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Remote Islanded Microgrid

A feasible and economical solution for providing resilience and reliability to power systems in rural areas.

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DISTRIBUTED ENERGY RESOURCES (DERS), such as distributed generators, batteries, and electric vehicles, have experienced rapid growth in recent years. For instance, in the third quarter of 2024 alone, the U.S. solar market installed 8.6 GW of capacity, maintaining its trend of record-setting quarterly growth (see Wood Mackenize/Solar Energy Industries Association 2024 in "For Further Reading"). This rapid expansion highlights the urgent need for solutions to integrate these flexible resources into power systems, as the systems carry the risk of insufficient and intermittent power supply. Microgrids offer a solution to this challenge by enhancing the reliability, resilience, and efficiency of power systems. Therefore, they have become a topic of significant interest among researchers and engineers.

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Introduction

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Microgrids, defined as active distribution networks consisting of DERs, represent a promising future for energy systems. They can be operated in either islanded or grid-connected modes, offering a versatile solution to power supply challenges. The grid-connected mode refers to the operation of microgrids directly linked to the primary power grid. In this mode, microgrids can draw electricity from the main grid to compensate for any mismatches between local energy demand and the power generated by DERs. When microgrids have enough capacity to transfer power back to the main grid, they can also be governed by the grid to support voltage regulation, frequency control, and economic dispatch of the main grid. In contrast, the islanded mode is the operation of microgrids when they are disconnected from the primary power grid and function as self-sufficient energy systems. In this mode, microgrids rely solely on locally available DERs to meet power demand, with energy management systems making localized operational decisions to balance generation and consumption. While the islanded microgrid may show less operational flexibility compared with the grid-connected microgrid due to its lack of connections with main grids, its isolated operating mode and localized power balance make it an excellent solution for remote communities. In these communities, autonomous power systems are urgently needed to guarantee power supply reliability.

In remote areas, power systems face multiple challenges, such as volatile markets and extreme events. With the technical functions of microgrids, local DERs, such as distributed photovoltaics (PVs) and battery energy storage systems (BESSs), can be effectively integrated into remote power systems so that power demand will be better satisfied by local resources than by costly transactions with the main grid. Furthermore, as an autonomous power system, the remote microgrid can also be operated locally in islanded mode when the lines to the main grid are out of service, which firmly guarantees power supply reliability in emergencies. The characteristics of microgrids enable fragile remote power networks to better exploit the potential of local DERs for secure and economical operations.

This article provides an overview of the remote islanded microgrid, including an introduction of the islanded microgrid and its utilization in improving the power systems in remote areas. Then, we present the design and control strategies of remote islanded microgrids, especially the different aspects to be considered during the application. Further, two practical engineering projects are introduced, which provide replicable models for other rural utilities to utilize microgrid technologies to enhance the reliability and resilience of power systems.

An Overview of Remote Islanded Microgrid

Introduction of Islanded Microgrid

Microgrids, as an emerging technology in the power sector, are localized power systems that interconnect distributed generators, energy storage systems, and various loads. Typically, microgrids operate in grid-connected mode, but they are capable of disconnecting from the main grid and operating in islanded mode as needed. A widely adopted definition of *microgrid*, provided by the Microgrid Initiative of the U.S. Department of Energy, is "a group of interconnected loads and DERs within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid." Based on this definition, a microgrid is a distinct cluster of interconnected grid components that can be separated from the larger grid. The local energy resources within such clusters should be sufficient to balance active/reactive power and stabilize system frequency and voltage, whether connected to or separated from the main grid. Microgrid technologies offer several benefits, especially for remote areas, such as harnessing on-site generation resources, reducing energy costs, and enhancing power supply quality, which can be a source of optimism for the economic benefits of microgrids.

One of the distinctive characteristics of a microgrid is its ability to flexibly switch between grid-connected and islanded modes. To operate in islanded mode, the reliability, sustainability, and adaptability of the energy supply are prioritized in microgrids. Thus, microgrids often orchestrate a diverse mix of fuel-based and renewable generators, such as diesel generators, microwind turbines, and PV panels. With the advancement of smart grid technologies, an increasing number of distributed flexible resources at the edge of the grid can be utilized to dynamically optimize microgrid operations. These technological advancements play a crucial role in the successful implementation of microgrids, which requires meticulous design and the coordinated interplay of grid infrastructure, generators, energy storage systems, and demand-side flexible resources, supported by tailored operation, control, and protection systems capable of functioning in the absence of grid support, as shown in Figure 1.

Grid Infrastructure

Since microgrids are typically designed to meet specific needs, there is no one-size-fits-all architecture. Both ac and dc microgrids have been extensively studied and demonstrated through pilot projects. Overall, ac microgrids are more common due to their relatively easy integration into the larger grid. However, given the dc nature of specific microgrid resources (e.g., PV panels, BESSs, and some loads), ac/dc power electronic converters are widely used in ac microgrids, resulting in higher energy losses. With better energy efficiency, dc microgrids are gaining popularity in scenarios with a high proportion of dc generators and loads. For both ac and dc microgrids, a radial grid topology is prevalent. In this configuration, the power flow is typically characterized by a single path from the generation resources to the loads, simplifying operation, control, and protection schemes. Thus, although microgrids can be looped or meshed, these configurations, which involve multiple interconnected paths for the power flow, are rarely implemented, due to their complexity and the challenges they pose for operation, control, and protection.

