electronics

MDPI

Article

A Novel Operation Regulation Method for Multi-Agent Distribution Network Considering Market Factors

Dongli Jia [1,*], Zhaoying Ren [1], Keyan Liu [1] and Xin Zhang [2]

[1] China Electric Power Research Institute Co., Ltd., Beijing 100192, China; renzhaoying@epri.sgcc.com.cn (Z.R.); liukeyan@epri.sgcc.com.cn (K.L.)
[2] School of Electrical and Information Engineering, Hunan University, Changsha 410000, China; zx01@hnu.edu.cn
* Correspondence: jiadl@epri.sgcc.com.cn

Abstract: In order to adapt to the development trend of large-scale access of distributed resource and power market reform, it has gradually become an industry consensus that multi-agent resources of a distribution network participate in regulation in the form of clusters. Based on the "centralized–distributed" regulation architecture, and relying on the regulation process of cluster partition, external characteristics calculation, command decomposition, and deaggregation, a cluster regulation strategy is proposed considering market factors. Firstly, the behavior characteristics of each agent are analyzed under the market trading mechanism. Then, the model of multi-agents participating in regulation in the form of a single point and a cluster is established. In the process of cluster partition, considering the active and reactive power–voltage coupling characteristics of the distribution network, a Monte Carlo random cluster partition sample generation method and screening mechanism are designed to deal with the problem of insufficient and inapplicable samples in the actual scene. At the same time, in order to reduce the difficulty of solving the cluster's external characteristics, a multi-agent output range simplification method is proposed for the process of "external characteristics calculation". Finally, the improved IEEE-33 bus system was taken as an example to verify the accuracy of the cluster regulation method when responding to the Automatic Generation Control (AGC) and Automatic Voltage Control (AVC) scheduling commands of the superior grid under market factors and different cluster partitions. The results show that the relative error of the command tracking of the proposed multi-agents in different cluster forms is less than 5.5%, which verifies the correctness of the proposed method.

Keywords: market factors; multi-agent; cluster segmentation; exogenous characteristic calculation; command decomposition; cluster regulation

check for updates

Academic Editor: Dorin Petreus

Received: 18 February 2025
Revised: 14 March 2025
Accepted: 22 March 2025
Published: 26 March 2025

Citation: Jia, D.; Ren, Z.; Liu, K.; Zhang, X. A Novel Operation Regulation Method for Multi-Agent Distribution Network Considering Market Factors. *Electronics* **2025**, *14*, 1306. https://doi.org/10.3390/electronics14071306

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

In the context of globalized energy transition, countries are actively promoting the development of power markets to achieve more efficient energy management and carbon emission reduction [1]. Especially driven by the goal of "low-carbon and environmental protection", multi-agent resource aggregation management has become a key trend in the development of global power systems [2]. Germany [3], the United States [4], Australia [5], and other countries have actively promoted the implementation of multi-agent resource aggregation management projects in distribution networks in terms of policy and engineering practice. The research and pilot application of these projects show that multi-agent resource aggregators not only participate in the operation and regulation of the power grid, but also

have become an important part of the centralized–distributed management of the power system, which plays an important role in enhancing the level of power system intelligence and energy management efficiency [6].

In terms of the power market trading mechanism, with the large-scale grid integration of new energy sources, how to aggregate flexible and adjustable resources dispersed in different nodes and effectively deaggregate these resource aggregators in grid scheduling has become a technical challenge to be solved [7]. Currently, the electricity market is experiencing a shift from the traditional model to a more flexible trading mechanism to accommodate the volatility and uncertainty of new energy sources. By designing a two-stage distributed robust optimization model, Ref. [8] proposed a cooperative scheduling mechanism of resource aggregator based on the guidance of time-of-use electricity price, and realized the adaptive aggregation of flexible resources in wind power (WP)/photovoltaic (PV) fluctuation scenarios. Ref. [9] discusses the importance of building a new type of power system with high quality and accelerating the development of low-carbon multi-agent resources, and suggests that power trading centers and grid scheduling departments should strengthen the design of the mechanism for new types of main players to participate in the market, and strengthen the portrayal and modeling of the cost structure of new types of low-carbon multi-agent resources in the scheduling system, including solar–thermal, flexible loads, and new types of energy storage (ES). Ref. [10] provides a review of optimal dispatch technology and market mechanism design for virtual power plants (VPPs). This literature analyzes the key technologies for VPPs to participate in the optimal scheduling of system operation from three perspectives: integrated energy, electric vehicles (EVs), and renewable energy, and describes the market strategies of VPPs in market environments based on game theory and other methods. Although the literatures provides a certain theoretical foundation and practical guidance for flexibility resource aggregation and management in the electricity market, further in-depth research is needed on the design of the market mechanism and scheduling strategy of VPPs.

The optimal regulation of clusters is built on the basis of the overall modeling of their adjustable space, and scholars have studied and discussed the feasible domain carving and external characteristic analysis of clusters. Ref. [11] proposed a mixed-integer convex optimization framework for feasible region partition, which effectively characterized the external characteristic curve of VPPs by fusing the physical constraints of a distributed PV, ES, and flexible load. Ref. [12] also used the feasible domain projection theory and applied it to the calculation of the security domain of the contact line and the cooperative operation of the distribution network. Ref. [13] proposes a flexible aggregation method of VPP with an aggregated equivalence algorithm and convex cell edge detection method for portraying the feasible domain of distributed ES. Ref. [14] proposes an approximate solution method for the feasible domain based on the Minkowski sum. Ref. [15] proposes a VPP scheduling boundary probability distribution inscribing method by taking the output uncertainty of distributed new energy into consideration. On the other hand, Ref. [16] solves the feasible domain of the VPP considering the multi-agent resource output uncertainty by the vertex enumeration method. Ref. [17] use robust constraints to characterize the set of resource outputs inside the VPP. Ref. [18] establishes a feasible domain solution model of the VPP, and realizes the low-complexity computation of feasible domains by decoupling the internal coupling constraint relaxation into a virtual queueing stability problem through Lyapunov optimization on the premise of considering the uncertainty of multi-agent resource outputs. Although the literatures has proposed various methods to characterize and calculate the feasible domains and capacity curves of VPPs, most of these studies have not adequately considered the output boundaries of each multi-agent

resource, and there is a need for further research in analyzing and calculating the output boundaries of multi-agent resources.

In the field of aggregation model construction, Ref. [19] utilizes the equivalent generator model and the equivalent ES model for multi-agent aggregation to achieve asynchronous scheduling of distributed resources. Ref. [20] considers network segmentation and reconfiguration on its basis, and aggregated complementary resources that are electrically close to each other with the objective of minimizing voltage deviation and power fluctuation at the point of common coupling (PCC). However, there are still some limitations in the practical application of these studies. These studies are not deep enough for aggregate analysis of multi-agents affected by market factors, and in the process of aggregation, the consideration of electrical characteristics is not complete (only considering the electrical distance under reactive power characteristics). The weak coupling characteristic of active and reactive power in a distribution network is not taken into account.

For distribution grids with a high proportion of distributed multi-agent resources, researching the resource aggregation model and proposing a cluster division method at the resource level can fully mobilize the multi-agent resources in distribution grids, optimize the management of the aggregators, alleviate the computational pressure of centralized management in the power dispatch department, and provide a more comprehensive solution for the intelligent and automated management of the power grid in the future.

Therefore, in this paper, the effective management and optimization of resources are realized by constructing an optimization model in which multi-agents participate in the regulation and control in the form of single points and clusters in the market environment. The method includes the whole process of cluster control, including cluster division, external characteristic calculation, command decomposition, and depolymerization calculation, and especially considers the active–reactive weak coupling characteristics of the distribution network.

The main contributions of this paper are as follows:

(1) It considers the active and reactive power–voltage coupling characteristics of a distribution network, proposes a cluster sample generation method, and standardizes the conditions that need to be met in the sample generation process, which solves the problems of insufficient cluster partition samples and generated samples that do not meet the conditions that may be encountered in the actual execution process.

(2) According to the analysis of distributed multi-agent resources and the influence of market factors, the timing output characteristics of PV and WP are obtained in the market environment, and the cluster scheduling strategy in the market environment is further simulated to verify the applicability and flexibility of the proposed method.

