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CHALLENGES AND DESIGN ASPECTS OF MICROGRID CLUSTERING

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With the growing penetration of distributed energy resources, the traditional microgrid concept is evolving into microgrid clustering, which decomposes the distribution system into interconnected microgrids to improve stability, reliability, and efficiency. Microgrid clusters coordinate power-sharing between microgrids and the main grid, effectively reducing problems such as voltage rise, harmonics, poor power factor, reverse power flow, and conventional protection scheme failures. However, there are challenges to overcome before adopting microgrid clustering, particularly in the design aspects. This paper critically reviews the challenges in the design of microgrid clustering, categorizing multi-microgrids into different architectures based on the interconnections' layout, evaluating reported control techniques in microgrid clustering, and presenting aspects of multi-microgrid protection. Possible areas of future research are highlighted to improve the operational aspects of microgrid clusters. Ref. 3, fig. 6, tables 2.

Keywords: energy management, microgrid cluster, ring connection, power converter, protection, synchronization.

Introduction. The demand for electricity has been on the rise, while the availability of fossil fuels has been diminishing. This has resulted in unpredictable fluctuations in electricity prices. However, in view of the growing concerns over greenhouse gas emissions and the need for sustainable energy sources, renewable power generation has been gaining attention as a means to meet future energy requirements [1]. In addition to energy dependence and the risks associated with energy shortages, the issue of environmental impact on electric power systems is a significant concern that is becoming increasingly important in society. The risk of an energy crisis looms large in the event of power outages, which may occur due to technical issues in the power grid, natural disasters, or political conflicts. Such crises can lead to significant economic losses and pose a threat to the country's security.

The demand for electrical power continues to rise while the availability of fossil fuels diminishes. This has led to unpredictable fluctuations in energy prices. In response to environmental concerns and the need for sustainable energy sources, renewable energy production is gaining significant attention as a future energy solution. Distributed energy resources such as solar, wind, hydro, and geothermal energy are being recognized as stable, environmentally friendly, and economically viable alternatives to traditional energy sources. Their use can reduce fuel import dependency, lower greenhouse gas emissions, and enhance energy independence.

Environmental issues and increasing power demand promote the development of microgrid (MG) technology [2, 3], which can be operated in AC, DC, or mixed AC/DC technology. Although the development of MGs has become more consummate, there are still some challenges, such as the lack of absorptive capacity for large-scale renewable energy technologies. Meanwhile, the development of energy storage systems and electric vehicles has an urgent demand for smart MG technology.

As the penetration of distributed energy resources grows, the traditional microgrid concept is evolving towards microgrid clustering, which involves breaking down the distribution system into interconnected microgrids to enhance stability, reliability, and efficiency. Microgrid clusters coordinate power distribution between microgrids and the main grid, effectively addressing issues like voltage rise, harmonics, poor power factor, reverse power flow, and protection scheme limitations. However, before adopting microgrid clustering, there are challenges, particularly in the design aspects.

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Objective. The aim of this article is to explore the technology of microgrid clusters and their utilization in addressing reliability and efficiency issues in the energy sector, particularly in the context of renewable energy sources. The objective is to analyze the advantages and challenges associated with microgrid development and investigate various architectures and interaction methods of microgrid clusters. Additionally, the goal is to compare different power transmission technologies within microgrid clusters and examine their respective merits and drawbacks. Special attention is also devoted to the control and management of microgrid clusters, along with highlighting directions for future research aimed at enhancing the integration of large-scale renewable energy sources and developing robust microgrid cluster management systems.

Main Results. A microgrid cluster is a technique for self-healing and reconfiguration that divides the distribution network into smaller, manageable grids. It combines multiple microgrids close to each other, creating a network of interconnected microgrids. This has several economic benefits for both the utility grid and the microgrids, including increased reliability, stability, and reduced costs.

When the main grid fails, individual microgrids may struggle to meet demand due to the intermittent nature of renewable-energy-based distributed generation. To address this issue, microgrids in a cluster can support each other during islanded operation through interconnections. Figure 1 provides an example of a microgrid cluster comprising two microgrids. Nonetheless, connecting several microgrids into a cluster requires a reliable control and energy management system to ensure the safe and efficient operation of the entire cluster during both grid-connected and islanded modes.

