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Hierarchical Coordinated Control Strategy for Active Power in Distribution Networks with Scaled Distributed Generation Access

Journal of Electrical Systems

Abstract: **-** Promoting scaled distributed wind turbines and photovoltaic, and other distributed generations access to the distribution network is an important measure for realize the goal of carbon peaking and carbon neutrality and to build new-type power systems. However, as the installed capacity of wind turbine, photovoltaic and other intermittent renewable energy sources climbs dramatically, the security and consumption problems of the distribution network are becoming increasingly prominent, and there is an urgent requirement to improve the active power control capability of distributed generation. To optimize the operation stability and consumption economy of the distribution network, a hierarchical coordinated control strategy for active power of scaled distributed generation is proposed based on the principle of unified control and hierarchical management, including peaking control, frequency control, mesh control and market trading control, to coordinate and optimize the system operation safety and consumption economy. The proposed strategy optimizes active power control instructions in the layer of distribution network layer, mesh layer, and functional area layer, thus fully expanding the depth and breadth of the consumption for distributed generation. The effectiveness of the proposed strategy is proved by the actual operation of Liaoning power grid.

Keywords: Scaled distributed generation; hierarchical coordinated control; peaking control; frequency control; electricity markets

1. Introduction

In order to build the new-type power system adapted to the high penetration of new energy, and to promote the low-carbon transformation of the energy consumption, the new operation mode oriented by scaled distributed photovoltaic and distributed wind turbine access to distribution network has emerged [1-2]. Distributed generation provides an important role for realizing sustainable energy development and constructing reliable and sustainable new-type power system, by virtue of its advantages of improving energy utilization efficiency, reducing energy transmission loss, and lowering environment pollution, etc., and has become a new trend of energy substitution and development for all countries in the world [3-4]. According to official statistics, the cumulative installed capacity of global distributed generation is about 758.92GW as of 2022, and the new installed capacity is 100.2GW. From the perspective of investment and construction, the global distributed generation investment in 2022 has grown significantly, and the global distributed generation investment is about US$100.9 billion as of 2022. It is worth noting that the Asia-Pacific region, represented by China, is currently the world's largest distributed generation investment market [5-6].

However, the problem of distributed power access to the distribution network is becoming more serious and complex [7-8]. Due to the distributed generation output has obvious uncertainty, especially in the case of high proportion of distributed generation access to the grid, the power generation process of wind turbines, photovoltaic and other distributed generation is greatly affected by weather factors, and its scaled access to the distribution network is often with power transmission bottlenecks encountered in the channel transmission and power curtailment during the low load periods, resulting the dispatch and control of active power by traditional thermal power units is difficult to satisfy the development demand of distributed generation [9-10].

Currently, research on active power control strategy and technology for distributed generation access to the power system has made some progress and has been widely applied in power system dispatch problems. A sequential optimization strategy was proposed in literature [11] for optimally allocating active and reactive power among dispatchable distributed power units in an islanded microgrid. Considering the uncertainty of distributed renewable energy generation, load and tariff, a multi-agent deep reinforcement learning based strategic objective algorithm for real-time optimal dispatch of active distribution systems was proposed in literature [12]. In Literature [13], a synchronous active proportional resonant-based control technique for interfaced converters was proposed to enhance the operational stability of the power grid under high penetration of distributed generation sources. In Literature [14], a control method for active power of distributed generation

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sources in an islanded microgrid was proposed to simultaneously enable active power sharing and frequency restoration in an islanded microgrid. In Literature [15], a comprehensive model predictive control model is developed for loop power flow controller-based active distribution networks in order to timely respond to the operational state and output changes of distributed generation sources under security constraints of multiple operation periods. However, all of the above literature simplifies the distribution network topology and fails to squarely address the complexity of electricity production and consumption among the distribution network meshes.

In general, scholars at home and abroad have proposed diversified optimization methods for different requirements for active power control of distributed generation. However, with the rapid development of distributed generation, the active power control of scaled distributed generation has put forward new challenges. First, how to control the scaled distributed generation clustering to actively respond to the frequency and peaking regulation demand of power system. Second, how to ensure the legal rights and interests of distributed generation in the process of participating in electricity market trading. Third, how to improve the distributed generation operation economy while considering the consumption fairness of wind power and photovoltaic power. To this end, for the new characteristics of large-scale distributed generation access to the distribution network, this paper proposes a hierarchical coordination control strategy for active power of the distribution network with scaled distributed generation access, optimizing the control instructions for the active power of distributed generation by layer, and realizing the operation security and consumption economic of distribution network. The main contributions are as follows:

1) A hierarchical coordinated control framework of the distribution network with scaled distributed generation access is proposed, which can optimize the active control instructions layer by layer according to the order of distribution network layer, mesh layer, and functional area layer to expand the depth and breadth of renewable energy consumption.