Generators and Energy Storage Systems

Integrating generation and storage devices is crucial to ensuring the sufficiency and reliability of microgrids. A diverse range of generation resources can be installed in microgrids, including reciprocating internal combustion engines (e.g., diesel generators), renewable energy sources (e.g., wind and solar farms), and fuel cells. The orchestration of generators must comprehensively account for capital investment, fuel costs, and dispatchability. To enhance load balancing capabilities, various energy storage systems can be integrated to act as buffers between electricity generation and consumption. While most attention is focused on electricity storage (e.g., batteries), fuel and kinetic storage systems (e.g., hydrogen and flywheels) are also viable alternatives.

Demand-Side Flexible Resources

Increasing penetration of information and communication technologies on the demand side unlocks the controllability of distributed flexible resources. Different from utility-scale ones, demand-side energy storage systems and on-site generators are typically small in capacity and dispersed in geography. Similarly, thermostatically controlled loads (e.g., air conditioners and water heaters) and other smart appliances in households can dynamically adjust their power but have limited capacity. Thus, operation and control strategies are essential to optimally leverage these resources, ensuring appropriate aggregation. **<AU: Please check that the preceding edited sentence conveys the intended meaning.>**

Control and Protection Systems

Microgrid control systems must be capable of ensuring a seamless transition between grid-connected and islanded modes as well as managing complex operational dynamics arising from renewable energy integration. Therefore, when designing control schemes, such as droop control and model predictive control, it is essential to balance operational efficiency, communication overhead, and scalability. Protection systems also face unique challenges, such as drastically changing fault currents due to the absence of main grid inertia, particularly in islanded mode. Adaptive protection schemes, both centralized and decentralized, appear to be promising solutions for addressing the continuous changes in operating conditions and microgrid architecture.

Utilizing Islanded Microgrid in Remote Areas

Electricity has long been recognized as a key driver of economic development and local community welfare. However, a 2023 report by the International Energy Agency (IEA) revealed that approximately 750 million people worldwide still lack access to electricity, with the majority residing in remote or underdeveloped areas (see IEA 2024). The commercialization and privatization of utility companies have led to a primary challenge in electrifying remote areas: a lack of sufficient incentives due to relatively lower economic attractiveness. To tackle this issue, the establishment of dedicated agencies is crucial. These agencies would be responsible for allocating resources for the development of remote power systems, moving away from a reliance on purely commercial activities. Another challenge faced by remote power systems is dispersed population distribution. Low population density typically results in high capital costs to supply electricity to each customer. At the same time, since loads are aggregated within a limited geographical area, the uncertainty of electricity consumption becomes more pronounced, posing

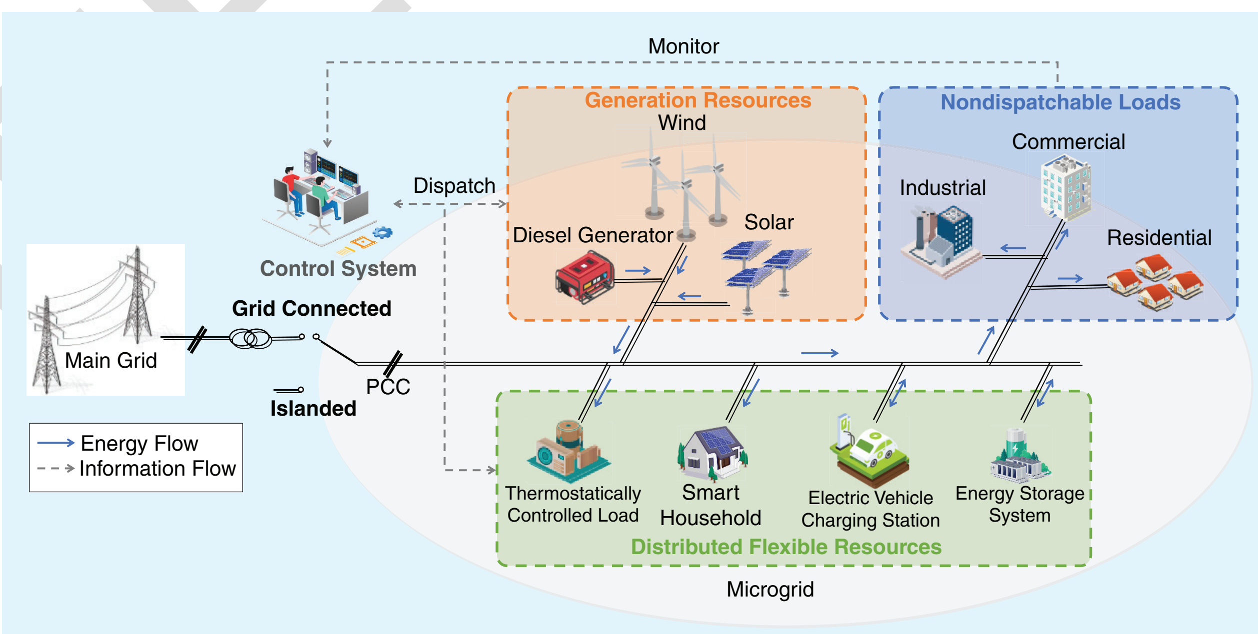

Figure 1. The structure of a microgrid. PCC: point of common coupling.

higher requirements for resource adequacy and grid management strategies.