(3) In the "external characteristics calculation" part of the regulation process in the form of clusters, a simplification method of a multi-agent resource contribution range model is proposed, which effectively reduces the difficulty of solving external characteristics in the process of cluster regulation under the premise of ensuring a certain accuracy.

This paper is organized as follows:

In the section of transaction mechanism analysis, the transaction mechanism of power generation resources combined with ES resources to participate in the market is explored.

In the section on the participation of each agent in regulation in the form of a single point, the optimal dispatch model is constructed to realize the response of a single agent's resources to the grid regulation commands.

In the part of each agent participating in regulation in the form of a cluster, the cluster regulation strategy is proposed, including cluster division and command decomposition, in order to improve the efficiency and response speed of power grid regulation.

In the case analysis and validation section, the effectiveness of the cluster regulation method is verified by simulating the improved IEEE-33 bus system.

2. Transaction Mechanisms Analysis of Different Agent

2.1. Analysis of Multi-Agent Trading Mechanisms

Power generation resources combined with ES realize revenue by storing electricity at low prices and selling it at high prices. Storing power during peak generation periods for PV resources such as at midday and delivering power during peak load periods such as the evening can, to a certain extent, smooth out peak and valley differential fluctuations and improve the power quality and utilization of multi-agent resources. For each generation resource, in addition to its own dependence on the surrounding environment (e.g., light intensity, wind speed), it is also affected by the parameters (charging and discharging power, capacity, and efficiency) of its supporting ES.

The ES needs to fully consider the relationship between distributed generation resources and loads, and reasonably arrange the charging and discharging strategies so as to realize the benefits. After considering the distributed resources, they are equivalent to a unit for ease of description. The objective function of the distributed resource trading decision model is

$$\max C = \sum_{t=1}^{T} \left(P_t^{DER} + \varepsilon_t^{dis} P_{ess}\right) \cdot \Delta t \cdot p^{DER} \tag{1}$$

ES is coordinated with distributed generation resources, guided by time-of-use electricity prices, and reasonable arrangement of charge and discharge strategies for different periods of time. When the electricity price is low, ES stores the electricity generated by distributed resources. When the electricity price is high, the ES and distributed resources are discharged together to maximize the revenue from electricity sales.

The constraints are as follows:

Energy storage charge/discharge state constraints:

$$\varepsilon_t^{\mathrm{c}} + \varepsilon_t^{\mathrm{dis}} \leq 1 \tag{2}$$

Charge state constraints:

$$Q_t = Q_{t-1} + \varepsilon_t^{\mathrm{c}} P_{ess} \eta_{\mathrm{c}} \Delta t + \varepsilon_t^{\mathrm{dis}} P_{ess} / \eta_{\mathrm{dis}} \Delta t \tag{3}$$

Energy storage capacity constraints:

$$S_{\mathrm{SOCmin}} Q_{\min} \leq Q_t \leq S_{\mathrm{SOCmax}} Q_{\max} \tag{4}$$

Distributed generation resource consumption constraints:

$$P_t^{\mathrm{DER}} + \varepsilon_t^{\mathrm{c}} P_{ess} \leq P_t^{\mathrm{DER.pre}} \tag{5}$$

where $P_t^{\mathrm{DER.pre}}$ and P_t^{DER}, respectively, denote the predicted output and actual output of distributed generation resources; $\mathrm{P}^{\mathrm{DER}}$ denotes the distributed generation resource tariff; ε_t^c and $\varepsilon_t^{\mathrm{dis}}$ denote the charging and discharging states of the ES, and η_{c}, η_{dis} denote the charging and discharging efficiencies; P_{ess} denotes the charging and discharging power; $Q_{\max}$ and $Q_{\min}$ denote the maximum and minimum storage capacity, Q_t denotes the remaining power in the ES at time t; and S_{SOCmax} and S_{SOCmin} denote the maximum and minimum charge states of ES.

The optimization model can provide the charging and discharging strategy basis for ES, and can also assist ES to manage distributed generation resources, so as to realize the

effective regulation and utilization of multi-agent resources (note: the parameters of the ES and the electricity purchase and sale price for 24 h are shown in Appendix A).

2.2. Multi-Agent Adjustable Range Constraint Modeling

Multi-agents are usually scattered in the distribution network, as shown in Figure 1. On the one hand, some nodes in the distribution network may have multiple different agent resources, while at some nodes, there are no agent resources at all. On the other hand, each agent resource may be distributed in the 10 kV power grid or the 400 V power grid. Due to different voltage levels, their power levels and controllability may also be different.

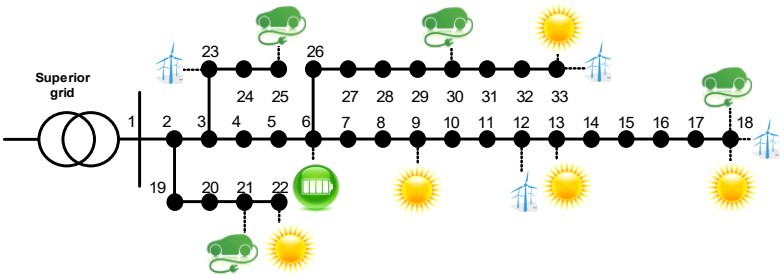


Figure 1. Schematic diagram of multi-agent distribution in distribution network.

In active distribution networks, all agents (e.g., distributed generators, flexible loads, and ES) are assumed to be equipped with power electronic interfaces, enabling continuous power regulation within their operational limits. For generation-oriented agents, the active power output can be steplessly adjusted from zero to their rated capacity. Load-oriented agents dynamically regulate their active power absorption between zero (no consumption) and the maximum negative value (full load absorption). ES agents bidirectionally control their active power within charging/discharging limits while adhering to state-of-charge (SOC) constraints. Their reactive power adjustable ranges are subject to the constraints of the actual active output value and its installed capacity, and it is stipulated that the power factor should be within a certain range. Then, the adjustable range constraints of each agent can be simplified as in Equation (6) and the output range constraints as shown in Figure 2.

$$\begin{cases} {p_l}^{\min} \le p_l \le {p_l}^{\max} \\ {p_l}^2 + {q_l}^2 \le {\delta_{l,N}}^2 \\ \cos\theta_l \le PF^{\max} \end{cases} \tag{6}$$

where l denotes the number of the distributed agent resource; p_l, q_l, and $\delta_{l,N}$ denote the agent resource l's active power output value, reactive power output value, and rated installed capacity, respectively; $p_l^{\max}$ and $p_l^{\min}$ denote the upper and lower limits of the active power output of the resource; $q_l^{\max}$ and $q_l^{\min}$ denote the upper and lower limits of the reactive power output of the resource (which will change with the actual active power output); θ_l denotes the phase angle of the distributed agent resource; and $PF^{\max}$ indicates the maximum power factor of the distributed agent resource. The lower limit of active power is zero for power-based agent resources and the upper limit of active power is zero for load-based agent resources.

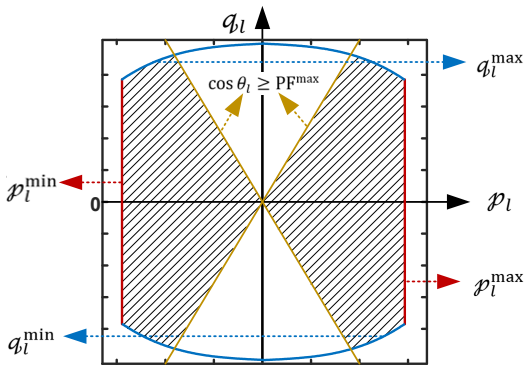


Figure 2. Multi-agent resource output range constraints.

3. Each Multi-Agent Resource Participates in Scheduling in the Form of a Single Point

In the active distribution network, the core of each agent participates in the grid regulation and control in the form of a single point is solve the optimal power flow problem [21]. Firstly, the active power and reactive power of all kinds of agent resources within the distribution network are defined as adjustable optimization variables; then, the objective function is set to minimize the absolute value between the transmission power of the upstream grid and the target power of the scheduling command. And in this process, it is necessary to ensure that the power output of each agent satisfies specific constraints and follows the generalized constraints of the system. Based on these conditions, this paper constructs the following optimal power flow model [22].