2) A hierarchical coordinated control strategy for active power of scaled distributed generation is proposed to optimize the operation safety, consumption economy and control fairness of distribution network.

3)The actual operation situation of Liaoning power grid proves the effectiveness of the hierarchical coordinated control strategy proposed in the paper.

2. Materials and Methodology

2.1 Active power hierarchical coordinated control framework for distributed generation

This paper proposes a hierarchical coordinated control strategy for active power of distribution network with scaled distributed generation access. Specifically, the active power control instructions are optimized by layer according to the order of the distribution network layer, the mesh layer, and the functional area layer to realize the reasonable transfer of the remaining power generation indexes within the distribution network. The active power hierarchical coordinated control framework of the distribution network with scaled distributed generation access is shown in Figure 1.

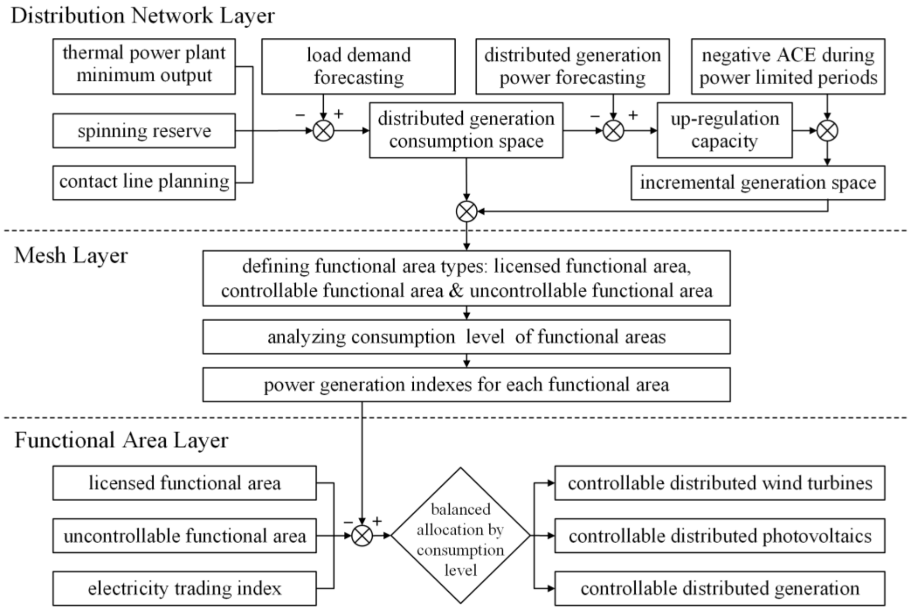

Figure 1 hierarchical coordinated control framework for active power in distribution network with scaled distributed generation access

1) Distribution Network Layer

At the distribution network layer, the distribution network has a peaking control module and a frequency control module. The peaking control module monitors the whole network load demand, contact line power, system standby power and other data that characterize the operation status of the distribution network in real time under the premise of guaranteeing the security constraints of the distribution network and the power balance constraints, it calculates the maximum acceptance capacity of the distributed generation in the control area, and allocates the power generation indexes of distributed generation to each mesh layer in accordance with the principle of power limitation level equalization. The frequency control module monitors the area control error (ACE) in real time, and when the ACE is negative, it adjusts the mesh with excellent frequency control performance to increase power generation, thus increasing the consumption space of distributed generation, and when the ACE is positive, it reduces the output of conventional units in the distribution network.

2) Mesh Layer

At the mesh layer, in order to further promote the full consumption and utilization of distributed generation power, the multi-functional areas under the mesh are divided into three categories according to their different regulating capabilities: licensed functional areas, controllable functional areas and uncontrollable functional areas. With the assistance of the mesh control module, the distributed generation output indexes of each mesh are automatically assigned to the respective functional areas according to the sequence of licensed functional areas, controllable functional areas and uncontrollable functional areas. In order to avoid the power generation indexes being wasted due to insufficient generation capacity of functional areas, the remaining power generation indexes of functional areas with insufficient upwardly adjusted generation capacity are allocated twice to functional areas with sufficient generation capacity, thus realizing the reasonable transfer of the remaining power generation indexes between multi-functional areas and maximizing the utilization rate of distributed generation power.