Given the usual absence of legacy infrastructure, islanded microgrids, which can function independently, are seen as the ideal solution for providing adaptable and robust electricity supply to customers in remote areas. In regions like the Arctic communities in Alaska or the mountainous villages in Nepal, the construction of electricity infrastructure around on-site generation resources can bring about a significant improvement in the quality of life for local communities. By integrating interconnected flexible resources and advanced control strategies, islanded microgrids not only reduce energy costs and enhance operational efficiency but also bolster the resilience of remote power systems. These benefits stem from the proximity of loads to generators, which reduces capital investments in transmission infrastructure and minimizes energy losses. Moreover, as systems that operate under standards similar to those of conventional power grids, islanded microgrids pave the way for remote power systems to seamlessly integrate with larger grids when the time is right, instilling hope for the future of remote electrification.

Design and Control Strategies

Remote Islanded Microgrid Design: Sufficiency, Resilience, and Economics

Designing remote islanded microgrid systems is a survival-first approach, prioritizing energy autonomy in remote areas where extending the main grid is either economically prohibitive or geographically infeasible. Besides common considerations, e.g., optimizing component sizing, integrating variable resources, and managing costs, remote islanded microgrids face uniquely stringent requirements due to their isolation from centralized grids. Unlike their grid-connected counterparts, islanded systems must achieve complete self-sufficiency. This necessitates more renewable generators to handle seasonal variability, multiday energy storage to cover extended periods of low solar or wind availability, and redundant backups for emergencies. Advanced control systems are essential to damping microgrid voltage and frequency dynamics without inertia support from external grids. Adaptive protection schemes must be capable of managing the low-fault currents in such small-scale grids with a high ratio of power electronic interfaces. One inappropriate design decision, such as undersizing the storage and underestimating load growth, can result in a blackout.

Sufficient and Reliable Power Supply

Ensuring a sufficient and reliable power supply to meet the local community's demand is the foremost priority for the remote islanded microgrid, as evident in the overall structure of the design strategies in Figure 2. To achieve this, one of the key design strategies is the use of diverse power generation, encompassing both renewable and traditional energy resources. The abundance, sustainability, and cost effectiveness of renewables, such as PV and wind power, make them popular choices for remote microgrids. However, the inherent uncertainty of renewable energy necessitates the presence of backup power sources to

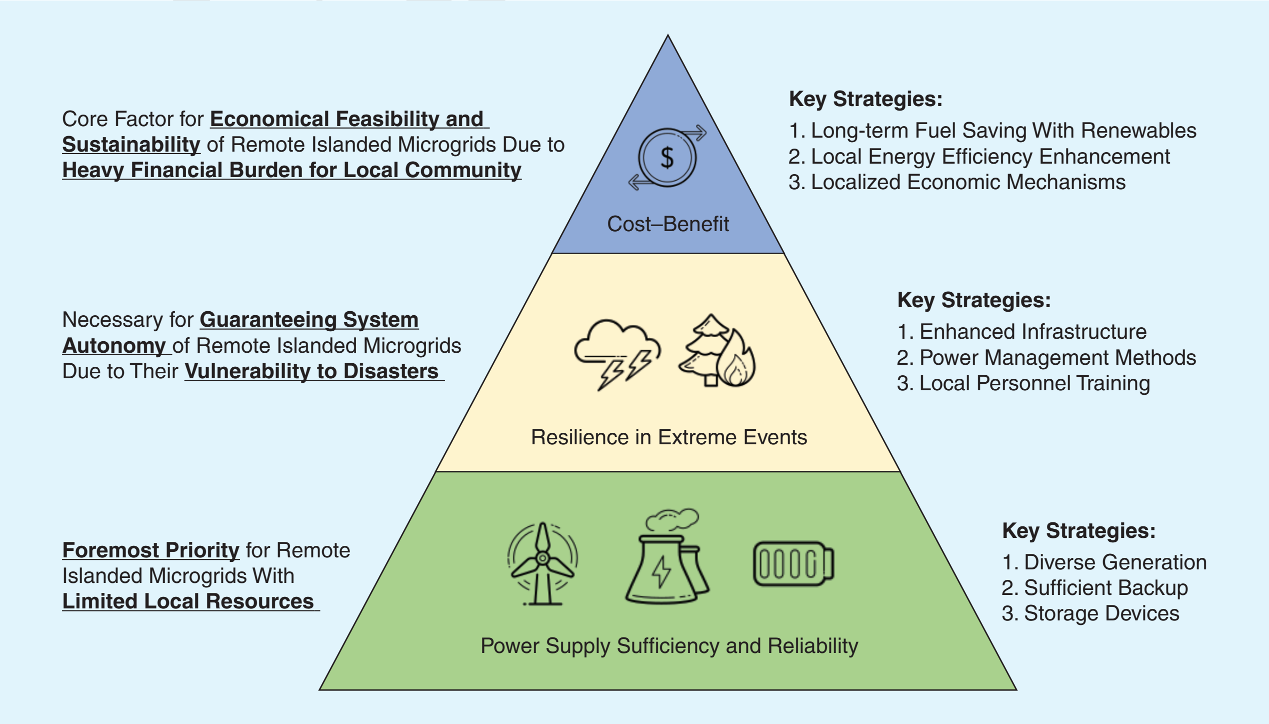

Figure 2. Key strategies for the design of remote islanded microgrids.