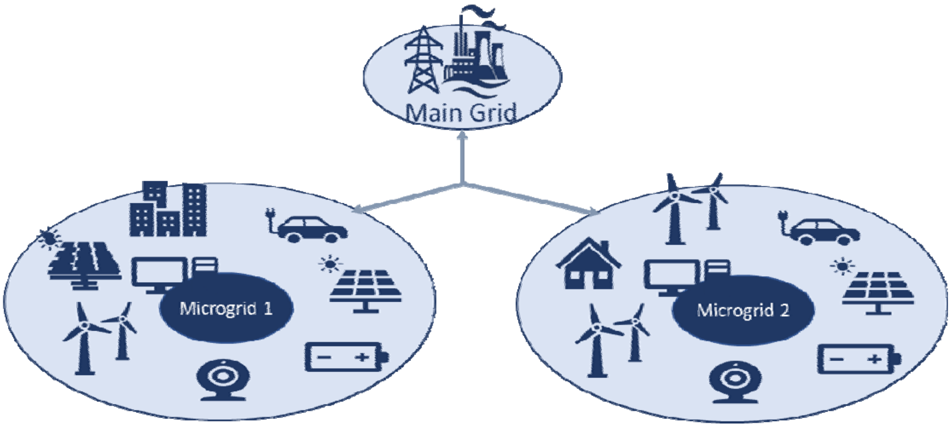

Fig. 1

The architecture of microgrid clusters can be classified into three types based on the network formation: parallel-connected, ring-connected, and mesh-connected (table 1). In the parallel-connected architecture (figure 2, 3), the microgrids are connected in parallel to the main grid in a radial or star topology. In the star topology (figure 2), multiple microgrids are connected to the main grid through a common bus bar. This allows surplus power to be transmitted to neighbouring microgrids or the main grid, and power deficits to be filled by neighbouring microgrids or the main grid.

In the radially connected topology (figure 3), larger microgrids are directly connected to the main grid, while smaller microgrids are connected to a large microgrid through a separate common bus bar, enabling power-sharing through the main grid.

In the ring-connected architecture, each microgrid is connected to two adjacent microgrids in the shape of a ring, allowing energy and information to be shared between them.

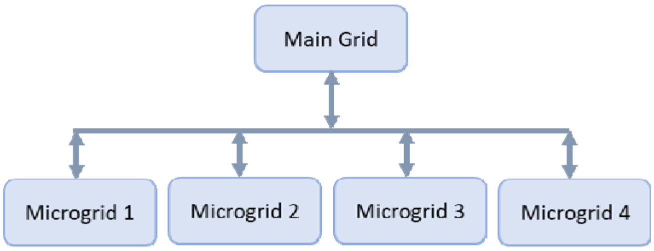

Fig. 2

Fig. 3

The ring network has improved redundancy and stability compared to the radial structure, but controlling and protecting the system becomes complex due to the multiple pathways for power exchange.

Microgrid clusters can also have a mesh architecture where all microgrids are interconnected, creating a complex network. In this type of configuration, each microgrid is connected to its neighbouring microgrids through a power transmission and communication network, as depicted in Figure 4. As a result, each microgrid can exchange power with the main grid and neighbouring microgrids, resulting in improved operational performance with increased stability and reliability due to redundant connections. However, controlling and protecting such a complex network is a challenging task. The dispatching and scheduling of distributed generation in each microgrid are influenced by all connected microgrids and their local demand and supply, making power-sharing management difficult.

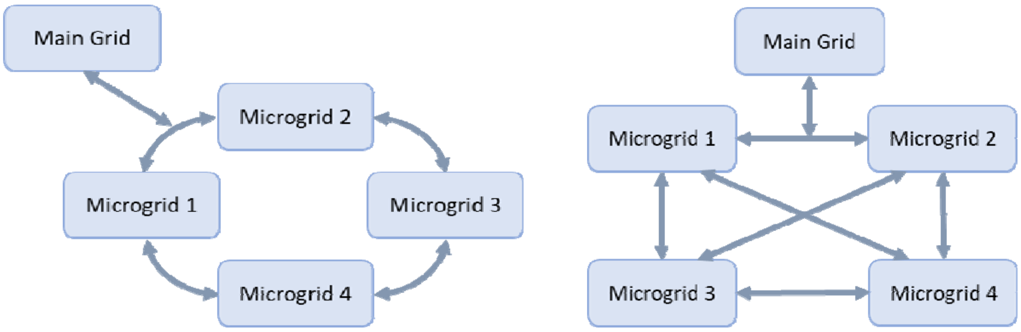

Fig. 4

Table 1 compares different microgrid cluster architectures based on various factors. The table evaluates the growing capacity of the cluster, individual microgrid growing capacity, overall scaling capacity, and complexity associated with each architecture.

Table 1

Layout architecture	Microgrid cluster growing capacity	Individual microgrid growing capacity	Overall scaling capacity	Complexity
Parallel	Low	Medium	Low	Low
Ring	High	Medium	Medium	Medium
Mesh	High	High	High	High

Line technologies used in microgrid clusters can be AC, DC, or hybrid, table 2 provides it's comparison. AC systems allow for voltage level changes and isolation using transformers, while also using established protection techniques. However, they require power and frequency control, are susceptible to transient and dynamic instabilities, and come with high operational costs due to losses, skin effect, and dielectric losses. They also need synchronism and suffer from large power oscillations, making them applicable only for short distances (<50 km).