3) Functional Area Layer

At the functional area layer, for functional areas participating in electricity market trading, the market trading module will prioritize the allocation of power trading indexes for distributed generation, and guarantee the priority completion of power trading for distributed generation. For the functional areas with distributed photovoltaic and wind turbine synergies under the same mesh, considering the differences in power output characteristics between distributed photovoltaic and wind turbine, the allocation according to the installed ratio will result in the lack of fairness in consumption, therefore, the distributed generation coordination module is used to formulate the generation allocation weight coefficients of distributed photovoltaic and wind turbine according to the principle of power limitation level equalization to guarantee the fairness of consumption between distributed photovoltaic and wind turbine under the same mesh.

2.2 Active power hierarchical coordinated control strategies for distribution network layer

Distribution network layer mainly considers peak regulation control constraints and frequency regulation control constraints. The distribution network will set the basic power generation index, i.e. the maximum output value of each mesh subject to transmission capacity constraints, and its basic principle is to ensure that the power limitation rate of each mesh is as consistent as possible under the premise of maximizing the consumption space of system peaking. In addition, the distribution network also further considers the distributed generation consumption space increased by the system frequency regulation demand, sets the incremental generation index and prioritizes the allocation to the meshes with higher flexibility regulating capability.

1) Basic power generation index setting

In order to maximize the consumption of distributed generation output, and fully make up for the consumption space of the distribution network peaking, the active power control system calculates the maximum accepted power of distributed generation in real time, i.e., the power generation index of distributed generation in each mesh.

$$P_{dis} = P_{load} - P_{line} - P_{tra} - P_{spin} \tag{1}$$

where P_{dis} is the power generation index of scaled distributed generation, P_{load} is the short-term load forecast, P_{line} is the planned power of the contact line, P_{tra} is the minimum output of traditional thermal power and P_{spin} is the spinning reserve.

In the allocation process of power generation indices of meshes, we set reasonable active power allocation weight coefficient β for each mesh by considering the mesh power limitation level and the installed capacity, in order to guarantee the fairness of distributed generation consumption among meshes. The objective function of β is the minimum value of the variance of the annual power limitation rate of each mesh, which is expressed as

$$\min\left\{\delta\left(\frac{\int_{P_{dis,i}}^{C_i}\left(P_i-P_{dis,i}\right)F\left(P_i\right)\mathrm{d}P_i}{\int_0^{C_i}P_i\cdot F\left(P_i\right)\mathrm{d}P_i}\right)\right\} \tag{2}$$

where δ is the variance of the annual power limitation rate of each mesh, P_i is the power demand of mesh i, $P_{dis,i}$ is the power ;generation index of distributed generations of mesh i, and $F(\cdot)$ is the power probability density function of meshes, which is obtained from the historical statistics of generation capacity of meshes.

The relationship between the active power allocation weight coefficients of each mesh and its power generation index of distributed generation is shown as follows

$$P_{dis,i}=\frac{\beta_i C_i P_{dis}}{\sum \beta_i C_i} \tag{3}$$

where C_i is the total installed capacity of mesh i, β_i is active power allocation weight coefficient of mesh i. Therefore, according to the current power limitation and future load forecast, the active power allocation weight coefficients of each mesh can be dynamically allocated on a daily basis, and the power generation index of distributed generations in each mesh can be calculated in accordance with Eq. (3).

From the perspective of mesh layer, when the allocated power generation index $P_{dis,i}$ of distributed generation in mesh i is larger than the maximum distributed generation consumption capacity C_i of mesh i cross-section, modify its power index to C_i, and the remaining power generation index, i.e., $\Delta P_{dis,i}=P_{dis,i}-C_i$, will be reallocated to other meshes. Iterate the above steps until power generation indexes of all meshes are less than the maximum consumption capacity of distributed generation in the corresponding mesh cross-section. For meshes without cross section constraints, their maximum consumption capacity of distributed generation can be set to the installed capacity.

2) Incremental power generation target setting

Due to the distributed photovoltaic as well as distributed wind turbines are not matched to the change rate of power output with conventional thermal generation units, the rapid change of renewable energy power output will lead to dramatic fluctuations in ACE. In this case, the conventional thermal generation unit should be regulated in the opposite direction to the power generation of distributed generation, which is not conducive to the consumption of power generation of distributed generation, and will lead to unnecessary regulation of thermal power units.