ensure a reliable power supply during periods of low renewable generation. By combining various renewables with conventional generation units like diesel generators, we can significantly enhance the overall reliability and availability of remote islanded systems, providing a sense of reassurance to the community.

Equally important in ensuring a reliable power supply in remote islanded microgrids is the BESS. Unlike grid-connected microgrids that can rely on external support, remote islanded microgrids depend entirely on local storage to bridge gaps between generation and demand. Batteries play a vital role in storing excess energy produced during peak renewable generation periods and supplying power in high-demand or low-generation scenarios. Advanced energy management algorithms and energy management systems are even more essential in these isolated systems, as they must independently regulate power supply and demand without the stabilizing influence of a central grid. Real-time data monitoring and automated control systems are indispensable for optimizing energy distribution within the community, mitigating the risk of shortages. Furthermore, with robust infrastructure, accurate load and renewable energy forecasting, and effective demand-side management strategies, remote islanded microgrids can dynamically adjust energy consumption to match available generation, enhancing resilience and long-term sustainability.

Resilience in Extreme Weather Conditions

Remote islanded microgrids are often situated in regions highly vulnerable to extreme weather events, such as hurricanes, wildfires, and heavy snowfall. For grid-connected microgrids, there are external power restoration efforts that can be relied on, but remote islanded microgrids must be self-sufficient during the whole process of disaster response and recovery. As a result, resilience planning becomes a fundamental necessity for the long-term viability of remote islanded microgrids.

One of the major strategies for guaranteeing system resilience is the utilization of specially designed and durable infrastructure. Considering geographic isolation, wind turbines, solar panels, and transmission lines should be able to endure severe environmental conditions, as external repair assistance may be delayed or unavailable. For example, hurricane-resistant wind turbines and reinforced solar panels can significantly reduce damage during extreme storms, while underground cabling can minimize vulnerability when facing strong winds and fire hazards.

Furthermore, in most cases, remote islanded microgrids operate without access to the main grid, requiring them to rely solely on internal power generation and storage. Therefore, robust islanding capabilities are essential for remote islanded microgrids. Adaptive power management strategies, such as demand curtailment, become crucial in prioritizing critical loads and extending energy availability during emergencies. DERs should also be carefully coordinated to ensure that essential services remain powered.

Additionally, local personnel training plays an even more significant role in remote islanded microgrid resilience. Unlike conventional power systems, where external experts may be readily available, remote islanded microgrids necessitate well-trained local operators who can implement contingency plans, deal with system failures, and make real-time operational decisions when control systems are unavailable. In microgrids equipped with black-start capabilities, skilled personnel can manually restore the power supply without reliance on external grid support. These measures collectively enhance the resilience of remote islanded microgrids, reducing risks associated with extreme weather and ensuring continuous energy access for isolated communities.

Cost–Benefit Analysis of Microgrid

Designing a remote islanded microgrid requires a more rigorous cost–benefit analysis than conventional microgrids, as these systems must function independently without financial or operational support from a central grid connection. The high upfront investment, ongoing operational expenses, and long-term financial sustainability must be carefully evaluated to ensure that the islanded microgrid remains a viable and resilient energy solution for an isolated community.

One of the significant cost considerations is the high initial capital investment. Establishing a remote islanded microgrid requires substantial funding for the procurement and installation of renewable energy systems, BESSs, and advanced monitoring and control devices. Unlike microgrids that can offset costs through interaction with an external grid, remote microgrids must be designed with sufficient generation and storage capacity from the outset, increasing the required investment. However, these costs can be gradually offset by long-term savings in fuel expenditures, minimized reliance on expensive diesel generators, and potential financial incentives for renewable energy deployment. Operational and maintenance expenses also play a crucial role in long-term economic feasibility. In remote locations where technical support may be limited, maintenance and continuous monitoring are even more critical to prevent failures that could lead to power outages, which would be far more disruptive than in grid-connected settings.

Enhancing energy efficiency is particularly necessary for remote islanded microgrids to maximize the value of available resources. Unlike conventional microgrids that can engage in real-time energy trading with external grids, remote islanded microgrids must develop localized economic mechanisms to manage power surpluses effectively. For instance, dynamic pricing strategies within a microgrid and community-based energy-sharing models can encourage optimal utilization of local DERs.