3.1. Objective Function

The objective function of the distribution network in response to active and reactive power commands from the higher grid is as follows:

$$\min J = \min\left\{\alpha\left|p_{pcc} - p^*\right| + \beta\left|q_{pcc} - q^*\right|\right\} \tag{7}$$

where p_{pcc} and q_{pcc} denote the active power and reactive power at the PCC point, respectively, where the subscript PCC denotes the PCC point, i.e., the transformer node connected to the upstream grid; p^* and q^* show the value of the active power command and the value of the reactive power command; α and β denote the weights of the tracking active power command and the tracking reactive power command, respectively, with the greater the weight indicating that the corresponding commands are more important. When $\alpha = \beta$, it means that the tracking active power command and tracking reactive power command are of equal importance.

3.2. Restrictive Condition

The constraints of the model refer to the generic constraints of the optimal power flow problem for radial distribution grids as well as the constraints to be satisfied by the distributed agent resources.

Power balance constraints:

$$\begin{cases} p_j = \sum\limits_{k\in\delta(j)} P_{jk} - \sum\limits_{i\in\pi(j)} \left(P_{ij} - {I_{ij}}^2 r_{ij}\right) + g_j {V_j}^2, \forall j \in \mathbf{B} \\ q_j = \sum\limits_{k\in\delta(j)} Q_{jk} - \sum\limits_{i\in\pi(j)} \left(Q_{ij} - {I_{ij}}^2 r_{ij}\right) + b_j {V_j}^2, \forall j \in \mathbf{B} \end{cases} \tag{8}$$

where subscripts i, j, and k denote different nodes in the distribution network; p_i and q_i denote the active and reactive power injected into the network from node i, respectively;

$\delta(i)$ and $\pi(i)$ denote the set of nodes downstream of node i and the set of nodes upstream of node i, respectively; P_{ij} and Q_{ij} denote the active and reactive power at the head end of branch ij (with the direction flowing from the head to the end); and **B** denotes the set of network nodes.

Ohm's law constraints:

$$V_j^2 = V_i^2 - 2\left(P_{ij}r_{ij} + Q_{ij}x_{ij}\right) + I_{ij}^2\left(r_{ij}^2 + x_{ij}^2\right), \forall ij \in \mathbf{E} \tag{9}$$

where V_i denotes the node voltage at node i, I_{ij} denotes the branch current on branch ij (in the direction from i to j), and both V_i and I_{ij} have upper and lower bounds; r_{ij}, x_{ij}, g_i, and b_i denote the resistance and reactance of branch ij, and the shunt conductance and conductance of node i, and **E** denotes the set of network branches.

Branch power constraints:

$$I_{ij}^2 = \frac{P_{ij}^2 + Q_{ij}^2}{V_i^2}, \forall ij \in \mathbf{E} \tag{10}$$

Branch current constraints:

$$I_{ij}^{\min} \le I_{ij} \le I_{ij}^{\max}, \forall ij \in \mathbf{E} \tag{11}$$

Node voltage constraints:

$$V_i^{\min} \le V_i \le V_i^{\max}, \forall i \in \mathbf{B} \tag{12}$$

Node injection power constraints:

$$\begin{cases} p_i \in R_i^p \\ q_i \in R_i^q \end{cases}, \forall i \in \mathbf{B} \tag{13}$$

where R_i^p and R_i^q denote the active power adjustable range and the reactive power adjustable range of node i.

In the specific scenario of an active distribution network, the constraints of Equation (13) can be further refined into the distributed agent resource output range constraints shown in Equation (14).

$$\begin{cases} p_l^{\min} \le p_l \le p_l^{\max} \\ p_l^2 + q_l^2 \le \delta_{l,N}^2 \\ \cos\theta_l \le PF^{\max} \\ p_i = \sum\limits_{l \in \rho(i)} p_l \\ q_i = \sum\limits_{l \in \rho(i)} q_l \end{cases} \tag{14}$$

where $\rho(i)$ denotes the set of distributed multi-agent resources in node i.

By solving the above optimal power flow problem, it is possible to determine the optimal allocation of active and reactive power of all distributed agent resources within the range of constraints. This process ensures that the output power of the distributed agent resources can respond accurately to the grid's regulatory commands, thus realizing efficient management of the grid.

However, while participating in grid regulation in a single-point form can fully utilize the potential of multi-agent resources in the network, the computational resource requirements of this approach are quite large and the computation process is time-consuming. This is highly challenging for real-time scheduling of large-scale active distribution networks

that require a fast response. In practice, this may lead to delays in scheduling decisions, which may affect the stability and reliability of the grid. Therefore, research on more efficient algorithms and optimization strategies to reduce the computational burden and shorten the response time is crucial to improve the performance of the real-time dispatch of active distribution grids.

4. Each Multi-Agent Resource Participates in Scheduling in the Form of Clustering

In order to effectively deal with the challenges of computational complexity and computation time faced by each agent participating in grid regulation in the form of a single point, this section proposes a centralized–distributed strategy, i.e., by combining the resources of each agent into clusters and participating in grid regulation in the form of clusters. Although this approach sacrifices the independent utilization of each resource to a certain extent, it can realize the decentralization of computational pressure by transforming a large number of dispersed resource regulation problems into regulation problems of several aggregates, which significantly reduces the computational burden at the grid level.

As shown in Figure 3, the strategy where each agent participates in regulation in the form of clusters involves four main steps: cluster division, cluster external characteristic calculation, decomposition of regulation commands, and deaggregation [23,24]. Firstly, on the distribution grid side, a reasonable way of dividing the clusters is determined based on the resource allocation of each agent in that distribution grid, and their power external characteristics are calculated for each cluster that is divided; and then, on the superior grid side, the superior grid management can issue a power command to the distribution grid, and the superior grid management department can decompose the power command according to the external characteristic data provided by the distribution network. After that, the results of the power command decomposition are sent to each distribution cluster, which is deaggregated within the cluster. Finally, the agent resources within each cluster regulate the power output in accordance with the results of the deaggregation, which in turn affects the power output of the whole distribution network to the higher-level grid. This process not only improves the computational efficiency, but also helps to realize faster decision response. By designing a reasonable clustering strategy, it can be ensured that the aggregation of multi-agent resources not only reduces the computational demand at the grid level, but also maintains the effectiveness of grid regulation in terms of power exchange between the distribution network and the higher-level power grid.

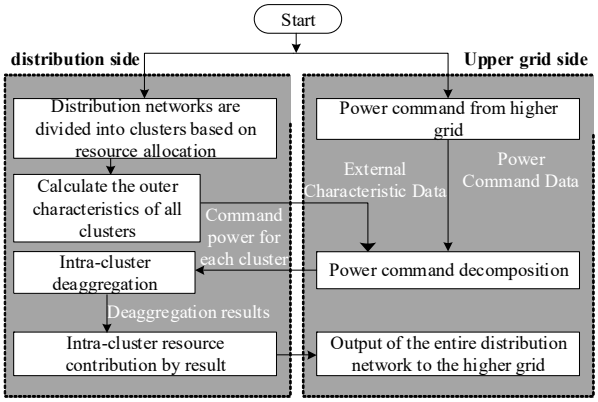


Figure 3. Flowchart of cluster regulation of distribution network.

4.1. Cluster Division

Cluster segmentation is the process of systematically organizing the nodes in an active distribution network into a number of cluster units with independent control capabilities.

Usually in this division mode, nodes within the same cluster are interconnected in the grid structure to form a tight network. Figure 4 illustrates a typical cluster division strategy, which divides the entire active distribution network into four parts, including three cluster units and a separate region that is not assigned to any cluster. Within the clusters, the distributed agent resources on each node will be managed in a unified manner, together exhibiting the overall out-of-power characteristics of the cluster. (Note: distributed flexibility resources are contained at each node in Figure 4.)