Table 2

System	Advantages	Disadvantages
AC systems	• voltage level changes • isolation using transformers • established protection techniques	• require power and frequency control, • susceptible to transient and dynamic instabilities, • high operational costs due to losses, skin effect, and dielectric losses • need synchronism • suffer from large power oscillations
DC systems	• higher efficiency with reduced losses and fewer conversion stages • better transient and dynamic stability with no electromagnetic interference • lower operational costs associated with conductors and insulators	• interfaces are costly • fault isolation is difficult due to the lack of a zero-crossing point.

On the other hand, DC systems have higher efficiency with reduced losses and fewer conversion stages. They offer better transient and dynamic stability with no electromagnetic interference and lower operational costs associated with conductors and insulators. However, their interfaces are costly, and fault isolation is difficult due to the lack of a zero-crossing point.

To connect different line technologies, power transformers and power electronics converters are commonly utilized. Power transformers offer a reliable and cost-effective method for changing AC/AC voltage levels. However, they have low controllability and operational performance. On the other hand, power electronics converters have better voltage regulation and high voltage controllability. They can be used to interconnect any line technology, whether AC/AC, AC/DC, or DC/DC. However, they have certain disadvantages, including protection requirements, communication dependency and being an expensive solution.

Achieving optimal power-sharing and regulation of voltage and frequency in a microgrid cluster can be challenging due to different operating scenarios and system architectures. Two major control structures are commonly used: hierarchical and distributed.

The hierarchical control structure divides control objectives into three control layers (figure 5). The primary control layer handles local control operations such as voltage and frequency regulation, active and reactive power control, islanding detection, and local protection. The secondary control layer ensures voltage and frequency regulation due to deviations caused by primary-level control actions. In addition, it performs grid synchronization, optimal operation of DERs, and real-time energy management. The third control layer, in collaboration with the distributed network operator, performs market operations such as economic dispatch and unit commitment.

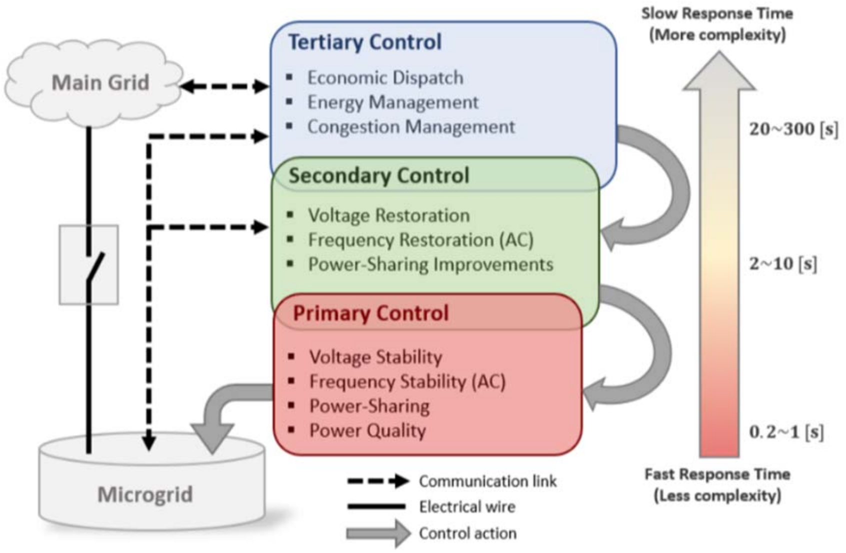

Fig. 5

The distributed control structure consists of a two-level structure (figure 6). In the distributed primary control layer, microgrids manage voltage, current and frequency regulation, islanding detection, grid synchronization, and load power management in a fully distributed manner. In the