Remote Islanded Microgrid Control: Stability, Restoration, and Energy Management

Control systems in remote islanded microgrids have multiple responsibilities: they must maintain stability, recover from outages, and manage energy flows in the absence of external grid support. Typically, microgrid control systems adopt a three-layer hierarchical control framework, as in Figure 3. At the core, droop-based primary control operates at the millisecond level and acts as system reflexes that stabilize system voltage and frequency. On top of primary control, secondary control corrects the steady-state deviation of system voltage and frequency from reference points at a minute level. Tertiary control further incorporates objectives like cost minimization, resilience, and long-term energy scheduling, operating on an hourly or daily timescale. Beyond efficiency, without the support from the main grid, control systems of remote islanded microgrids need to guarantee sufficient synthetic inertia to ride through disturbances and the capability of black starting from a blackout. These control systems are required to act proactively to manage renewable intermittency, potential fuel shortages, and extreme weather events to ensure an affordable and reliable electricity supply to remote communities.

Primary Control

The primary control of remote islanded microgrids is crucial for maintaining voltage and frequency stability. Operating on a millisecond timescale, it responds to fluctuations in power demand and generation rapidly. Unlike grid-connected systems that benefit from the stabilizing effect of a more extensive power network, remote islanded microgrids must entirely utilize local control mechanisms to manage stability. These decentralized control strategies are especially essential to ensure reliable operation in these isolated environments, considering the absence of external frequency and voltage support.

Droop control is one of the most fundamental techniques among the various primary control approaches. It regulates the output power of DERs based on frequency and voltage deviations, achieving load sharing among multiple DERs simultaneously without requiring direct communication between neighboring DERs. Load sharing is the process of distributing the power generation and consumption among the DERs in a microgrid, ensuring that each DER contributes its fair share to the overall power balance. This feature is particularly advantageous for remote islanded microgrids, due to the unavailability of robust communication infrastructures. By eliminating the need for centralized coordination, droop control enhances system resilience and simplifies deployment in remote locations.

In addition to conventional droop control, advanced techniques, such as virtual inertia control and adaptive droop control, further improve the stability and performance of remote islanded microgrids. By emulating the inertial response of rotating machines, virtual inertia control mitigates frequency fluctuations and enhances dynamic stability. Meanwhile, adaptive droop control dynamically adjusts control parameters in response to

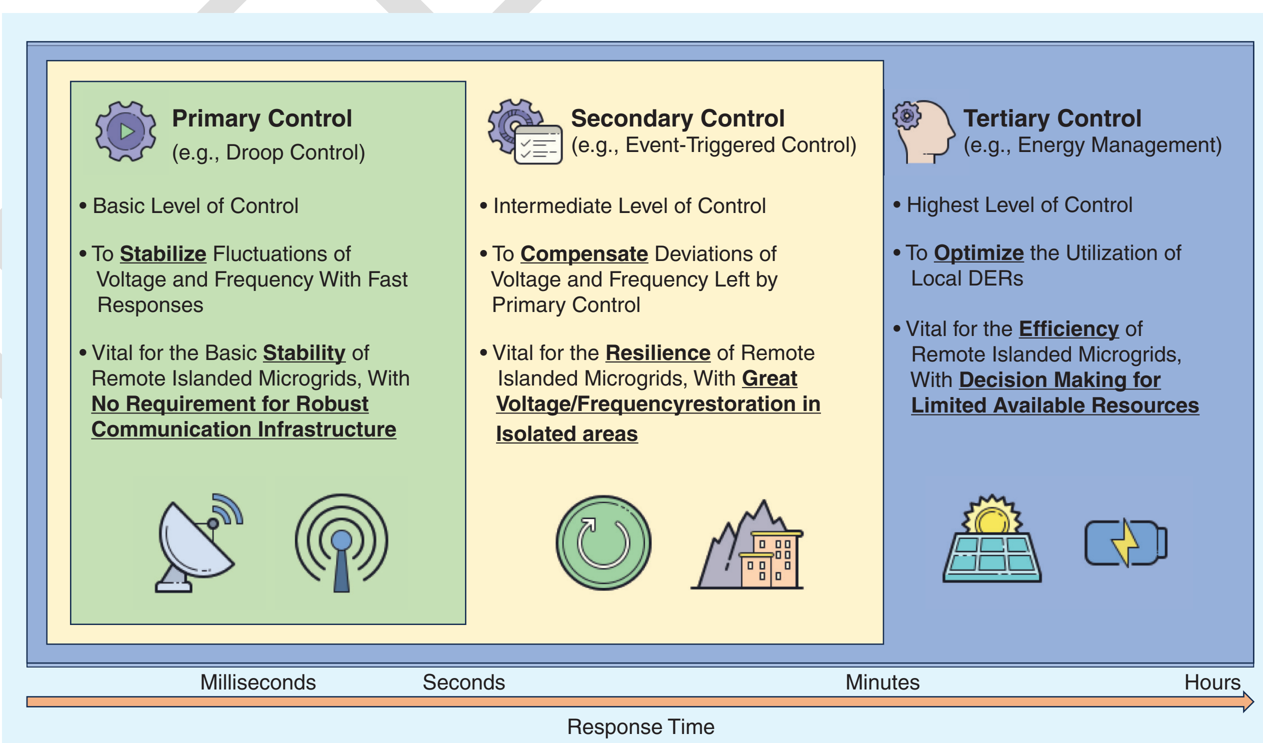

Figure 3. The control hierarchy for remote islanded microgrids.

changing operating conditions, ensuring the robustness and accuracy of load sharing. These advanced control strategies, with their adaptability, are particularly vital for remote islanded microgrids, where maintaining stability without external grid support is a unique and ongoing challenge.

