Recent Advances in Regional Microgrid Cluster Technology (Postprint)

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Abstract

Following the integration of high-penetration distributed generation into distribution networks, traditional distribution network dispatching systems fail to satisfy the monitoring requirements of microgrids, leaving a large number of distributed generation units in an uncontrollable state. To achieve coordinated control of distributed generation, research on microgrid cluster technology is of great necessity. This paper first describes the concept, structure, and composition of microgrid clusters, investigates the operational characteristics and partitioning methods of regional microgrid clusters under high-penetration integration scenarios, and designs a microgrid cluster control framework based on spatiotemporal distribution.

Full Text

Preamble

The New Progress on Technology of Regional Micro-Grids Cluster

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Abstract: The integration of high-penetration distributed generation (DG) into distribution networks renders traditional dispatching systems inadequate for monitoring and controlling microgrids, leaving numerous distributed power plants in an uncontrolled state. To achieve coordinated control of distributed power sources, research on microgrid cluster technology is essential. This paper first describes the concept, structure, and composition of microgrid clusters, investigates the operational characteristics and partitioning methods for regional microgrid clusters under high-penetration conditions, and designs a spatiotemporal distribution-based control framework for microgrid clusters.

Keywords: High penetration, microgrids cluster, control framework, system structure, space-time distribution

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1 Introduction

Distributed generation (DG) systems exhibit diverse attributes and are numerous and geographically dispersed. Without an appropriate dispatching architecture, dispatch commands cannot be transmitted and executed rapidly, effectively, and accurately. Therefore, in distribution networks, the most practical solution for directly dispatching and managing large numbers of distributed power sources is to cluster them into microgrid clusters. The presence of numerous microgrid clusters in distribution systems transforms the structure and operation mode of power distribution networks, enhancing system security and reliability while enabling real-time monitoring, control, and regulation. Through coordination, grid benefits can be maximized. Such microgrid clusters ensure that during fault and abnormal operating conditions, adjustments can be made not only within individual clusters but also through inter-cluster communication and coordination, thereby significantly improving the stability and security of the entire microgrid cluster and distribution network.

2.2 Internal System Structure

After microgrids form large-scale clusters, certain technical challenges arising from their wide geographical distribution and unified common connection points for grid integration must be addressed. However, this approach enables effective integration of distributed power sources with distribution systems. This study establishes regional microgrid clusters based on high-penetration DG integration in distribution networks, moving beyond traditional zonal and hierarchical control schemes. The microgrid cluster incorporates a multi-agent system, where the basic unit is an agent. The system comprises multiple agents that can interact with their environment. Through research and analysis of control frameworks and system structures for microgrid clusters, effective management of microgrids can be achieved after clustering according to their spatiotemporal distribution, thereby reducing the impact of individual distributed power sources on distribution system security.

The hierarchical distributed control framework for microgrid clusters is shown in [Figure 1: see original paper]. As illustrated, the regional control employs three layers of coordinated control, with corresponding agent modules at each layer. Information is transmitted layer by layer, ensuring bidirectional communication between upper and lower levels. From the distribution network perspective, distributed power cluster control treats the entire microgrid cluster as an integrated entity. The execution stations/field station collection stations coordinate voltage, frequency, and stability, while the dispatch center serves as the "general agent," enabling data interaction, real-time supply-demand coordination, and economic control for all subordinate units and connecting users to transmit historical and real-time data. Through this three-layer coordination, the entire cluster becomes observable and controllable.

2.1 Microgrid Cluster Concept Based on Clustering Analysis

Power systems follow specific operational patterns, achieving automatic control through mode superposition at different time scales, including unit commitment, day-ahead scheduling, online dispatching, and real-time control. This automatic control relies on power source reliability and the predictability of loads across large spatial and temporal regions. However, intermittent renewable energy sources such as wind and photovoltaic power fail to meet grid standards in terms of reliability and predictability. Consequently, as the penetration of new energy sources continues to increase, exploring advanced operational modes and control strategies for distributed power sources becomes particularly crucial.

Cluster analysis, also known as group analysis, is a multivariate statistical method that classifies samples or indicators based on the principle that "like attracts like." It deals with large numbers of samples and requires reasonable classification according to their characteristics. This paper applies cluster analysis to distributed power sources, enabling coordination and control of stable, dispatchable power sources. For instance, all wind power equipment in a region can be clustered to form a local wind microgrid cluster; all photovoltaic equipment can form a PV microgrid cluster; and hybrid energy microgrid clusters such as wind-solar, wind-storage, and wind-solar-storage can also participate. Clustering enables various distributed power sources to form larger-scale modules with uniform or complementary internal types, facilitating unified real-time control. Clustering can improve power quality, adapt to distribution network relay protection systems, and enhance safe and stable operation.