Therefore, on the basis of peaking control of distribution network, the active power control system of the distribution network monitors the ACE situation in the control area in real time. When ACE is negative, it will prioritize to increase the power output of distributed generation, and the distribution network will allocate the frequency regulation command according to the comprehensive performance index calculated by mesh response time, regulation rate, and regulation accuracy. When ACE is positive, it will prioritize to reduce the output of conventional units, thus increasing the output of distributed generation while reducing the carbon emission of traditional thermal power units.

2.3 Active power hierarchical coordinated control strategies for mesh layer

Within the single mesh, each functional area initially allocates the basic power generation index of the mesh located according to the proportion of installed capacity. However, during real-time operation of the distribution network, the output fluctuation of distributed photovoltaic and distributed wind turbine will make some functional areas unable to fulfill the basic power generation index. In order to avoid the waste of distributed generation output, it is necessary to re-allocate the power generation indexes among the functional areas that currently have the ability to up-regulate.

According to the evaluation of the types and regulation capacity of functional areas, when the current output of the uncontrollable functional area is lower than the basic power generation index, the remaining power generation index will be prioritized, the licensed functional area will be prioritized to obtain its basic power generation index. While, when the current output of the uncontrollable functional area is higher than the basic power generation index, the licensed functional area will be prioritized to obtain the remaining power generation index, and the remaining margin will be allocated to the controllable functional area according to the proportion of installed capacity. Although the controllable functional areas have lower priority, they can be allocated index margins when they have the ability to up-regulate, and it is rather easier to realize high power generation in long-term regulation.

If there are functional areas under the mesh to participate in electricity market trading, the market trading module will prioritize executing the allocation of electricity trading indexes and guaranteeing the priority completion of electricity trading at all levels of distributed generation. The specific modeling and control strategies for each type of functional area are as follows:

1) Licensed functional area

Due to the highest priority of power generation in the licensed functional area, the trial method is required to up-regulate the active power instruction when allocating power generation indexes to the licensed functional area. If the actual power of the licensed functional area is p_A^t at the t-th instruction period, then the active power instruction at the $t+1$-th instruction period is expressed as:

$$p_A^{t+1} = p_A^t + \lambda I \tag{4}$$

where λ is the regulation step, I is the installed capacity of distributed generation in the functional area.

2) Uncontrollable functional area

For functional areas in which there are wind farms operating squirrel-cage asynchronous wind turbines and some newly built distributed photovoltaic clusters in the grid-connected commissioning stage, such functional areas are defined as uncontrollable functional areas due to the fact that they have no continuous active power regulation capability. Therefore, the basic power generation index p_0 is issued for the uncontrollable functional area, and the uncontrollable functional area is not allowed to over-generate. In order to avoid the waste of the active power fixed instruction of the uncontrollable functional area, the virtual active power instruction at the $t+1$-th instruction period is set according to the actual power p_B^t at the t-th instruction period, which is given by

$$p_B^{t+1} = \min\left(p_B^t + \lambda I, p_0\right) \tag{5}$$

where p_B^{t+1} is the virtual active power instruction at the $t+1$-th instruction period, p_B^t is the actual power at the t-th instruction period.

3) Controllable functional area

As mentioned above, controllable functional areas within the same mesh are then allocated the remaining power generation indexes in proportion to their installed capacity, which is given by

$$p_{C,i,j} = \frac{C_{i,j}}{\sum_{j \in S_C} C_{i,j}} \left(p_i - p_{i,s} - \sum_{k \in S_A \cup S_B} p_{i,k} \right) \tag{6}$$

where $p_{C,i,j}$ is the active power generation instruction of the uncontrollable functional area j in mesh i, p_i is the overall power generation index of mesh i, $p_{i,s}$ is the cross-section safety margin of mesh i, S_A, S_B, and S_C are the licensed functional area, uncontrollable functional area, and the set of controllable functional areas, respectively.

To summarize, when the active power instruction $p_{i,j}$ assigned to a functional area is greater than the functional area's up-regulation capacity $p_{i,j}^* = p_t + \lambda I$, its active power instruction is corrected to be $p_{i,j}^*$, and the remaining active power instruction $\Delta p_{i,j} = p_{i,j} - p_{i,j}^*$ of the functional area is reallocated to the other functional areas under the same mesh. Iterate the above procedure until the active power instructions of all functional areas are less than the up-regulation capability of the functional area.