Secondary Control

Secondary control in remote islanded microgrids, operating on a much slower timescale than primary control, plays a crucial role in maintaining stable operation. Its primary function is to restore voltage and frequency to their nominal values, ensuring long-term stability and power quality. While primary control mitigates immediate fluctuations, slight deviations can be left. In a remote islanded microgrid, where external grid support is unavailable, secondary control actively compensates for these residual deviations, thereby ensuring stable operation.

Secondary control can be implemented through either centralized or decentralized methods, but for remote islanded microgrids, the choice of control strategy must consider the urgent challenges posed by limited communication infrastructure and harsh environmental conditions. In a centralized framework, a single controller gathers operational data from across the microgrid and sends corrective signals to DERs after processing the control algorithms. However, this approach relies on robust communication links, which may be unreliable or expensive to maintain in remote areas. Decentralized secondary control, on the other hand, leverages local controllers with limited communication between neighboring DERs, reducing dependency on extensive communication networks and making it more suitable for remote islanded microgrids.

Furthermore, resilience in fault scenarios is not just important but particularly crucial for remote islanded microgrids. Their geographic isolation and limited access to external technical support make them highly vulnerable. The lack of high-reliability communication channels in these regions necessitates advanced control strategies, such as distributed consensus algorithms and event-triggered control, which enable cooperative voltage and frequency regulation and support voltage and frequency restoration with minimal communication requirements. By integrating these advanced control methods, remote islanded microgrids can enhance their operational reliability, ensuring stable power delivery even under adverse conditions.

Tertiary Control

Going beyond primary and secondary control, tertiary control operates at the highest level of the control hierarchy in remote islanded microgrids, focusing on system-wide optimization, economic dispatch, energy management, and restoration strategies. Operating at a much slower timescale, which ranges from minutes to hours, tertiary control is designed to balance cost efficiency, energy availability, and system constraints. This balance is a necessity for the long-term sustainability of remote islanded microgrids.

Unlike primary and secondary control, which are mainly responsible for voltage and frequency stabilization, tertiary control focuses on resource dispatch and operational decision making. This distinction is especially critical in remote islanded microgrids, where energy autonomy is essential due to the lack of external support. One of the key functions of tertiary control is energy management, which involves strategies such as demand-side management. In remote islanded microgrids, where supply and demand must be carefully balanced in real time, certain power demands in local communities, such as specific industrial loads, can be shifted to align with renewable energy availability. By coordinating generation and consumption dynamically, tertiary control maximizes efficiency and reduces the risk of energy shortages.

Additionally, black-start coordination and load prioritization, as part of tertiary control, are crucial for system restoration after an outage. In remote microgrids, black-start strategies ensure that local generation sources can sequentially restore power without overloading the system. Since external grid assistance is unavailable, tertiary control strategically prioritizes critical loads, such as health-care facilities or emergency response centers. This strategic prioritization guarantees that restored power demands can be well satisfied by the limited energy resources in remote islanded microgrids.

Practical Engineering Applications

The rural areas of Iowa face similar technical issues, such as aging infrastructures and market volatility. The solutions to the enhancement of power system reliability in these districts, particularly the effectiveness of microgrid solutions, can be easily generalized to other remote areas. Here, we introduce two engineering cases of microgrids in Iowa, which have been or will be fully functional in practical applications and demonstrate the superiority of microgrids in enhancing reliability and resilience.

Mobile Microgrid for Disaster Recovery

Led by the Iowa Economic Development Authority and Iowa State University (ISU), the project Mobile Microgrid for Disaster Recovery was developed to explore the potential of utilizing renewable energy-fueled mobile microgrids to support local power systems. The project features specifically designed power equipment that can withstand extreme environments, such as water and cold. This equipment is connected within a container, or pallet, creating a self-contained microgrid with excellent mobility. The container, a unique foundation for establishing mobile microgrids, offers increased availability and simplicity while ensuring seamless integration with the power equipment.

Figure 4. The configuration of the mobile microgrid in a container.

As illustrated in Figure 4, the general structure of the mobile microgrid in the container includes power sources, control systems, communication hubs, and other supporting devices. The electricity demand of the mobile microgrid is usually satisfied by solar panels in different sizes. The smaller panels glued to the roof are flexible and conform to the contours of the container. They are designed to capture enough energy to maintain the balance of the plant during times when the larger panels and racking are inside the unit and the microgrid is in a "ready-to-ship" state. In comparison, the larger panels are the primary fuel source to meet self-consumption, transfer to local loads, and export to the main grid. In practical applications, PVs configured with batteries usually provide the primary power generation, allowing for significant fuel and maintenance savings compared with traditional fossil-fueled generators. The container also includes a diesel generator for long-term energy needs during periods of natural resource shortage, such as a black-sky event (i.e., sustained cloud cover). While the container microgrid is designed to run in grid-connected mode to satisfy local energy needs while offsetting demand from the local power grid, it can also be directly operated in islanded mode by the local control system. Supported by the BESS, metering devices and control systems are monitored and operated through remote data connections via the Internet. During Internet outages, local control can be maintained through a computer interface and Ethernet connection. As displayed in Figure 5(a), the inner space is enough for human activity when operating the mobile microgrid in the container. Moreover, the abundant inner space of the container also allows the solar panels and racking to fit inside for shipment as a fully contained unit, as shown in Figure 5(b). At the same time, the control system is accessible by a cellular network and remote login, which allows users to monitor the operations of the microgrid even if they are not on site. This characteristic provides more flexibility in data collecting and real-time control, especially when the mobile microgrid is operating in remote areas.