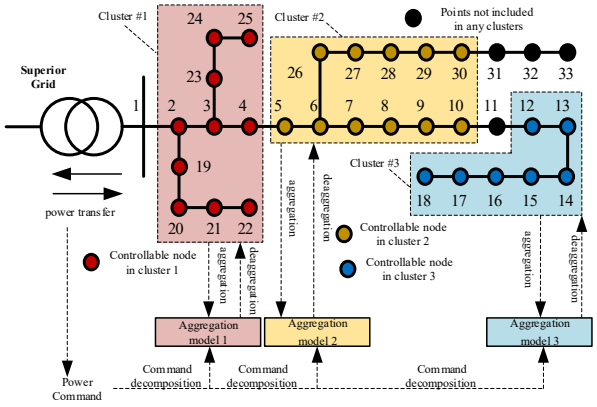


Figure 4. Distribution network cluster form regulation and control architecture diagram.

As the first step of the cluster regulation scheme, the rationality of cluster division is crucial to the whole regulation process. A well-designed cluster division scheme not only reduces the errors in the regulation process and improves the accuracy of command tracking, but also balances the distribution of resources within the cluster to ensure the effective use of resources. Such a balance helps to reduce the average computational complexity of each cluster, thus shortening the time of regulation operation and improving the efficiency and response speed of the whole grid regulation. In this way, the active distribution grid can respond to various grid regulation demands more flexibly and efficiently, and realize the optimal allocation of resources.

In order to obtain a suitable cluster division sample, this paper sets the following division bases: firstly, the nodes in the cluster need to remain interconnected; secondly, the number of adjustable resources in the cluster should be kept above two; and finally, the average electrical distance of the cluster should be controlled below a given threshold. However, the traditional electrical distance only focuses on the pair of coupling quantities of "voltage-reactive power" in the distribution network, but for the actual distribution network, due to the small difference between the reactance and resistance of the lines, the electrical connection cannot simply use the pair of coupling quantities of "voltage-reactive power" in the division of clusters. Based on this, this paper proposes a sensitivity matrix that integrates the active and reactive voltages to describe the electrical connection of each node within the cluster, and the expression is as follows:

$$d = \underset{m\in\varphi(n)}{mean}\left\{\underset{i,j\in\gamma(m)}{mean}\left\{dd_{ij}\right\}\right\} \tag{15}$$

where $\varphi(n)$ is the set containing all nodes, $\gamma(m)$ denotes the set of nodes in cluster m, and dd_{ij} denotes the logarithm of the ratio of the value of the change in its own voltage to the value of the change in the voltage of node i when node j undergoes a change in unit power, i.e.,

$$dd_{ij} = \lg\left(\frac{S_{jj}^{VQ}}{S_{ij}^{VQ}}\right) + \lg\left(\frac{S_{jj}^{VP}}{S_{ij}^{VP}}\right) \tag{16}$$

where S_{ij}^{VQ} and S_{ij}^{VP} denote the *ith* row and *jth* column of the voltage-reactive and voltage-active sensitivity matrices, respectively. Larger values indicate that node *j* is electrically farther away from node *i* and more loosely connected electrically, and thus, the division prefers a cluster division method with a small electrical distance index. When considering the interests of the aggregator and the power grid, an efficient cluster division strategy should ensure that the average electrical distance of nodes within the cluster is kept within a reasonable range, so as to avoid affecting the control effect of the aggregator due to too weak an electrical connection. Therefore, this study sets the threshold of electrical distance:

$$d \leq \lambda_{\max} \tag{17}$$

where $\lambda_{\max}$ is the upper bound value of d. The screening effect of different $\lambda_{\max}$ on the number of cluster samples will be analyzed in the subsequent simulation section.

According to the description above, the process for generating cluster division samples that meet the conditions is illustrated in Figure 5. First, starting from node 2, all nodes are sequentially assigned a cluster number to indicate which cluster they belong to (note: node 1 is connected to the upstream grid and does not belong to any cluster). It is assumed here that downstream nodes have a higher probability of being in the same cluster as their upstream nodes (this paper sets this operation probability to 80%), and a smaller probability of being in different clusters from their upstream nodes (this paper sets this operation probability to 20%). Then, it is evaluated whether this cluster division method satisfies the corresponding conditions, and if the conditions are met, this cluster division method is recorded. Finally, when the iteration time exceeds the preset threshold, the program determines that it has undergone a sufficient search and obtained effective cluster division samples that can approximate the full set to a certain extent, and these samples are output.

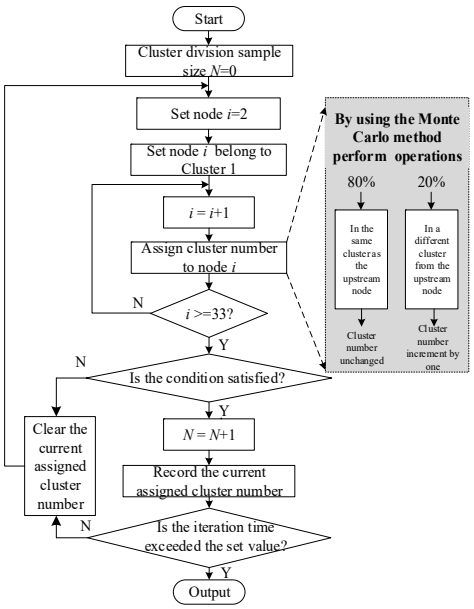


Figure 5. Generation method of cluster division samples.

4.2. Calculation of External Characteristics

The aggregation model of a cluster describes the out-of-power characteristics exhibited by the cluster at a specific bus connected to the upstream grid (i.e., the PCC point). The core of this model is to unify the range of controllable power for all resources within the cluster, which directly determines the bounds of the externally adjustable power of the aggregation model. The external characteristics of the cluster can be characterized by Equation (18), an

expression that accurately reflects the overall power regulation capability of the cluster in the grid.

$$\begin{cases} P_m^{\min} \le P_m \le P_m^{\max} \\ Q_m^{\min} \le Q_m \le Q_m^{\max} \\ \cos\theta_l \le PF^{\max}, \forall l \in \sigma(m) \end{cases} \tag{18}$$

where m denotes the cluster number; P_m and Q_m denote the active power and reactive power of cluster m, respectively, both of which have upper and lower bound constraints; and $\sigma(m)$ denotes the set of distributed resources in cluster m.

To reduce the computational complexity of the clusters' external characteristics, this paper simplifies the power output constraint models of agent resources based on Equation (18), and proposes a simplified methods through Equation (19). The simplification process for characterizing adjustable power ranges of agent resources is illustrated in Figure 6.

$$\begin{cases} {q_l}^{\max} = \sqrt{{\delta_{l,N}}^2 - {p_l}^{\max 2}} \\ {q_l}^{\min} = -\sqrt{{\delta_{l,N}}^2 - {p_l}^{\max 2}} \end{cases} \tag{19}$$

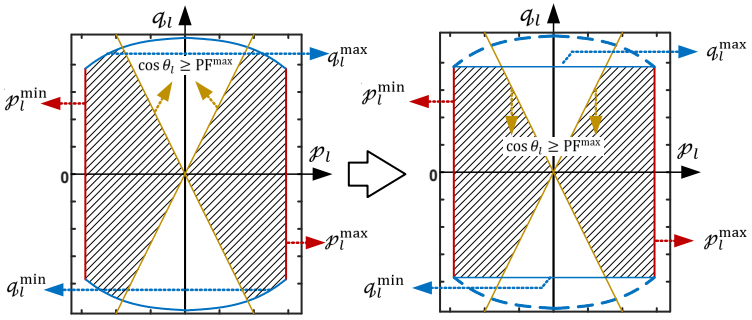


Figure 6. Constraint simplification process for agent resources.

This approximation process of external characteristic calculation can effectively simplify the management of complex resources within the cluster, enabling the cluster to participate as a whole in the rapid optimization and regulation of the power grid.