4) Active power control strategies for market trading

The active power control strategies for distributed generation in the distribution network to participate in electricity market trading are as follows:

Step 1: Based on the total amount of electricity traded on the distribution network and the total hours of the load valley period in the current month, calculate the baseline trading power on the distribution network for the next month and allocate the baseline trading power L_k for each mesh in proportion to the installed capacity, which is given by

$$L_k = \frac{D_L C_k}{T_L \sum_{k \in S_L} C_k} \tag{7}$$

where D_L is the total amount of electricity traded in the distribution network, T_L is the total number of hours of load valley periods, S_L is the set of functional areas participating in electricity market trading, C_k is the installed capacity of distributed generation in the functional area.

Step 2: With the consideration of the baseline traded power under the mesh cross-sections, the active power instructions for each functional area under the mesh are assigned and corrected on the basis of Eq. (6), which in turn yields the baseline active power instructions for each functional area.

$$p_{C,i,j} = \frac{C_{i,j}}{\sum_{j \in S_C} C_{i,j}} \left(p_i - \sum_{k \in S_L} L_k - p_{i,s} - \sum_{k \in S_A \cup S_B} p_{i,k} \right) \tag{8}$$

Therefore, the active power instruction of the functional area with distributed generation without participating in electricity market trading is the baseline active power instruction $p_{C,i,j}$, while the active power instruction of the functional area with distributed generation participating in electricity market trading is obtained by multiplying the baseline active power instruction $p_{C,i,j}$ and the baseline traded electricity L_k.

2.4 Active power hierarchical coordinated control strategies for functional layer

In order to ensure the power consumption fairness of distributed wind turbines and distributed photovoltaics, we assigned reasonable weight coefficients ε to distributed wind turbines and photovoltaics and incorporated them into Eq. (6), i.e., the calculation process of active power instruction allocation for functional areas. The objective function is to minimize the difference between the annual power limitation rate of distributed wind turbine cluster and distributed photovoltaic cluster, and thus guarantee the fairness of distributed generation consumption under the same mesh, which is expressed as follows:

$$\min\left|\rho_{wind}-\rho_{pv}\right|^2 \tag{9}$$

where Eq. (9) denotes the power limiting rate of distributed wind turbine clusters and distributed photovoltaic clusters as equal as possible, ρ_{wind} and ρ_{pv} represent the power limiting rate of distributed wind turbines and distributed photovoltaic cluster, respectively, which is given by

$$\begin{aligned}\rho_{wind}=\Bigg[&\iint_{p_{pv}\le P_{pv}}\left(p_{wind}+p_{pv}-p_s\right)f\left(p_{wind},p_{pv}\right)\mathrm{d}p_{wind}\mathrm{d}p_{pv}\\&+\iint_{p_{pv}>P_{pv}}\left(p_{wind}-P_{wind}\right)f\left(p_{wind},p_{pv}\right)\mathrm{d}p_{wind}\mathrm{d}p_{pv}\Bigg]\\&/\iint p_{wind}f\left(p_{wind},p_{pv}\right)\mathrm{d}p_{wind}\mathrm{d}p_{pv}\end{aligned} \tag{10}$$

$$\begin{aligned}\rho_{pv}=\Bigg[&\iint_{p_{wind}\le P_{wind}}\left(p_{wind}+p_{pv}-p_s\right)f\left(p_{wind},p_{pv}\right)\mathrm{d}p_{wind}\mathrm{d}p_{pv}\\&+\iint_{p_{wind}>P_{wind}}\left(p_{pv}-P_{pv}\right)f\left(p_{wind},p_{pv}\right)\mathrm{d}p_{wind}\mathrm{d}p_{pv}\Bigg]\\&/\iint p_{pv}f\left(p_{wind},p_{pv}\right)\mathrm{d}p_{wind}\mathrm{d}p_{pv}\end{aligned} \tag{11}$$

where p_{wind} and p_{pv} are the output power of distributed wind turbine and distributed photovoltaic respectively, $f\left(p_{wind},p_{pv}\right)$ is the joint probability density function of distributed generation, P_{wind} and P_{pv} are the active power instruction limits of distributed wind turbine and distributed photovoltaic respectively, which is given by

$$P_{wind}=\frac{b_{wind}C_{wind}p_s}{b_{wind}C_{wind}+b_{pv}C_{pv}} \tag{12}$$

$$P_{pv}=\frac{b_{pv}C_{pv}p_s}{b_{wind}C_{wind}+b_{pv}C_{pv}} \tag{13}$$

where b_{wind} and b_{pv} are the active power control weight coefficient of distributed wind turbine clusters and distributed photovoltaic clusters respectively, C_{wind} and C_{pv} are the installed capacity of distributed wind turbine clusters and distributed photovoltaic clusters respectively.

