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RENEWABLE ENERGY MICROGRIDS: FROM CONVENTIONAL ARCHITECTURES TO SMART AND DIGITAL-TWIN-ENABLED SYSTEMS

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ABSTRACT

Renewable energy microgrids (RE-MGs) have become a cornerstone technology in modern power systems to address energy security, environmental constraints, and rising global electricity demand. Their hybrid architecture, incorporating distributed renewable energy resources (RERs) together with advanced controls and storage technologies, enables resilience, reduced emissions, and improved flexibility. This article provides a concise technical review of conventional microgrid topologies, transitions to smart microgrids, and emerging digital-twin-enabled frameworks. Drawing from recent literature review, this article highlights key architectural features, operational strategies, cyber-physical integration, and future directions for intelligent renewable energy microgrid systems.

KEYWORD

Microgrid, renewable energy, hybrid storage, Energy Management System, Digital Twin

INTRODUCTION

Increasing environmental concerns and the rapid adoption of distributed renewable energy resources are transforming traditional power systems. Conventional centralized grids face challenges such as transmission losses, grid congestion, and vulnerability to disturbances. Microgrids—localized energy networks integrating distributed generation, storage, and loads—offer a promising solution by allowing both grid-connected and islanded operation modes [1,2]. Their ability to enhance reliability and integrate renewable energy makes them suitable for remote communities, industrial facilities, and future smart cities [3,4].

The evolution of microgrids extends beyond basic renewable integration. Emerging smart microgrids incorporate sensors, communication infrastructure, internet of things connectivity, and advanced control algorithms [5,6]. Digital twin (DT) technology further extends capabilities by enabling real-time synchronization between physical microgrids and virtual models, supporting predictive maintenance, optimization, and fault diagnosis [7,8]. This article consolidates these developments, referencing key findings from recent literature.

This article synthesizes microgrid architecture review and a digital-twin-enabled microgrid review. Key topics—such as microgrid topologies, distributed generation, storage technologies, smart grid features, cyber-physical integration, and digital twin architectures.

MICROGRID ARCHITECTURES

Microgrids typically comprise distributed generators (solar photovoltaic (PV), wind turbines, microturbines), energy storage systems, and load centers arranged in AC, DC, or hybrid AC–DC configurations. AC microgrids (Figure 1(a)) integrate well with existing grids but require power electronics for DC-based renewable systems. DC microgrids (Figure 1(b)) reduce conversion losses and are increasingly suitable for high-efficiency PV-battery systems. Hybrid AC–DC microgrids combine both advantages, providing greater flexibility and adaptability [1,3].

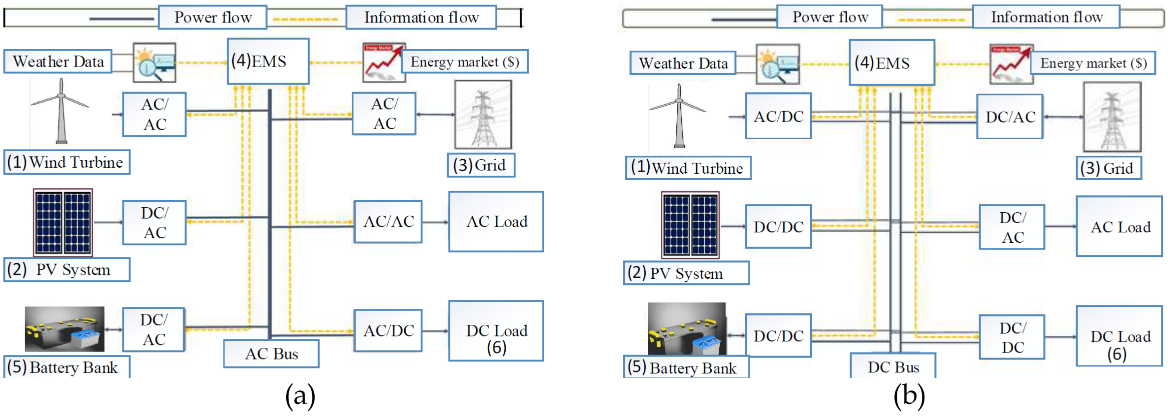

Figure 1: The architecture of microgrids based on renewable energy sources, (a) AC microgrid, (b) DC microgrid.

ENERGY STORAGE AND POWER MANAGEMENT

Energy storage mitigates intermittency in renewable sources. Batteries, supercapacitors, and hydrogen systems enable load shifting, peak shaving, and frequency regulation. Advanced energy management systems (EMS) use rule-based, predictive, and optimization-based algorithms to coordinate power flows [4,9-11].