4.3. Command Decomposition and Deaggregate Calculations

The command decomposition process involves the detailed allocation of the overall control commands of the grid based on the out-of-power characteristics of each controllable cluster. This process aims to ensure that the entire distribution network can efficiently follow the overall dispatch commands while guaranteeing that each cluster can achieve its specific control objective, i.e., the target power assigned by the cluster must be within the range allowed by its extra-power characteristics. This paper allocates power commands to each cluster according to their adjustable power ranges, and the strategy is mathematically formulated in Equation (20).

$$\begin{cases} P_m^* = p^* \dfrac{P_m^{\max} - P_m^{\min}}{\sum_{m=1}^{M} (P_m^{\max} - P_m^{\min})} + P_m^{\min} \\ Q_m^* = q^* \dfrac{Q_m^{\max} - Q_m^{\min}}{\sum_{m=1}^{M} (Q_m^{\max} - Q_m^{\min})} + Q_m^{\min} \end{cases} \tag{20}$$

where P_m^* and Q_m^* denote the AGC active and AVC reactive commands of cluster m, respectively.

This simplification not only reduces the computational complexity, but also improves the efficiency of the deaggregation process, allowing the clusters to respond faster to the regulatory demands of the grid while maintaining the optimization of the overall grid stability and efficiency.

4.4. Evaluation of the Cluster Partition Samples

In order to analyze and evaluate whether the generated cluster partition sample results are reasonable, multiple random scheduling commands (which need to ensure that the scheduling commands are within the power adjustable range of the entire distribution network) are used to test the error of each cluster partition sample. If the average scheduling error of the cluster partition sample is not within a reasonable range, it means that there is a problem with this cluster partition sample, so it is necessary to exclude this cluster partition sample.

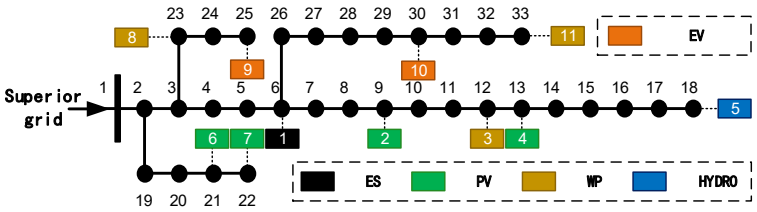
5. Simulation Analysis and Verification

5.1. Simulation Case Overview

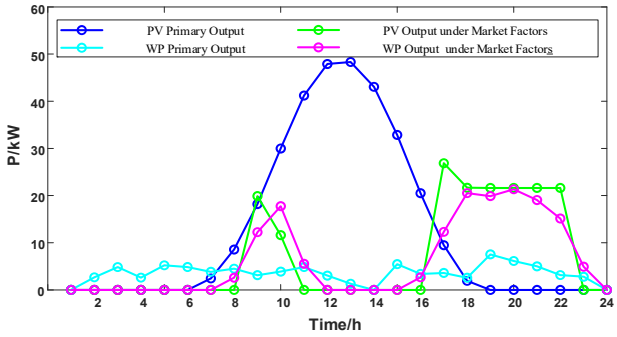
In order to verify the rationality of the multi-agent resources proposed in this paper to participate in grid scheduling by clustering, as well as the sample validity of the cluster division scheme, and the applicability of cluster participation in scheduling in a market environment, the improved IEEE-33 bus system with different distributed agent resources is utilized. The simulations in this study were implemented in MATLAB R2023b, with the Matpower 7.1 toolbox. In the model, 11 agent resources are deployed at some nodes. please refer to Table 1 for the detailed configuration, and the corresponding network topology can be seen in Figure 7a, and the total capacity of these resources occupies about 20% of the total system capacity (i.e., the regulation capacity accounts for about 20% of the total capacity). Except for the PV and wind resources, the output characteristic curves of each type of main resource are shown in Figure 7b (note: the curve data shown in the figure are based on actual measurements and are appropriately adjusted for the power level of the distribution network). From the transaction mechanisms mentioned in Section 2.2, the output characteristics of PV and WP in the market environment can be obtained as shown in Figure 7c. The total storage energy of the ES system is 1 MWh, and the initial storage energy is set to 0.5 MWh.

Table 1. Configuration of each agent resource in the IEEE-33 bus system.

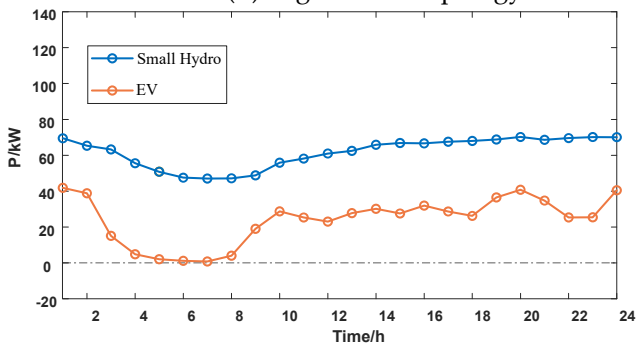
Agent ID	Participating Node	Resource Agent	Power Bound
1	6	ES	100 kVA
2	9	PV 1	150 kVA
3	12	WP 1	100 kVA
4	13	PV 2	150 kVA
5	18	Micro Hydro Resources	100 kVA
6	21	PV 3	150 kVA
7	22	PV 4	150 kVA
8	23	WP 2	100 kVA
9	25	EV 1	100 kVA
10	30	EV 2	100 kVA
11	33	WP 3	100 kVA



(**a**) Algorithmic topology



(**b**) Algorithmic topology



(**c**) PV and WP output under market factors

Figure 7. Algorithm topology and resource allocation.

5.2. Analysis of the Form of a Single Point

In order to evaluate the power tracking effect of each agent resource mentioned later in Section 5.3 when it participates in scheduling in a clustered manner and to provide a reference basis for the content of that section, this section shows the power output characteristics of PCC points and their tracking effect when the agent resources in the distribution network participate in scheduling in a single-point manner under different conditions.

In solving the single-point scheduling problem, we set two objectives: one is to maximize the power output of the PCC point (i.e., node 1 in Figure 7a), and the other is to minimize its power output. Under these two objectives, we consider several constraints, including but not limited to: the general constraints of optimal power flow problems such as power balance constraints, Ohm's law constraints, branch power constraints, branch current constraints, node voltage constraints, etc. and, in addition, we consider the range of the outputs of the distributed agent resources, which include but are not limited to PV systems, etc. In the solution process, we pay special attention to the power outgoing characteristics of the IEEE-33 bus system to the superior grid. The results, as shown in Figure 8, show that the adjustable out-of-power characteristics of the PCC point show a significant change during the noon hour, which is mainly attributed to the increase in the PV system's output during the noon hour, and the change in the PV system's output has a significant impact on the system characteristics compared to other adjustable resources. It is worth noting that since we consider the reactive power characteristics of PV and WP as power electronic devices, in the AGC power outlier characteristic, the upper limit of the

power outlier characteristic is a straight line (i.e., all distributed resources are switched off) because they do not have the ability to absorb active power, whereas in the AVC power outlier characteristic, since the distributed resources absorb reactive power, their reactive power in the noon hour is expected to see a demand increase scenario.

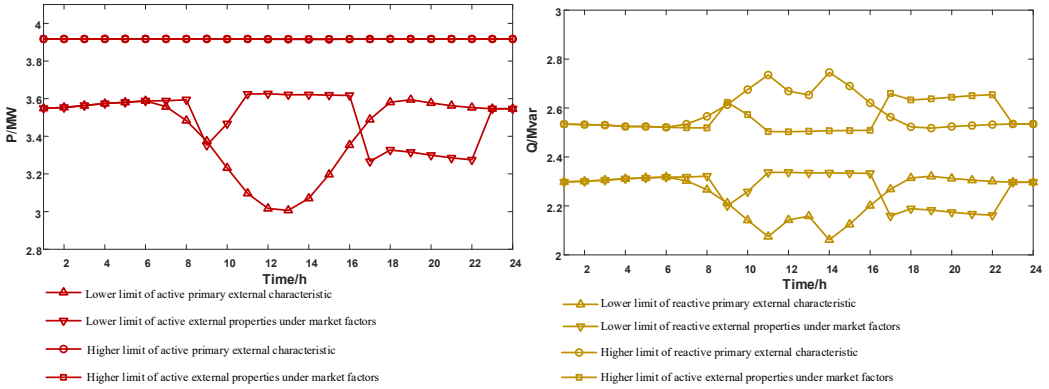


Figure 8. Out-of-power characteristics of PCC points for each scenario of IEEE-33 bus.