As previously mentioned, the mobile microgrid can operate in both islanded and grid-connected modes, making it suitable for a wide range of applications. These include food supply, vehicle charging in extreme weather conditions, and wastewater treatment, as demonstrated in Figure 6. With its impressive scalability and adaptability, the mobile microgrid offers an efficient solution to diverse power demands across various regions, particularly those with unreliable power sources and limited

Figure 5. The interior of the container mobile microgrid (a) without solar panels and racking and (b) with solar panels and racking.

system resilience, such as remote areas. The successful deployment of mobile microgrid technology represents a significant leap in microgrid utilization and holds great potential for enhancing the reliability of power systems in remote locations.

Building the First Renewable Community Microgrid in Rural Iowa

Proposed by ISU, the microgrid project Building the First Renewable Community Microgrid in Rural Iowa aims to establish a feasible and replicable solution for enhancing the resilience and reliability of remote power systems with microgrid technologies. With a total investment of US$11,860,955, where funding from the U.S. Department of Energy accounts for 80%, the project is located in Montezuma, which can be seen as a representative rural low-income community. Similar to counterparts in other remote areas, the power system in Montezuma faces representative energy challenges, including market vulnerability, aging infrastructure, reliance on fossil fuels, and exposure to extreme events. To address these challenges, the project aims to transform Montezuma into a state-of-the-art remote microgrid. Led by ISU in collaboration with Montezuma Municipal Light and Power (MMLP) and industry leaders, this project seeks to construct the first utility-scale microgrid in Iowa, with the best reliability and resilience, and establish a scalable and replicable model for other rural municipalities across the Midwest.

As represented in Figure 7, this project proposes three major improvements: 1) the installation of a 2.5-MW solar array with a BESS on an 8.5-acre site owned by MMLP, connected to a power plant substation via three step-up transformers and a newly constructed underground distribution line; 2) the replacement of aging switchgear with modern metal-clad switchgear equipped with digital relays, enabling the integration of solar–BESS and microgrid islanding operations; and 3) the deployment of a supervisory control and data acquisition system and a microgrid controller for remote monitoring dc and control, along with advanced metering infrastructure to enhance grid edge visibility, automate billing, and enable load control. Collectively, these upgrades will improve Montezuma's ability to efficiently manage local energy generation and consumption, mitigate market volatility, and ensure energy availability during extreme events.

The Montezuma microgrid will play a crucial role in reducing the community's exposure to market volatility and dependence on fossil fuels. By integrating renewable energy sources, such as PVs, the project will help lower greenhouse gas emissions while providing MMLP with a new revenue stream to compensate for the anticipated financial loss from planned coal plant shutdowns in the future. This transition will also contribute to long-term energy stability and

Figure 6. The mobile microgrid supporting a wastewater plant.

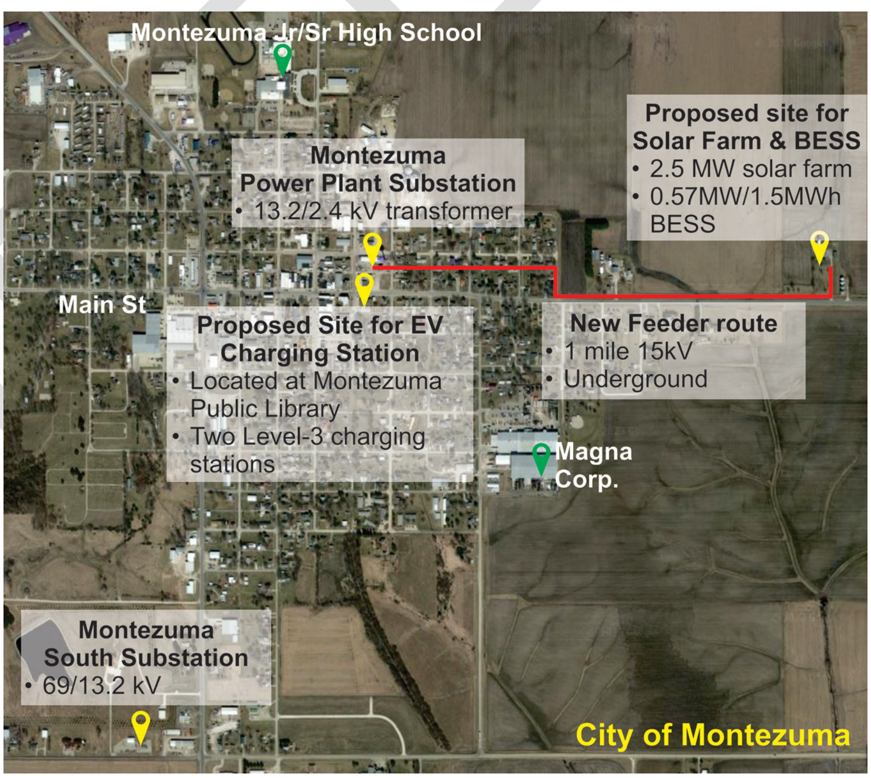

Figure 7. Deployment sites of the Montezuma microgrid.