2.3 Regional Microgrid Cluster System Structure

In microgrid clusters, microgrids must possess certain characteristics to ensure safe and reliable operation of the distribution network after integration. A simplified structural diagram of a wind-solar-storage microgrid cluster system is shown in [Figure 2: see original paper]. As depicted, the microgrid cluster is a large-scale comprehensive system with close internal connections and inter-cluster coordination for control.

Microgrid clusters require the following characteristics: (1) Capability for grid-connected or islanded operation to fully leverage regional cluster advantages and spatiotemporal complementarity of new energy sources, enabling both power trading with the distribution network and support for its secure operation. (2) Microgrid dynamic characteristics should be reflected at the cluster level—for example, when a particular microgrid requires full support, the cluster exhibits that microgrid' s characteristics while other modules need not consider economic factors. (3) Each microgrid in a cluster must connect to at least one other microgrid to enable cluster operation. (4) Each microgrid cluster should have its own resource control system for internal resource integration, optimization, and reconfiguration. (5) Clusters must possess their own economic operation strategies to directly reflect their characteristics across large regions when needed. (6) Clusters require dedicated security systems to ensure safe and stable operation.

In [Figure 2: see original paper], Microgrid 1, 2, 3, and 4 are independent microgrid cluster modules, each connected to at least one other cluster. Microgrid Clusters 1, 2, and 3 reflect the demand characteristics of Microgrid Cluster 1, while Microgrid Cluster 4 operates independently to maintain its own supply-demand balance. Each cluster contains various distributed power sources such as wind turbines, solar panels, and storage modules, along with its own economic operation strategy (software) and security assurance system.

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3 Partitioning Methods and Operational Characteristics of Regional Microgrid Clusters Under High-Penetration Conditions

Based on the random output characteristics of distributed power sources, microgrids composed of multiple units are regrouped to establish cluster models for wind, PV, PV-storage, wind-solar, wind-storage, and wind-solar-storage microgrids.

3.1 Wind Microgrid Cluster (1,000 kW and Above)

With large-scale wind energy development, the number of wind farms has increased dramatically. Wind power exhibits strong regional characteristics, often allowing cascaded construction of multiple wind farms along the same wind belt for rational wind energy utilization, with rapidly increasing single-unit and single-farm capacities, thus forming ultra-large wind farm microgrid clusters. Existing independent regulation methods for individual wind farms can no longer meet regional grid voltage and frequency regulation requirements. Therefore, wind farm clusters and their collection stations must be treated as a microgrid for coordinated control between collection stations and cluster center stations, implementing integrated management of energy, voltage, frequency, and cost through system optimization. [Figure 3: see original paper] shows a typical topology of a wind farm cluster integrated into the power system.

Reactive voltage coordinated control in wind microgrid clusters is a key issue requiring resolution in wind power generation.

3.2 Photovoltaic Microgrid Cluster

Large-scale PV power plants connect to distribution networks at medium-high voltage due to concentrated installation and large equipment capacity, exhibiting centralized large-scale characteristics. Different PV capacities, grid-connection methods, and system configurations impose higher requirements for grid integration. Grid-connected PV systems primarily consist of PV arrays, inverters, and other grid-connection components. PV arrays comprise series-parallel connected PV cells, while inverters and corresponding filters deliver the generated power to the grid, requiring maximum power point tracking (MPPT) control and inverter control. The basic framework of a large-scale grid-connected PV power station cluster is shown in [Figure 4: see original paper].

Large-scale PV power stations face issues such as component performance differences, amplified circulating current harmonics from multiple parallel inverters, and power quality, voltage fluctuation, and islanding problems in local grids. Future grid integration of PV clusters requires coordinated control to ensure safety and reliability of all components. The four types of microgrid clusters can coordinate their output to achieve economical, secure, and reliable power supply.

3.3 Wind-Solar, Wind-Storage, PV-Storage, and Wind-Solar-Storage Microgrid Clusters

Currently, widely studied clusters include wind-solar, wind-storage, PV-storage, and wind-solar-storage configurations. When wind farm capacity ranges from 10 kW to 1,000 kW, wind-solar complementary clustering is typically adopted for grid connection. When wind farm capacity is below 10 kW, different distributed generation types are combined to balance uncertainty and intermittency through cluster operation.