Based on the external characteristics provided in Figure 8, this paper defines a set of AGC active power commands and AVC reactive power commands (see Figure 9). By solving the optimal power flow problem with the objective of tracking commands, we obtain the curve of node 1 absorbing P-Q power from the superior grid under the single-point participation mode of multi-agent resources, as shown in Figure 9. In order to simulate the deviation of the superior grid in the process of directive issuance due to various reasons (e.g., communication problems), the active demand issued by the AGC decreases in the two time periods after 8:00 a.m. versus before 11:00 a.m., as well as after 18:00 a.m. and before 21:00 a.m. Without considering the market factors, since the second time period is at night, the distributed PV active power output is close to 0, so there will be a large deviation in tracking AGC commands. However, in the market environment, the combination of PV and ES enables it to emit active power in the second period, so it can maintain a good power flow tracking effect within the external power characteristic range. When tracking the AVC commands, the power tracking effect under the market scenario is not as good as the tracking effect without considering the market factor, but overall, both can have a decent tracking effect.

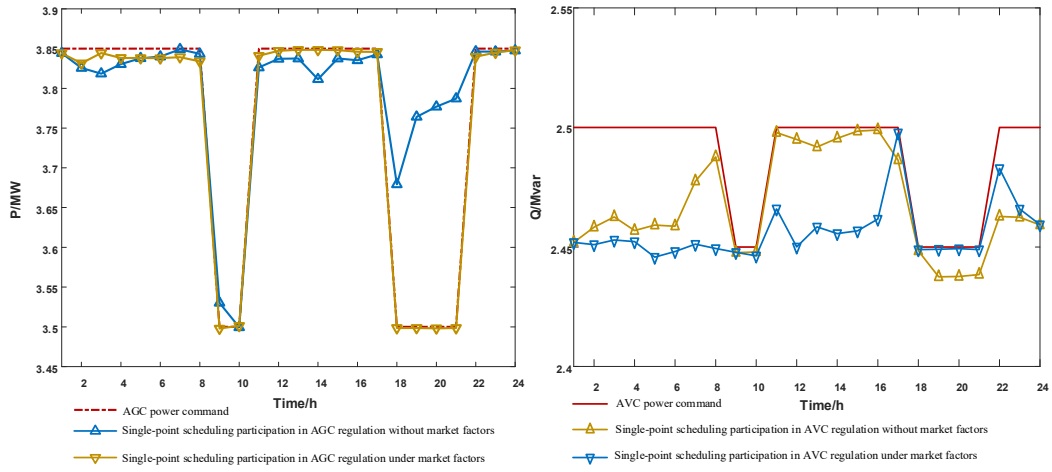


Figure 9. PCC point power tracking curve in IEEE-33 bus market environment [21].

5.3. Analysis of the Form of Clustering

5.3.1. Sample Generation and Screening

Figure 10 illustrates the number of cluster partition samples under different λ_{max}. Figure 10 shows that with the decrease in λ_{max}, the number of cluster partition samples satisfying the condition decreased slowly at first (λ_{max} = 0.4~0.5, note: when λ_{max} = 0.5, the number of samples is 755). Then, it entered a rapid decline range (λ_{max} = 0.3~0.4). In the range λ_{max} = 0.2~0.27, the number of samples continued to decrease (note: when λ_{max} = 0.27, the number of samples was only 48), but the overall change was not large. In fact, the upper limit value λ_{max} of the electrical distance should not be too small or too large because this will excessively limit (or weaken) the sample screening ability of the cluster partition method, resulting in too small (or too many) a number of eligible samples. In order to obtain a batch of representative cluster partition samples, this paper finally sets λ_{max} = 0.35 according to Figure 10. According to this setting, 342 effective cluster partition samples can be finally obtained in this example (note: for power systems of different scales, the value of λmax should also be determined by the total number of samples, the representability of samples, and the final time-consuming solution).

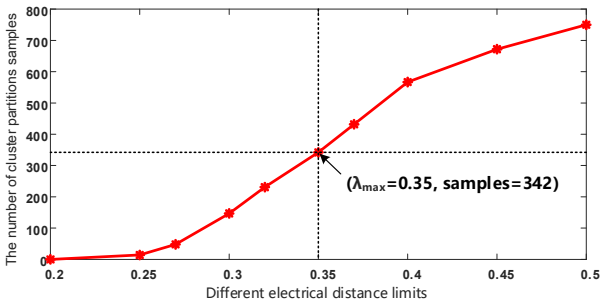


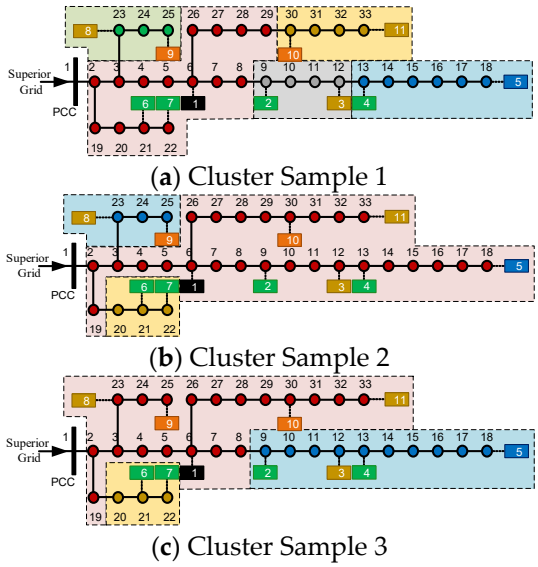
Figure 10. The relationship of cluster partition samples' number with λ_{max}.

According to the arithmetic and the cluster division conditions proposed in the previous section, 342 valid cluster division samples are screened (note: three typical samples are shown in Figure 11). In order to further study the tracking effect of the power command under the influence of market factors in different cluster division methods, three typical cluster division schemes are selected for simulation comparison. The tracking error of the power command under different cluster division methods under market factors is obtained as shown in Table 2.

Table 2. Power command tracking error under the market environment.

Scenarios	Classification	Active Command Error/%	Reactive Command Error/%
Disregarding market factors	1	5.4530	0.6089
	2	5.3862	0.6041
	3	5.3984	0.6076
	Single-point scheduling [21]	5.3386	0.6006
Considering market factors	1	2.0272	3.1526
	2	2.0156	3.1567
	3	2.0195	3.1545
	Single-point scheduling [21]	2.0060	3.1366

(Note: error = |(actual power − power command)/power command| × 100%).



(**a**) Cluster Sample 1

(**b**) Cluster Sample 2

(**c**) Cluster Sample 3

Figure 11. Sample of a typical cluster division.

From Table 2, it can be seen that the AGC power command tracking effectiveness of the system is significantly improved after considering the market factor, regardless of whether or not it is divided into clusters. This is because, after considering the market factor, the output of the distributed generation resources is more closely aligned with the load, and thus, it can cope well with the reduced demand of the AGC power command even during the night time peak power consumption, whereas it is not able to fetch a better result when tracking the AVC command. Meanwhile, we can also see that, although different cluster divisions will have some influence on the tracking effect of the system's power commands, the relative errors of such influences are less than 5.5% (the relative percentage of the error of cluster scheduling and the error of single-point scheduling), which indicates that different cluster divisions do not have any significant influence on the tracking effect of the commands of the multi-agent resource aggregation. This result effectively verifies the robustness and applicability of the cluster scheduling strategy under diverse resource allocation.

5.3.2. Results of Participation in Grid Scheduling

Taking the cluster division scheme (cluster samples 1 to 3 corresponding to Figure 11a to Figure 11c, respectively, as examples of the three participating cluster scheduling divisions in this paper) as an example, the AGC active commands and AVC reactive commands are tracked (note: The objective of optimal power flow is to minimize the error between the active/reactive power command received at the PCC point and the actual active/reactive power at the PCC point), and the results are shown in Figures 12–14.