2.5 Active power hierarchical coordinated control strategy calculation process

The calculation process of the active power hierarchical coordinated control strategy for scaled distributed generation is shown in Figure 2. The optimized allocation for generation indexes of distributed generation is realized according to the strategy of top-down level-by-level allocation and bottom-up level-by-level calibration. In the actual operation process, the flow condition of each mesh section is monitored in real time. When the section index is remaining, the remaining generation index is transferred to the upper section and allocated, while when the section flow crosses the limit, the section generation index is reduced and recalculated. In a command cycle, the deviation of the output and command of the scaled distributed wind turbine and distributed photovoltaic will be counted in the total of the next command allocation. The wind and light weighting coefficients are dynamically corrected and optimized every month according to the actual and forecasted consumption of wind and light for the year, in order to ensure the consistency of the limiting rate of wind and light resources.

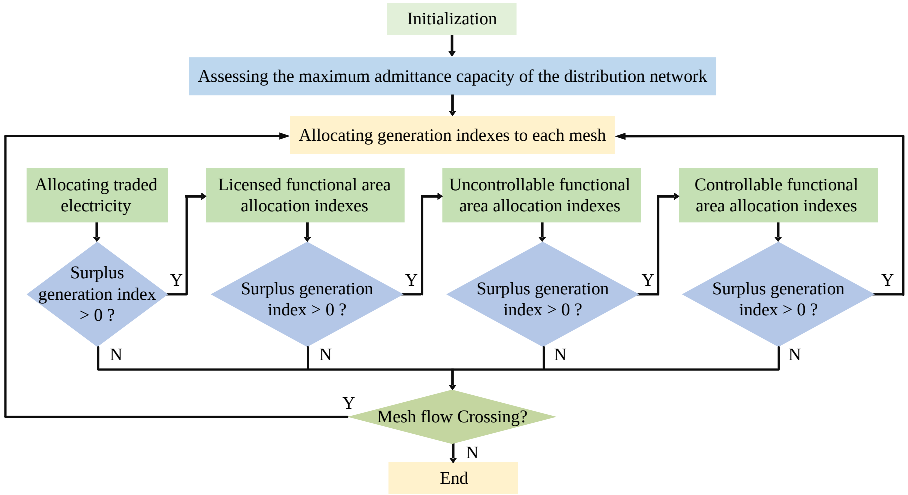

Figure 2 Active power hierarchical coordinated control strategy process

where D_L is the total amount of electricity traded in the distribution network, T_L is the total number of hours of load valley periods, S_L is the set of functional areas participating in electricity market trading, C_k is the installed capacity of distributed generation in the functional area.

3 Results and Discussion

The hierarchical coordinated control strategy proposed in this paper has been practically applied in the active power control system with distributed generation in Liaoning power grid. The research object of this paper is a municipality-level distribution network in Liaoning Province, China.

3.1 Active Power Control Effects on Distribution Network Layer

According to the actual situation of distributed generation access to the distribution network, the active power control system divides the distribution network into four meshes, three of which are subject to cross-section constraints. The generation index of the distribution network and the active power curves of the four meshes under typical day are shown in Figure 3. It can be seen that during the 0:00-5:00 and 12:00-17:00 periods, as the load of the distribution network continuously decreases, the distributed generation enters the peaking limitation period. In order to fully utilize the peak regulation space of the distribution network, the active power control system calculates the power generation indexes of distributed generation on a rolling basis and allocates it to four meshes according to the corresponding weighting coefficients.

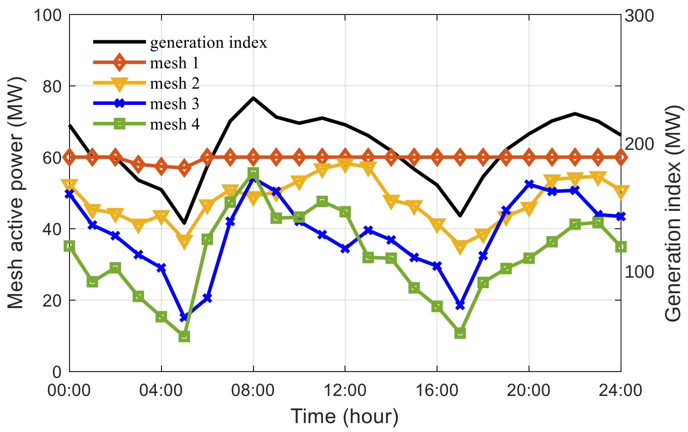

Figure 3 Active power hierarchical coordinated control framework of the distribution network with scaled distributed generation access