sustainability for the region. A key benefit of the microgrid is its ability to optimize energy usage through the combination of the solar array, BESS, and optimal dispatch from the microgrid controller. These elements will enable peak shaving, which reduces demand charges during high-cost periods, and energy arbitrage, allowing MMLP to store energy when prices are low and discharge it when prices are high. As a result, MMLP will decrease its reliance on external energy imports, lower its coincident peak demand, and significantly reduce transmission costs. The projected solar generation will contribute an obvious portion of MMLP's total energy demand, directly decreasing the amount of energy the utility must purchase from the market. Additionally, the solar–BESS system will lead to a considerable reduction in coincident peak demand, which is a major factor in determining transmission charges. By mitigating these expenses, the microgrid will help stabilize electricity rates for Montezuma. Beyond economic benefits, the microgrid will strengthen Montezuma's resilience to power disruptions. The upgraded switchgear and advanced microgrid controller will support both intentional and unintentional islanding. In such events, the controller will enable the BESS to function as a grid-forming resource, working alongside diesel generators to regulate voltage and frequency. This capability will substantially lower the risk of blackouts, ensuring a reliable power supply for the community during extreme weather events or other emergencies.

Montezuma's transition to a renewable community microgrid marks a significant step toward energy security, sustainability, and economic resilience. The energy challenges faced by MMLP are common among rural municipal utilities in the Midwest, as many rely on aging diesel units, incur high transmission costs, must meet reserve requirements, and are vulnerable to volatile markets and extreme weather events. Therefore, the insights gained from this project will be useful and replicable to other Midwest municipal utilities, fostering the broader application of microgrids as a technically sound and economically feasible energy solution.

Conclusion and Future Challenges

Driven by the increasing integration of various DERs and higher demand for resilient and sustainable power networks, the microgrid has experienced rapid development in recent years. With the advantages of improving energy efficiency and reliability with local resources, microgrids have been vital infrastructure in distribution systems, especially those in remote and underdeveloped regions where access to stable power supply remains a challenge. Supported by superiority in the exploitation of renewable energy resources and energy storage devices, microgrids can serve as excellent alternatives to traditional centralized power systems. The characteristic of working in both grid-connected and islanded modes further enhances the flexibility of microgrids, making them a sound solution for power system improvement in rural areas.

In this article, we introduced the definition, design strategies, control methods, and engineering applications of remote islanded microgrids, demonstrating the importance of microgrids in enhancing the resilience and sustainability of rural power systems. First, the overall structure and components of microgrids were presented to better illustrate the concept, and then major planning and operating ideas were provided for the application of microgrids. Finally, two practical engineering cases in Iowa were introduced, demonstrating the great potential of islanded microgrids in further enhancing power system reliability, resilience, and economics with localized energy resources in remote regions.

Despite their advantages, remote islanded microgrids still face various technical challenges, which require more research and exploration. To better capitalize on microgrid technologies and improve power systems in rural areas, we summarize several aspects to be further studied:

1) Further development of cost-effective generation and storage technologies, such as microhydro systems, gravity cells, and biofuels, is necessary. By providing low-cost and sustainable alternatives to conventional generators, these technologies can help reduce dependency on expensive fossil fuels while improving power supply reliability in remote areas.
2) Advancing demand response strategies will be crucial for optimizing microgrid operations. By exploiting real-time load management, adaptive pricing models, and demand-side control, remote islanded microgrids can dynamically adjust consumption patterns to match available renewable generation, reducing curtailment and improving energy efficiency.
3) To cope with potential outages or natural disasters, black-start capabilities for remote microgrids should be fully guaranteed to ensure resilience. Developing autonomous black-start strategies that leverage local resources will be essential for restoring power, especially for remote islanded microgrids, where external grid supports are unavailable.
4) Probabilistic analysis can be integrated into the operational decision-making process so that the uncertainty of local renewable energy resources will be fully considered to better balance the potential risks and the operational cost of microgrids.

Acknowledgment

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For Further Reading

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The characteristics of microgrids enable fragile remote power networks to better exploit the potential of local DERs for secure and economical operations.

Microgrids, as an emerging technology in the power sector, are localized power systems that interconnect distributed generators, energy storage systems, and various loads.

Typically, microgrids operate in grid-connected mode, but they are capable of disconnecting from the main grid and operating in islanded mode as needed.

Approximately 750 million people worldwide still lack access to electricity, with the majority residing in remote or underdeveloped areas.

The construction of electricity infrastructure around on-site generation resources can bring about a significant improvement in the quality of life for local communities.

In most cases, remote islanded microgrids operate without access to the main grid, requiring them to rely solely on internal power generation and storage.