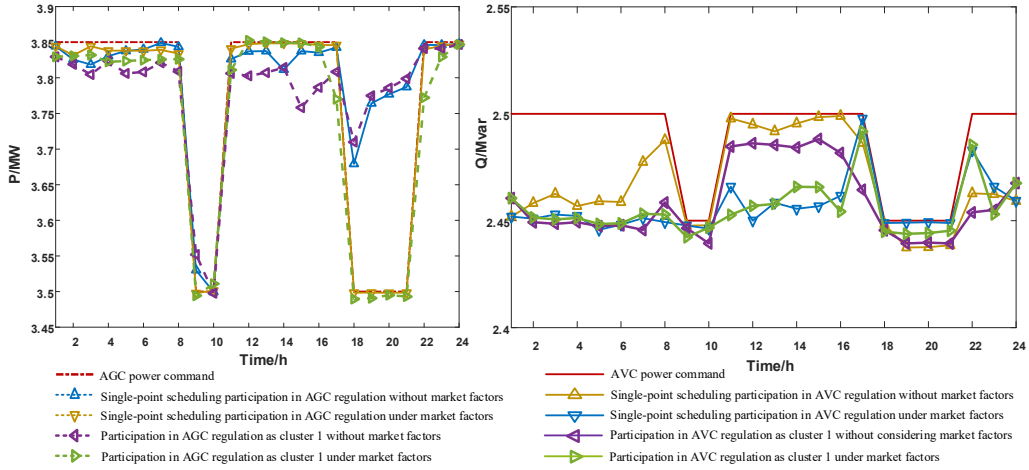


Figure 12. PCC point power tracking curves for cluster 1.

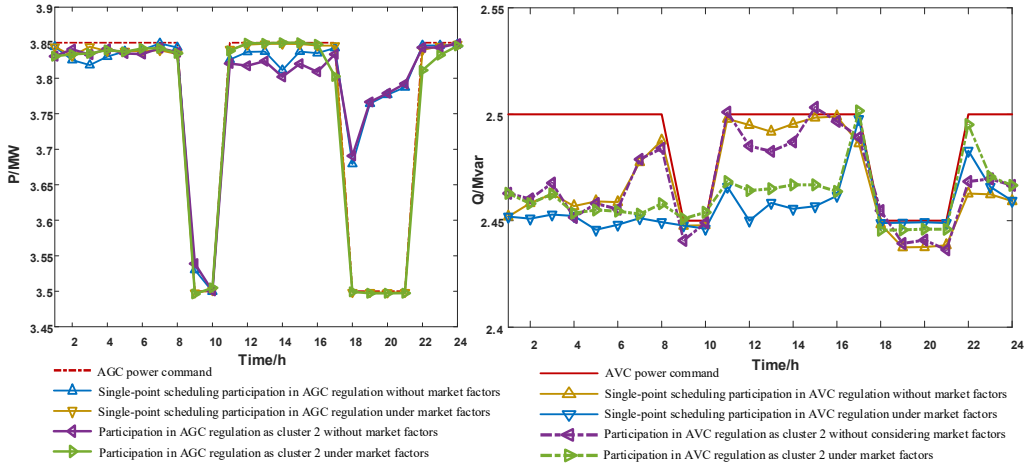


Figure 13. PCC point power tracking curves for cluster 2.

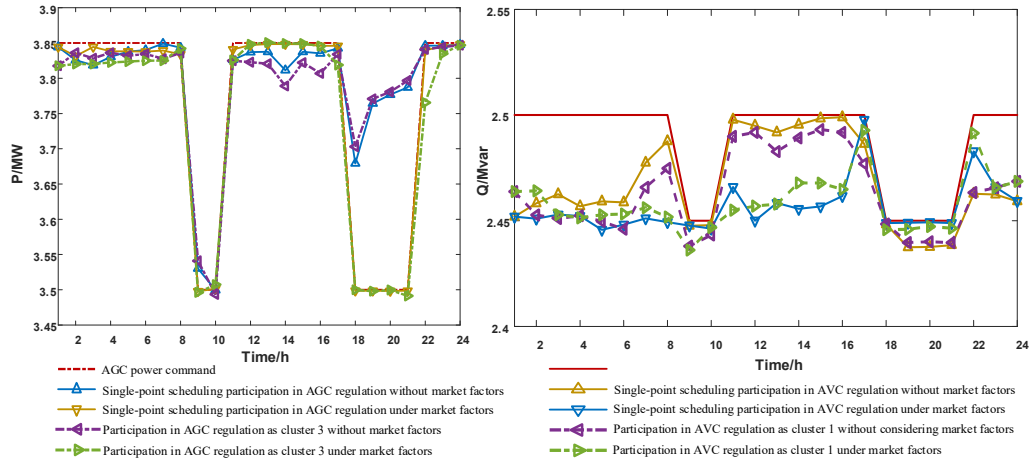


Figure 14. PCC point power tracking curves for cluster 3 partitioning schemes.

From Figures 12–14, it can be seen that the command tracking effect of using cluster division to participate in regulation is slightly inferior to the command tracking effect of all the adjustable resources participating in regulation in the form of a single point, but the tracking effect is still satisfactory in general. Especially when the commands exceed the external characteristic boundary of the cluster power, each partition method can successfully track the upper (lower) limit of the external characteristic. In addition, if we

take a closer look, regardless of market factors, whether participating in AGC scheduling in the form of a single point or cluster, the power command cannot be accurately tracked between 11:00 and 16:00. This is because the active power output of the multi-agent generation resources is high during this period, which reduces the active power demand, so the power command cannot be tracked. After considering the market factors, the power of multi-agent generation resources is stored in energy storage, so the power command can be tracked. Similarly, between 18:00 and 20:00, Whether participating in AGC scheduling in the form of a single point or cluster, power commands cannot be accurately tracked without considering market factors. This is because the active power output of multi-agent power generation resources is less in the night period, so the power command cannot be tracked. After considering the market factors, the energy storage will release the energy stored during the day, so it can track the power command. However, after participating in AVC scheduling, the power command error without considering the market factor is lower than the error considering the market factor between 11:00 and 16:00. This is because without considering the market factors, the active power output of multi-agent generation resources increases during this period, so the reactive power output will decrease, which is in line with the situation that the reactive power command increases (the reactive power demand increases) during this period.

By evaluating the three cluster division methods under the influence of the above market factors, the tracking analysis was conducted with two active and reactive power commands, which produced a total of eight different command tracking results. Despite the subtle differences between the various division methods, all of them are effective in realizing command tracking. In particular, in the case where the command exceeds the boundary of the outer characteristic of the cluster power, all the division methods are able to successfully track to the upper (lower) limit of the outer characteristic. In conjunction with the time-of-use prices in Table A2 in Appendix A, we can also perform an analysis of the economic benefits of multi-agent resources. From the tracking effect of power commands, after being guided by the market price, the active power output of multi-agent resources is more concentrated in the peak period of electricity price, so there will be a higher economic profit. At the same time, it is also verified that the proposed method can obtain higher benefits for multi-agent resources while keeping the command tracking error within a reasonable range, and realize the balance between dispatching and economy.

6. Concluding Remarks

In this paper, we propose a method for multi-agent resources to participate in power grid regulation in the form of clusters. Considering the active and reactive power–voltage coupling characteristics of the distribution network, we proposed a cluster partition sample generation and selection method based on Monte Carlo sampling. It relies on the regulation process of cluster division, external characteristics calculation, command decomposition, and deaggregation. In this method, the external characteristic model of a multi-agent resource is simplified, and we established the control model with the goal of command tracking. It realizes the effective division and regulation of clusters under the "centralized–distributed" regulation architecture of a distribution network. Simulation results show that the relative error of command tracking of multi-agents in different cluster forms is less than 5.5%.

The results of this study can provide a theoretical basis for the aggregation behavior of aggregators. Because this method also comprehensively verifies the tracking performance of multi-agent resources under market factors, the results based on the cluster regulation strategy are more acceptable. The balance between the concerns of power grid companies and aggregators is better achieved under the market environment. Although this paper has

made significant progress in multi-agent resources cluster regulation, there are still some limitations. In order to further improve the applicability and practicability of the method, future research will focus on the following directions:

(1) In the future, it is planned to apply the proposed method to larger-scale power grid systems, such as the IEEE-118 bus system, to evaluate its performance and scalability in a complex power grid structure and large-scale data environment. To this end, we will optimize the cluster sample generation algorithm to cope with higher computational complexity.