SMART MICROGRID FEATURES

Smart microgrids leverage bidirectional communication, automated monitoring, and demand-side management. Communication standards and cyber-physical security frameworks play key roles in ensuring system resilience [12,13]. Smart microgrids also support dynamic pricing, real-time monitoring, and distributed decision-making. Smart grid architecture is made up of numerous components and technologies that work together to provide a dependable, intelligent, and effective electrical grid infrastructure. Figure 2 depicts the integration of smart grid components.

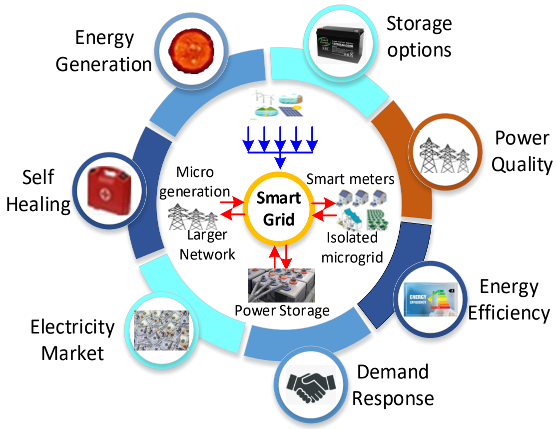

Figure 2: The integration of smart grid components.

DEMAND-SIDE MANAGEMENT AND ENERGY MANAGEMENT SYSTEMS

Demand-Side Management (DSM) aims to reshape load profiles by encouraging consumers to shift consumption from peak to off-peak periods. This improves load factor, reduces operational costs, and stabilizes grid performance. EMS, often optimization-driven, coordinate power flow between generation units, storage devices, and loads. Methods such as rule-based scheduling, heuristic algorithms, and evolutionary optimization are widely investigated to improve operational efficiency.

DIGITAL TWIN-ENABLED MICROGRIDS

DT frameworks create a virtual-replica environment capable of simulating, predicting, and optimizing microgrid operation. DT-enabled microgrids support enhanced fault detection, predictive maintenance, and optimization under varying load and generation scenarios [7,8,14,15]. They also strengthen cybersecurity through continuous anomaly detection and modeling of cyber-physical interactions [13]. As shown in Figure 3, microgrids without DT technology had various shortcomings, such as high maintenance costs and time, poor real-time performance, lack of intelligence in operation, and imprecise predictions.

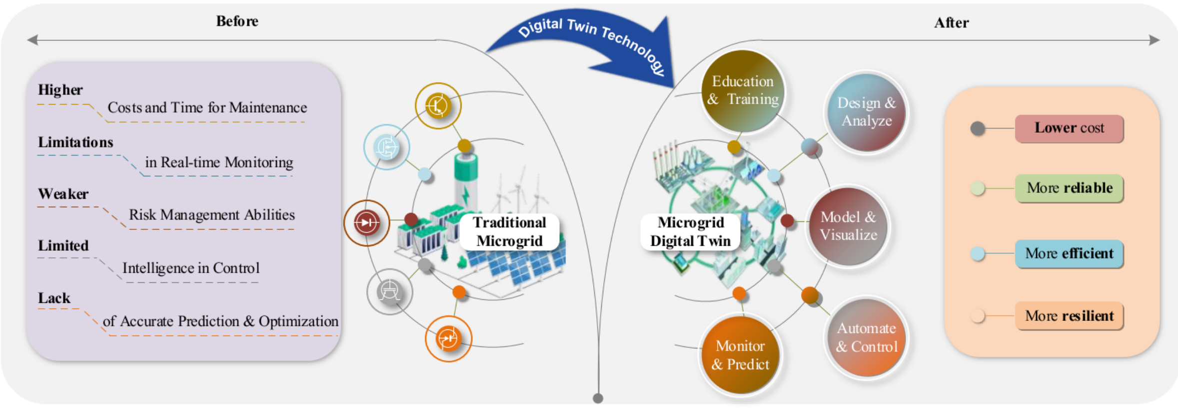

Figure 3: The illustration of before and after using digital twin technology within microgrid.

CHALLENGES AND FUTURE PROSPECTS

Despite their advantages, renewable energy microgrids face several ongoing challenges. Technical obstacles include the need for robust control strategies capable of handling multiple energy sources, varying load profiles, and real-time uncertainties. Policy and regulatory barriers vary across regions and can hinder widespread adoption. Economic considerations remain significant, as high initial investment and long payback periods deter deployment. Furthermore, cybersecurity threats are increasing as microgrids rely more heavily on digital communication networks. DT-enabled microgrids face additional issues such as data availability, model accuracy, and computational demands. Future directions include integrating AI, blockchain-secured energy trading, and autonomous control architectures [16,17].

CONCLUSION

Renewable energy microgrids are transforming traditional power systems into intelligent, decentralized, and resilient networks. Smart microgrids and digital twin technologies represent the next major evolution, enabling advanced monitoring, predictive analytics, and real-time optimization. Continued innovation is essential for enabling flexible, sustainable, and secure future power systems.

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