Specifically, at the 8:00 moment, the generation index of distribution network is 219 MW. According to the corresponding weighting coefficients, mesh 1 has the largest installed capacity, so its power generation index is allocated as 60MW, and the power generation index of mesh 2 distributed power source should be allocated as 58MW, but it is larger than the maximum capacity of the channel it belongs to, so its power generation index is corrected to 55MW. Meanwhile, mesh 3 is insufficient in the capability to regulate power upward because of resource reasons, so its power generation index is corrected to 49MW according to the actual power in the previous period. The specific allocation of distributed generation indexes for distributed generation at the 8:00 moment is shown in Table 1

Table 1 Generation index allocation for distributed generation in each mesh

Mesh	mesh 1	mesh 2	mesh 3	mesh 4
Installed Capacity/MW	174	120	100	94
Cross-section Limitation/MW	60	55	50	——
Weighting Coefficient	4.23	3.85	2.91	1
Power Allocated in Previous Period/MW	63	53	45	58
Initial Allocation of Generation Index/MW	60	58	50	55
Final Allocation of Generation Index/MW	60	55	49	55

3.2 Active Power Control Effects on Mesh Layer

To further verify the effectiveness of the strategy proposed in this paper, the comparison of the cumulative power limitation rate of each mesh is shown in Table 2. In original operation state, the active power control system only allocates the power generation indexes for distributed generation according to the installed capacity ratio, which results in a large deviation in the power limitation rate among the meshes due to the different cross-section constraints. Specifically, the power limitation rate of mesh 1 is as high as 16.6%, while that of mesh 4 is only 6.0%. After adopting the control strategy proposed in this paper, all meshes can obtain reasonable allocation weighing coefficients of active power, and the maximum deviation of power limitation rate is only 1.6%.

Table 2 Cumulative power limitation rate of each mesh

	original operation state	hierarchical coordinated control strategy
Mesh 1	16.6	9.6
Mesh 2	9.3	8.4
Mesh 3	7.2	8.2
Mesh 4	6.0	8.0

Due to the large uncertainty in the output of distributed generation such as distributed photovoltaic and distributed wind turbines, the error-free control of the weight coefficient allocation is difficult to achieve, and the deviation of power limitation rate will still exist. Considering the equalized consumption between distributed photovoltaics and wind turbines, the consumption results of distributed generation in each mesh are demonstrated in Table 3. It can be seen that with the accumulation of system operation data and the rolling optimization of weight coefficients, the maximum power limitation rate deviation between distributed photovoltaics and distributed wind turbines is 0.6%, and the minimum limitation rate deviation is only 0.1%.

Table 3 Consumption results of distributed generation in each mesh

	distributed photovoltaic	distributed wind turbines
Mesh 1	10.0	9.2
Mesh 2	8.5	8.3
Mesh 3	8.4	8.2
Mesh 4	9.3	8.7

3.3 Active Power Control Effects on Functional Area Layer

The analysis is carried out using mesh 2 as the typical representative, mesh 2 contains two residential areas, two commercial areas and one working area. The active power curve of distributed generation in each functional area of mesh 2 is shown in Figure 4.

