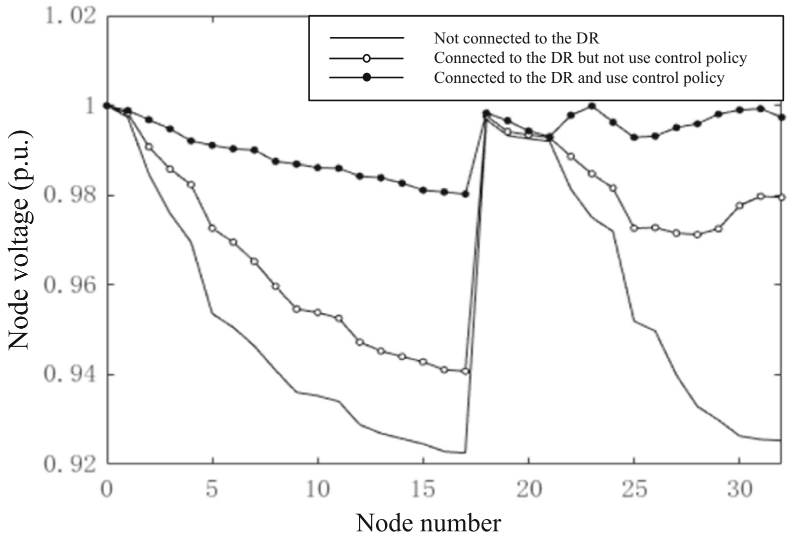

Fig. 4. The voltage distribution of the system nodes in radial wiring mode during rated load

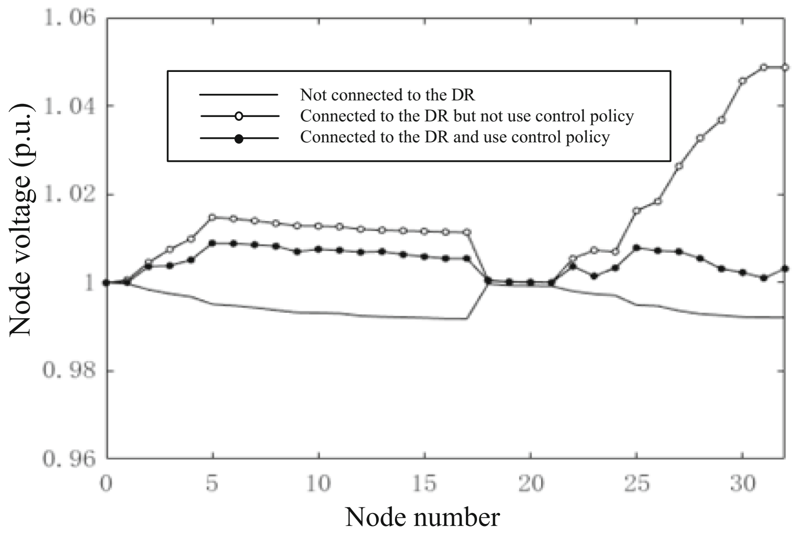

Fig. 5. The voltage distribution of the system nodes in radial wiring mode during low load

time, there are several nodes with voltage deviation in the range of 0.02–0.05 (p.u.), which has exceeded the upper limit of node voltage for normal operation of the power distribution network system.

As can be seen from Fig. 4 and Fig. 5, after accessing the distributed resource and controlling it, the voltage of leading nodes 23 and 31 converge to the rated value. The voltage offset of each node in the system is significantly reduced, and the voltage of all nodes is finally in the range of 0.98–1.02 (p.u.). Simulation results show that the proposed voltage control strategy can achieve good control of node voltage under different load conditions in power distribution network.

4.2 Example 2 (Loop Mesh Wiring Mode)

When the contact switch of the system is unlocked, the system is in ring mesh connection mode. Four distributed resources are connected to the system, which are located at nodes 29, 29, 31 and 31 respectively. The four distributed resources connected to nodes 29 and 31 constitute a distributed resource cluster, and the dominant node is 30.

In this example, Fig. 6 shows the node voltage distribution after iteration when the system is under the rated load of the loop mesh wiring mode. Figure 7 shows the node voltage distribution after iteration when the system is under the low load (10% load rate) of the loop mesh wiring mode.

Similar to the node voltage distribution in the radiant wiring mode of the system in example 1, when the system is in the ring-mesh wiring mode without voltage control, the voltage deviation of some nodes reaches 0.02–0.04 (p.u.).

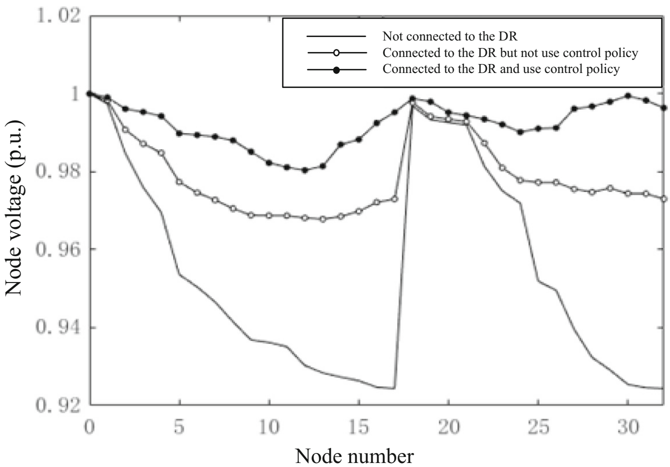

Fig. 6. The voltage distribution of the nodes in the system loop mesh wiring mode during rated load

As can be seen from Fig. 6 and Fig. 7, after the distributed resource is connected and controlled, the node voltages of the system under different loads in the ring-mesh wiring mode are finally within the normal range of the power distribution network system.

The comprehensive analysis of example 1 and example 2 shows that the voltage control strategy proposed in this paper can achieve good control of node voltage under different wiring modes of the power distribution network.

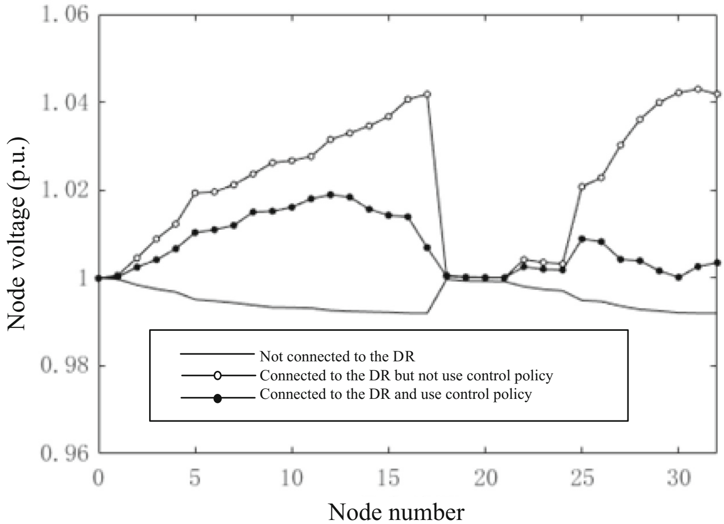

Fig. 7. The voltage distribution of the nodes in the system loop mesh wiring mode during low load

5 Conclusion

In this paper, distributed control mode is adopted to realize voltage control of power distribution network with high proportion of distributed resource access based on distributed resource cluster. By calculating the capacity utilization ratio between the leading node and the distributed resource, the quantitative relationship between the node voltage and the output of the distributed resource is established. Simulation results show that the proposed control strategy can achieve good global voltage distribution under different load conditions and different wiring modes.

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