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A dynamic hierarchical partition method for active distribution networks with shared energy storage aggregation

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1 Introduction

The high penetration of renewable energy sources in distribution networks increases the difficulty of centralized operation and regulation (Chai et al., 2018; Magdy et al., 2021; Zhang et al., 2022). To improve the integration and schedulability of distributed energy, various distributed control methods based on the distributed generation cluster are proposed in (Muhtadi et al., 2021; Patel et al., 2022). The premise of realizing distributed control of distribution network is the reasonable division of distribution network cluster, which can be found in many studies. The electric distance is one of the most commonly used indicators of cluster division in distribution networks (Lagonotte et al., 1989). Ref (Islam et al., 2014). separated the network into multiple regions clusters in view of the electrical distance, and proposed a decentralized adaptive emergency control scheme to stabilize the voltage of power system. According to the improved modularity index, the distribution network with distributed photovoltaic systems was divided into multiple clusters (Zhao et al., 2017). Furthermore, k-means algorithm was applied in (Cotilla-Sanchez et al., 2013) to divide the power network. Vinothkumar et al., comprehensively considered the planning prospect of distribution network and used hierarchical clustering algorithm to obtain the best siting for distributed generation (Vinothkumar and Selvan, 2014). The indexes and algorithms of cluster division are studied in (Cotilla-Sanchez et al., 2013; Vinothkumar and Selvan, 2014; Liang et al., 2020), which take different demands of distribution network operation planning and scheduling into account. However, there are rare studies that consider the shared energy storage in cluster division.

In this paper, a dynamic partition method of the shared energy storage and prosumers based on community detection algorithm is proposed. The main opinions of this paper are as follows: 1) A comprehensive performance index of cluster division considering network structure and function is proposed. The local comprehensive index and global comprehensive performance index are established on the basic of the structural index and the functional index. The former is the combination of the electrical coupling index and spatial distance index, and the latter adopts the storage load demand matching index.

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Based on the comprehensive performance index, the shared energy storage and prosumers in the whole region are divided into multiple internally closely connected and externally non-interfering storage prosumer clusters ulteriorly; 2) A hierarchical method based on the adaptive k-means clustering is put forward of shared energy storage. Through the adaptive k-means clustering algorithm, the energy storage resources, which belong to the same cluster, are finally segmented into multiple shared energy storage sets with different loss characteristics and transient response characteristics.

2 Cluster partitioning of active distribution networks with prosumers

2.1 Cluster division indicators of active distribution networks

Firstly, the shared energy storage and prosumers are preliminarily clustered from the aspects of electrical coupling degree, geographical spatial correlation and supply-demand balance. The specific cluster division indexes are as follows:

The electrical coupling degree index reflects the mutual influence of electrical quantities between nodes where prosumers and shared energy storage are located in. The comprehensive electrical distance between various nodes is adopted as the electrical coupling degree index in this paper. Due to the strong coupling relationship between active and reactive power in distribution network, it is essential to comprehensively consider the impact of active and reactive power on node voltage when partitioning. As well as the relationship between the two nodes is not only related to itself, but also related to other nodes. Therefore, the comprehensive electrical distance is the weighted sum of the comprehensive electrical active distance, which can be calculated by the he Euclidean distance method based on node voltage active power sensitivity, and the comprehensive electrical reactive distance, which can be obtained with the analogous calculating method.

The spatial geographical location index is applied to describe the geospatial correlation degree between distributed park prosumers and shared energy storage resources. Geographically close distributed energy sources have high similarity in power waveform, which is convenient for unified prediction of user-side distributed energy. Meanwhile, the proximity of prosumers and shared energy storage in spatial location is suitable for unified collection of energy storage information, which is conducive to real-time transmission of user demand data and timely response of shared energy storage services. The Euclidean distance of geographical space is used as the spatial location index in this paper. Taking the weighted sum of the electrical distance and the spatial geographical distance as the comprehensive distance, which can be defined as the edge weight of the network nodes of modularity index, so as to obtain the improved modularity index (Zhao et al., 2017), which can comprehensively describe the structural strength of the cluster from both the electrical topological structure and the spatial geographical structure.