Due to uncertainty and intermittency, power forecasting and real-time scheduling for different microgrid clusters cannot be perfectly accurate. Real-time control strategies such as primary frequency regulation, automatic voltage control, and emergency active power control can achieve short-term active power balance from a security perspective. For reactive power, real-time coordinated control of various reactive power sources based on their characteristics can realize automatic voltage distribution functions.

4 Microgrid Cluster Control Based on Spatiotemporal Distribution

Microgrid clustering integrates geographically adjacent, characteristic-related distributed power sources such as wind farms and PV stations that share a common connection point, forming a microgrid cluster for centralized coordinated control. This effectively mitigates the volatility and randomness of single small-scale distributed sources (e.g., wind) and the intermittency of PV generation. Through mutual scheduling and complementation of storage modules with wind and solar resources—charging storage when DGs generate power, using wind power as the primary supply when PV is inactive at night, and utilizing storage when both are insufficient—clusters can approximate conventional power plants in scale and external regulation characteristics. This enables flexible response to grid dispatch and control, adapts to high-penetration DG development, and improves intermittent power source utilization.

Microgrid cluster control technology forms the core of microgrid cluster control systems. Developing control strategies tailored to cluster output characteristics and local grid conditions is crucial. The fairness of control strategies involves stakeholders' interests, requiring cluster coordination to address both technical and economic considerations. A complete power purchase and feedback mechanism must be established to ensure fair and equitable power exchange between clusters and with the grid. Due to the inherent hierarchical nature of distributed power sources, both temporal and spatial indices require deep consideration during hierarchical and zonal coordinated control, leaving room for coordination improvement in all functions.

4.1 Spatiotemporal Distribution

4.1.1 Temporal Scale Based on real-time control (minute-level ultra-short-term forecast data), dispatching plans are adjusted (hour-level ultra-short-term forecast data), which in turn inform long-cycle (day-level short-term forecast data) configuration settings for large time periods. These temporal cycles are interrelated and mutually restrictive, forming a microgrid cluster temporal planning pattern as shown in [Figure 5: see original paper].

4.1.2 Spatial Scale Clusters can respond to distribution network commands, reflect microgrid demands, control various stations and equipment, and achieve coordination among generation devices, between microgrid clusters, and with the distribution network. The cluster spatial dispatch coordination control diagram is shown in [Figure 6: see original paper].

The establishment of cluster spatial scales facilitates horizontal coordination among different generation devices within microgrids and vertical coordination from microgrids to clusters to the grid. Horizontal coordination enables complementary support between devices to complete voltage control, while vertical coordination reflects spatial transmissibility, allowing grid commands to be transmitted layer by layer to each generation device with precise information delivery.

4.2 Cluster Control Mode

The objective of spatiotemporal cluster control is to unify dispersed microgrid systems with temporal and spatial interconnections into large-scale cluster systems. To achieve this, clusters must first reduce grid impact and second, provide grid support capabilities—cooperating during normal operation and offering effective power support or disconnection during abnormal or fault conditions.

(1) **Active Power Support and Frequency Regulation**: Clusters must respond to upper and lower level active power and frequency regulation, calculate economic margins and reliability, and actively participate in peak shaving and valley filling. When frequency regulation is insufficient, clusters should provide short-term secondary frequency regulation to adjust grid frequency deviation.

(2) **Reactive Power and Voltage Control**: Large-scale networked clusters can ensure reactive power and power factor stability while supporting voltage stability, enabling rapid voltage recovery during faults and preventing large-scale disconnection before fault clearance.

(3) **Security Assurance System**: Clusters must implement real-time monitoring and fault alarm online regulation, emergency switching during critical situations, and optimal splitting point identification when faults cannot be cleared, ensuring reliable system operation.

(4) **Coordinated Operation**: As microgrids form clusters, internal components can obtain information through agents and receive internal support when necessary, ensuring coordinated operation where each part obtains what it needs.

5 Conclusion

As an emerging concept, microgrid clusters have not yet been widely applied. However, as a novel dispatching model and method, they can mitigate the volatility and uncertainty of single distributed power sources while improving microgrid stability. Regional microgrid clusters, combined with new hierarchical and zonal control, system control structures, and spatiotemporal distribution-based cluster control, demonstrate the superiority of cluster operation. With increasing distributed power penetration, microgrid clusters warrant further research and exploration.

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