(2) Since the current research is limited to the application of synthetic data, in the future, real grid topology and operation data will be obtained in cooperation with power companies or related research institutions. A simulation study under practical examples will be carried out to verify the practicability of the proposed method in the actual operating environment.

(3) The electricity market environment has an important impact on the effect of multi-agent resource regulation. Future research will deeply analyze the impact of different market structures on the performance of the proposed method. The resource scheduling strategy will be optimized to improve the adaptability of the proposed method under diversified market conditions.

(4) The ES model in this study has not yet considered practical operation characteristics such as the self-discharge rate. In the future, it is planned to introduce the self-discharge rate as a constraint in the model to more accurately reflect the operation behavior of ES, so as to improve the authenticity of the regulation method.

(5) In order to further improve the intelligence level of the power grid, the collaborative application of the proposed method with other smart grid technologies, such as energy management system (EMS), will be explored in the future to realize the comprehensive optimization of power grid operation efficiency and overall performance.

Through the above future work, we expect to further improve the theoretical framework and application potential of the proposed method, provide more practical solutions for resource regulation in market environments, and promote the wide application of multi-agent resource cluster regulation technology in the field of smart grids.

Author Contributions: Investigation, K.L.; resources, D.J.; writing—original draft, X.Z.; supervision, Z.R.; project administration, K.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the project "Research on the Key Technology of Modeling and Simulation Analysis of Peer-to-Peer Distribution System." [grant numbers 5400-202355767A-3-5-YS].

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Authors Dongli Jia, Zhaoying Ren, and Keyan Liu were employed by the company of China Electric Power Research. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Appendix A. Data Supplement

The parameters of the ES as well as the 24 h electricity purchase and sale price are recorded in Tables A1 and A2.

Table A1. ES parameter.

Parameter Types	Parameter Values	Parameter Types	Parameter Values
Power of charge/kW	100	Rated capacity/MW·h	1
Power of discharge/kW	100	Maximum SOC/%	90
Efficiency of charge/%	90	Minimum SOC/%	10
Efficiency of discharge/%	90		

Table A2. Twenty-four hour electricity purchase and sale price.

Time	1	2	3	4	5	6	7	8	9	10	11	12
purchase price/(CNY/kW·h)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.53	0.53	0.53	0.82	0.82
sale price/(CNY/kW·h)	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.42	0.42	0.42	0.65	0.65
Time	13	14	15	16	17	18	19	20	21	22	23	24
purchase price/(CNY/kW·h)	0.82	0.82	0.82	0.53	0.53	0.53	0.82	0.82	0.82	0.53	0.53	0.53
sale price/(CNY/kW·h)	0.65	0.65	0.65	0.42	0.42	0.42	0.65	0.65	0.65	0.42	0.42	0.42

References

1. Cheng, X.; Liu, P.; Zhu, L. The impact of electricity market reform on renewable energy production. *Energy Policy* **2024**, *194*, 114306. [CrossRef]
2. Li, Y.; Chang, W.; Yang, Q. Deep reinforcement learning based hierarchical energy management for virtual power plant with aggregated multiple heterogeneous microgrids. *Appl. Energy* **2025**, *382*, 125333. [CrossRef]
3. Koraki, D.; Strunz, K. Wind and Solar Power Integration in Electricity Markets and Distribution Networks Through Service-Centric Virtual Power Plants. *IEEE Trans. Power Syst.* **2017**, *33*, 473–485. [CrossRef]
4. Li, J.; Ai, Q.; Yin, S. Market Mechanism and Foreign Experience Reference for Virtual Power Plants Participating in Peak Shaving and Frequency Regulation Services. *Proc. CSEE* **2022**, *42*, 37–56.
5. Tan, Z.; Zhong, H.; Wang, X.; Tang, H. An Efficient Method for Estimating Capability Curve of Virtual Power Plant. *CSEE J. Power Energy Syst.* **2022**, *8*, 780–788.
6. Tian, X.; Wen, Y.; Lu, Z. Modeling Techniques and a Hierarchical Coordinated Control Framework for Various-Type Flexible Resources. *Distrib. Energy* **2024**, *9*, 10–18.
7. Cui, B.; Zamzam, A.; Bernstein, A. Network-Cognizant Time-Coupled Aggregate Flexibility of Distribution Systems Under Uncertainties. *IEEE Control Syst. Lett.* **2020**, *5*, 1723–1728.
8. Xie, P.; Liu, M.; Chen, C.; Tang, W.; Wang, H. Optimal two-stage arbitraging and scheduling strategy for distributed energy resource aggregators. *Heliyon* **2024**, *10*, e37666.
9. Yasuda, Y.; Carlini, E.M.; Estanqueiro, A. Flexibility chart 2.0: An accessible visual tool to evaluate flexibility resources in power systems. *Renew. Sustain. Energy Rev.* **2023**, *174*, 113116.
10. Naval, N.; Yusta, J.M. Virtual power plant models and electricity markets—A review. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111393.
11. Chen, L.; Tang, Z.; He, S. Feasible operation region estimation of virtual power plant considering heterogeneity and uncertainty of distributed energy resources. *Appl. Energy* **2024**, *362*, 123000. [CrossRef]
12. Lin, W.; Yang, Z.; Yu, J.; Jin, L.; Li, W. Tie-line power transmission region in a hybrid grid: Fast characterization and expansion strategy. *IEEE Trans. Power Syst.* **2020**, *35*, 2222–2231. [CrossRef]
13. Yi, Z.; Xu, Y.; Gu, W.; Yang, L.; Sun, H. Aggregate operation model for numerous small-capacity distributed energy resources considering uncertainty. *IEEE Trans. Smart Grid* **2021**, *12*, 4208–4224. [CrossRef]
14. Kalantar-Neyestanaki, M.; Sossan, F.; Bozorg, M.; Cherkaoui, R. Characterizing the reserve provision capability area of active distribution networks: A linear robust optimization method. *IEEE Trans. Smart Grid* **2020**, *11*, 2464–2475. [CrossRef]
15. Wang, S.; Wu, W. Stochastic flexibility evaluation for virtual power plant by aggregating distributed energy resources. *arXiv* **2006**, arXiv:2006.16170.
16. Qu, M.; Ding, T.; Wei, W.; Dong, Z.Y.; Shahidehpour, M.; Xia, S. An analytical method for generation unit aggregation in virtual power plants. *IEEE Trans. Smart Grid* **2020**, *11*, 5466–5469. [CrossRef]
17. Hao, H.; Somani, A.; Lian, J.; Carroll, T.E. Generalized aggregation and coordination of residential loads in a smart community. In Proceedings of the IEEE International Conference on Smart Grid Communications, Miami, FL, USA, 2–5 November 2015.
18. Wen, Y.; Hu, Z.; You, S.; Duan, X. Aggregate feasible region of DERs: Exact formulation and approximate models. *IEEE Trans. Smart Grid* **2022**, *13*, 4405–4423. [CrossRef]

19. Wang, L.; Wu, W.; Lu, Q.; Yang, Y. Optimal Aggregation Approach for Virtual Power Plant Considering Network Reconfiguration. *J. Mod. Power Syst. Clean Energy* **2021**, *9*, 495–501. [CrossRef]
20. Farivar, M.; Low, S.H. Branch flow model: Relaxations and convexification-part II. *IEEE Trans. Power Syst.* **2013**, *28*, 2565–2572. [CrossRef]
21. Farivar, M.; Low, S.H. Branch flow model: Relaxations and convexification-part I. *IEEE Trans. Power Syst.* **2013**, *28*, 2554–2564. [CrossRef]
22. Gan, L.; Li, N.; Topcu, U.; Low, S.H. Exact convex relaxation of optimal power flow in radial networks. *IEEE Trans. Autom. Control* **2015**, *60*, 72–87. [CrossRef]
23. Sun, J.; Xu, J.; Ke, D. Cluster partition for distributed energy resources in Regional Integrated Energy System. *Energy Rep.* **2023**, *9* (Suppl. S8), 613–619.
24. Lu, R.; Hong, S.H.; Yu, M. Demand response for home energy management using reinforcement learning and artificial neural network. *IEEE Trans. Smart Grid* **2019**, *10*, 6629–6639. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.