Except for taking the close connection degree of the topological structure between prosumers in the park into consideration, the storage and prosumers partition should also ensure that the shared energy storage resources within the cluster can satisfy the active and reactive power demand as much as possible. According to the minimum active power limit negotiated by the shared energy storage aggregator and the prosumers in advance, the active power charge and discharge unbalance of energy storage in any cluster z can be obtained. Assuming that the intra-day time length is T, the active demand matching index of cluster z can be acquired based on the charge and discharge imbalance of energy storage. Besides, the reactive power of each node in the cluster should be balanced locally as far as possible to reduce the reactive power transmission across clusters. Based on the maximum historical voltage deviation of each node and the reactive power sensitivity matrix, the minimum reactive power demand (Zhao et al., 2017) required in the cluster can be figured out and then the reactive demand matching index of cluster z is obtained, which reflects the reactive power balance ability of the cluster. When the inverter capacity of energy storage in the cluster is greater than the sum of reactive power requirements, the demand reactive power of this cluster is completely satisfied. Consequently, the local comprehensive index of cluster is the weighted sum of the modularity index, the active demand matching index and the reactive demand matching index, and the global comprehensive index is the average of the local comprehensive index.

2.2 Cluster partitioning algorithm based on community detection

The community detection algorithm is used in the optimal cluster division to achieve the maximum global comprehensive index (Javed et al., 2018). The local comprehensive index of each cluster is used as the local optimization objective, and the global comprehensive index of all clusters is regarded as the global optimization objective for adjusting the cluster division. Then, the community detection algorithm is applied to divide the shared energy storage and prosumers into clusters. The specific process is as follows:

1) Initialize each node as a separate cluster; 2) For any node m, moving it to the cluster where node n is located, and the increment of local optimization objective after joining is calculated and recorded. The node with the maximum increment of local optimization target after joining is divided into the cluster where node n is located; 3) Repeat step 2) until the

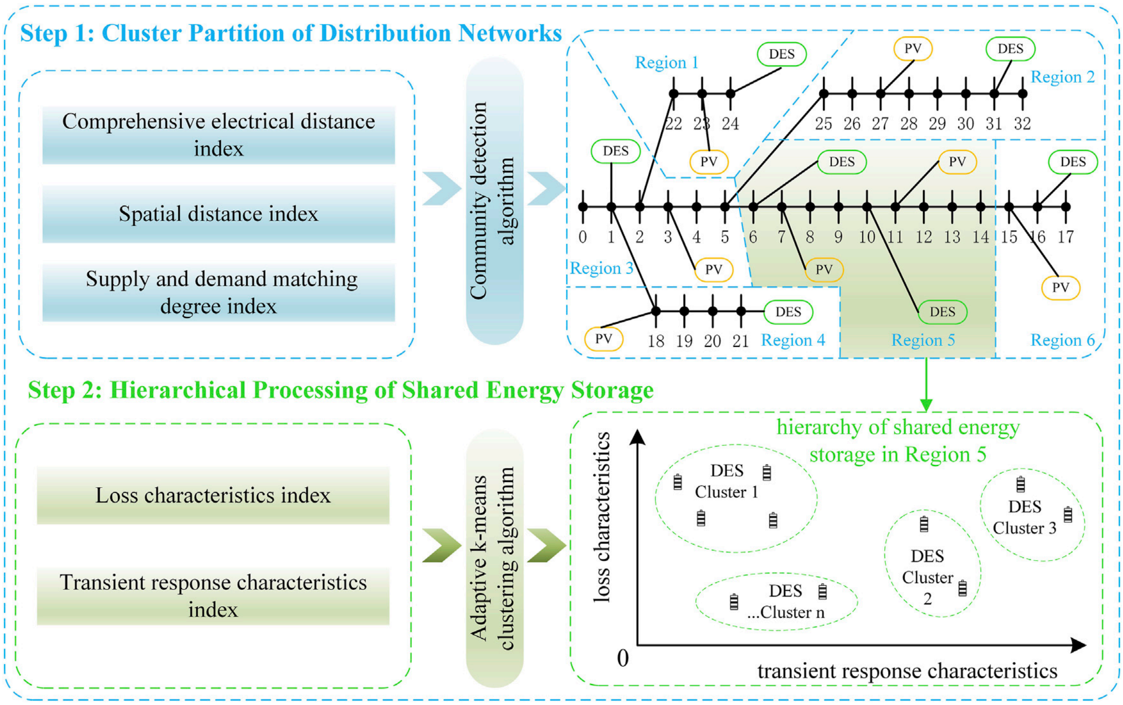

FIGURE 1
Dynamic hierarchical partition schematic diagram.

global optimization objective reaches the maximum, and then the optimal clusters can be solved.