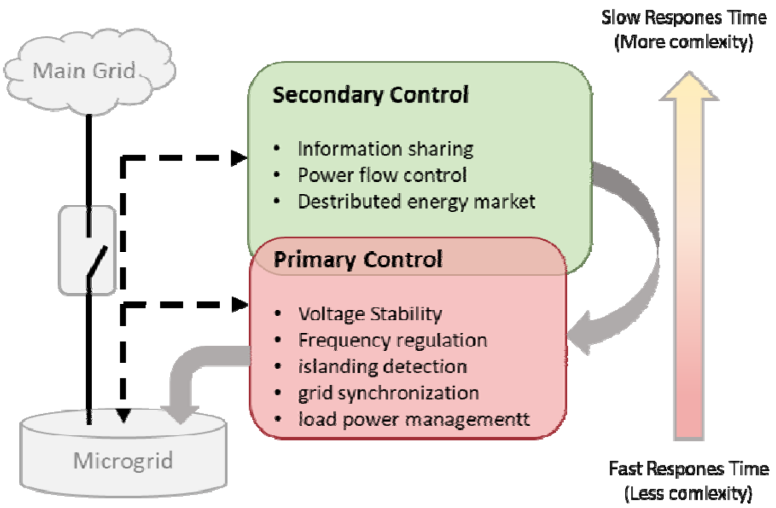

Fig. 6

secondary control level, each microgrid shares information with other microgrids and the distributed network operator to perform market operations and optimal power flow.

While the hierarchical control strategy can provide better economic operation of the microgrid cluster, it doesn't support the growth of the microgrid cluster. On the other hand, the distributed control strategy offers more flexibility and scalability, allowing for "plug-and-play" functionality.

Future research in microgrid cluster technology can focus on several key areas. Firstly, addressing the lack of absorptive capacity for large-scale renewable energy technologies within microgrids is crucial. Developing strategies to improve the integration and utilization of renewable energy sources, such as advanced forecasting techniques and optimized scheduling methods, can be explored. Secondly, the demand for smart microgrid technology should be addressed, considering the development of energy storage systems and electric vehicles. Research can focus on enhancing intelligence and automation in microgrids through advanced control algorithms, machine learning, and real-time optimization methods. Thirdly, reliable control and energy management systems need to be developed to ensure the safe and efficient operation of microgrid clusters. This can involve investigating novel control strategies, communication protocols, and distributed coordination mechanisms to enhance performance and resilience.

Conclusions. Various aspects of microgrid clusters have been discussed, wherein the distribution system is divided into interconnected microgrids to enhance stability, reliability, and efficiency. The different line technologies employed in microgrid clusters, along with their respective advantages and disadvantages, and their interconnections using power transformers and power electronics converters, have been explored. Additionally, the challenges related to optimal power sharing, voltage and frequency regulation in microgrid clusters have been addressed, considering hierarchical and distributed control strategies. The design challenges of microgrid clustering have also been reviewed, including the categorization of multi-microgrids into different architectures, evaluation of reported control techniques, and presentation of multi-microgrid protection aspects. Potential areas for future research aimed at refining the operational aspects of microgrid clusters have been highlighted.

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ПРОБЛЕМИ ТА АСПЕКТИ КЛАСТЕРИЗАЦІЇ MICROGRID СИСТЕМ

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Зі зростаючим проникненням розподілених енергетичних ресурсів традиційна концепція мікромереж еволюціонує до кластеризації мікромереж, яка декомпозує розподільчу систему на взаємопов'язані мікромережі для підвищення стабільності, надійності та ефективності. Кластери мікромереж координують розподіл електроенергії між мікромережами та основною мережею, ефективно зменшуючи такі проблеми як підвищення напруги, гармоніки, низький коефіцієнт потужності, зворотні перетоки електроенергії та збої в роботі традиційних схем захисту. Однак, перш ніж впроваджувати кластеризацію мікромереж, необхідно вирішити низку проблем, зокрема, пов'язаних з проектуванням. Метою цієї статті є вивчення технології кластерів мікромереж та їхнє використання для вирішення питань надійності та ефективності в енергетичному секторі, зокрема в контексті використання відновлюваних джерел енергії. У даній статті критично аналізуються проблеми проектування кластеризації мікромереж, вивчаються переваги та виклики, пов'язані з розвитком мікромереж. Досліджуються різні архітектури мікромережевих кластерів та методи їхньої взаємодії. Класифікація кластера мікромережі проводиться за різними архітектурами на основі розташування з'єднань. Також проводиться порівняння різних технологій передачі електроенергії в межах мікромережевих кластерів, зокрема систем змінного струму та постійного струму, з оцінкою переваг і недоліків кожної технології. Значна увага приділяється контролю та керуванню мікромережевими кластерами, висвітлюються можливості ієрархічних та розподілених структур управління для забезпечення оптимального розподілу потужності та регулювання напруги та частоти. На завершення статті розглядаються перспективні напрями подальших досліджень, спрямованих на поліпшення інтеграції великомасштабних джерел відновлюваної енергії, розробку інтелектуальних систем управління. Висвітлено можливі напрями майбутніх досліджень для покращення експлуатаційних аспектів кластерів мікромереж. Бібл. 3, рис. 6, табл. 2.

Ключові слова: управління енергією, кластер мікромереж, кільцеве з'єднання, силовий перетворювач, захист, синхронізація.

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