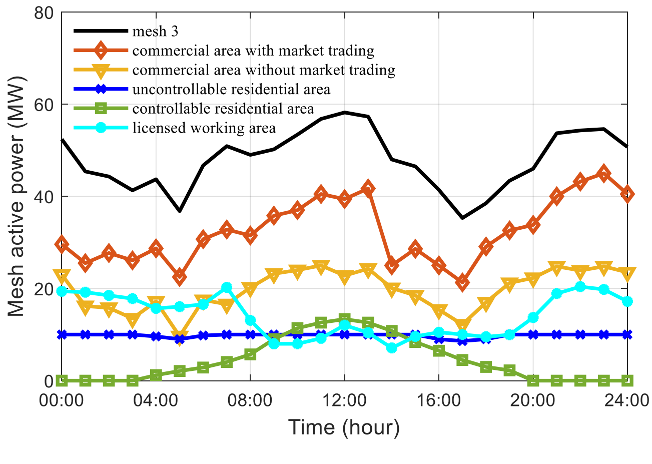

Figure 4 Active power curve of distributed generation in functional area

The two residential areas are equipped with distributed photovoltaics and distributed wind turbines respectively with 15MW installed capacity, which are further divided into controllable and uncontrollable residential area due to the different flexibility regulation performance, and we can see that the power generation of the uncontrollable residential area is rigorously constrained under the fixed power generation index, i.e., 10MW.
The working area is equipped with distributed turbines with the installed capacity of 20MW, which is defined as licensed functional area due to it involves the power administration function unit, and we can see that it still generates power freely even during the peaking and limiting period.
The commercial area is equipped with distributed wind turbines with the installed capacity of 25MW, which can participate in the electricity market trading on the basis of responding to the demand of the distribution network, and we can see that there exists a commercial area participating in electricity market trading, and consumption level of distributed generation is significantly higher in the commercial area participating in electricity market trading.
Therefore, the strategy proposed in this paper can realize the rational allocation of active power indexes to distributed generation in different functional areas under the same mesh, and the rights and interests of power generation in each functional area can be effectively guaranteed.

3.4 Active Power Control Effects on Power Consumption of Distributed Generation

The increased generation effect of distributed generation in the typical day is shown in Figure 5. In the original operation state, under the situation of retaining a certain security margin, distribution network allocates distributed power generation indexes according to the proportion of installed capacity, and sends out peaking instruction curves manually, with a limited number of instruction issuance times and a large regulation amplitude, which is not beneficial to the fully consumption for distributed generation.

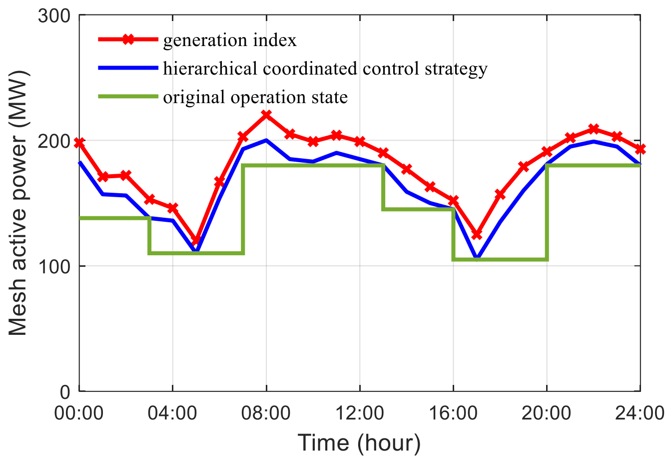

Figure 5 The increased generation effect of distributed generation in the typical day

In contrast, the strategy proposed in this paper can monitor the peak consumption space of the distribution network in real time, dynamically decompose the power generation index of distributed generation, realize the optimal allocation of active power instructions in the functional area, and improve the breadth and depth for power consumption of distributed generation, and the strategy proposed in this paper increases the amount of power consumption of distributed generation by 465MWh compared with the original strategy in the typical day. In addition, through the optimal transfer of power generation indexes among the functional areas under the mesh, the utilization rate of the mesh channel can be effectively improved while guaranteeing the safe and stable operation of the mesh, especially during the peak period of renewable energy output.

4 Conclusion

This paper proposes a hierarchical coordinated active power control strategy for distribution network access by scaled distributed generation, which realizes the hierarchical coordinated control of peaking, frequency regulation and market trading. The main conclusions are as follows:
1) The proposed strategy realizes the optimal allocation for power generation indexes of distributed generation in accordance with the principle of level-by-level allocation and level-by-level calibration, and fully expands the depth and breadth of consumption for distributed generation.
2) The rational allocation for active power weighting coefficients of distributed generation effectively guarantees the consumption fairness between meshes and functional areas.

3) The simulation verifies that the proposed strategy can dynamically assess the maximum consumption capability of distributed generation in the whole network according to the actual operation of the distribution network, which greatly reduces the power limitation rate of distributed generation.

With the continuous maturity of distributed power market-oriented trading, adapt to the active power control of distributed generation for cross-regional and multilateral trading will be a direction worthy of in-depth research.

Ethical Approval

No ethical approval was required as it did not involve the collection or analysis of data involving human or animal subjects.

Data Sharing Agreement

The datasets used and analyzed during the current study are available from the corresponding author on reasona ble request.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Funding

This article was supported by Science and Technology Project of State Grid Liaoning Electric Power Co., Ltd. "Research on Power Control Strategy of Distribution Network with Large-scale Distributed Generation Access" (2022YF-111).

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