3 Hierarchical processing of shared energy storage aggregation

3.1 Multi-characteristic indexes of shared energy storage

In order to select the appropriate shared energy storage unit to achieve diversified application of energy storage in multiple scenarios with the minimum operating cost (Dai et al., 2021; Liu et al., 2021; Li et al., 2022), such as peak regulation and frequency modulation, renewable energy consumption, demand side response, reactive power compensation, and emergency reserve, the loss characteristics and transient response characteristics of energy storage can be hailed as the selection indicators and the energy storage resources with the same characteristics are aggregated and regulated optimally in this paper.

The shared energy storage resources are mainly composed of the energy-type energy storage, such as lithium iron phosphate battery, all-vanadium flow battery, sodium sulfur battery and lead-acid battery, and the power-type energy storage including electrochemical supercapacitor and superconducting magnetic energy storage. The capacity and power loss characteristics of energy storage are determined by a series of energy storage loss characteristic parameters. The life loss of energy-type energy storage is related to the depth of discharge, the state of charge, and the charging/discharging power (Wang et al., 2020; Liang et al., 2022). The life of power-type energy storage is greatly limited by the number of charge and discharge cycles. These influencing factors can be expressed by the related loss characteristic parameters which are taken as the loss characteristic indexes of energy storage in this paper.

Different energy storage differs in active regulation capacity and regulation efficiency, which will affect the economy of shared energy storage and the stability of power system. Therefore, in the aggregation process of abundant shared energy storage, the regulation response time should be taken as one of its characteristic quantities. There is a specified relationship between the transient response time and the response time constant of energy storage, that is, the response time constant reflects the transient response speed. Thus, the response time constant is chosen to be the transient characteristic index of energy storage in this paper.

3.2 Dynamic partition method based on adaptive clustering

As one of the most commonly used clustering algorithms, k-means algorithm is uncomplicated and has fast convergence rate (Cotilla-Sanchez et al., 2013). The main feature of k-means algorithm is to randomly determine k initial clustering centers, divide the network into k regions on the basic of distance comparison, and minimize the sum of squared errors (SSE) of all points and their related clustering centers in the iterative process. However, the random k may lead the results converge to local optimum. For achieving the better partitioning results, the elbow method is used in this paper to optimize the selection of clustering center k and realize adaptive clustering additionally.

The shared energy storage in the cluster is divided by the improved k-means clustering. With the evaluation index SSE consisted of the loss characteristics and transient response characteristics of energy storage, the optimal number of clusters depends on the reduced contribution rate of SSE so as to achieve the adaptive clustering. The shared energy storage sets with different loss characteristics and transient response characteristics can be obtained additionally.

The schematic diagram of the dynamic hierarchical partition method described in this paper is presented in Figure 1. Firstly, for maximizing the global comprehensive performance index composed of the electrical coupling index, spatial location index, and storage demand matching index, the distribution network with the distributed energy storage and renewable energy is segmented into several clusters. Then, the shared energy storage in the cluster is processed hierarchically. Taking region 5 as an example, according to the loss characteristics and transient response characteristics, the hierarchical processing of shared energy storage resources in region 5 is completed by adaptive k-means clustering.

4 Discussion and conclusions

A dynamic partition mechanism of shared energy storage and distributed prosumers based on community detection algorithm and adaptive clustering is proposed in this paper. First of all, a global comprehensive performance index considering the electrical coupling degree, spatial location, and the demand matching degree of storage is established. With the goal of maximizing the global comprehensive performance index, the community detection algorithm is used to divide the shared energy storage and prosumers into clusters. Then, for each cluster, according to the loss characteristics and transient response characteristics of energy storage, the reduction contribution rate of the k-means clustering evaluation index is introduced to realize the adaptive judgment of the optimal cluster number, so as to complete the hierarchical processing of shared energy storage resources in the cluster. The proposed scheme is a feasible and realistic cluster partition method, which can aggregate the shared energy storage with the same characteristics, simplify the difficulty of operation scheduling, and realize a variety of applications of energy storage with a low operating cost.

Author contributions

Writing the original draft and editing, ZP; Conceptualization, XG; Formal analysis, RC; Visualization and contributed to the discussion of the topic, HY and ZZ.

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Conflict of interest

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