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(Review Article)

A comprehensive review of energy management in microgrids utilizing energy storage systems

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Abstract

Microgrids (MGs) are essential in advancing energy systems towards a low-carbon future, owing to their highly efficient network architecture that facilitates the flexible integration of various DC/AC loads, distributed renewable energy sources, and energy storage systems. They also offer enhanced resilience and cost-effective control, operation, and energy management for both on-grid and off-grid scenarios. Nevertheless, as new entrants to the utility grid, MGs encounter challenges stemming from the economic deregulation of energy systems, the restructuring of generation, and market-driven operations. This paper provides a thorough overview of existing research on MGs .It categorizes MGs and energy storage systems into several branches and typical combinations, which serve as the foundation for MG energy management.

Keywords: AC; DC; Hybrid; Micro-grid; Storage

1. Introduction

A microgrid (MG) refers to a collection of interconnected loads and distributed energy resources (DERs) that operate within well-defined electrical boundaries, functioning as a single controllable unit in both grid-tied and islanded configurations [1]. Initially, MGs were developed to support critical loads and remote locations, enhancing the reliability of power systems and facilitating the electrification of various industrial sectors. The emergence of AC, DC, and hybrid AC/DC microgrids is increasingly recognized as a promising avenue for advancing power system architectures. With advancements in power electronics and energy storage system (ESS) technologies, a variety of MG configurations have recently surfaced, including clustering MGs [2], community MGs, interconnected MGs, multiple MGs, networked MGs (NMGs), and marine/aerospace MGs [3]. These innovative variations have the potential to enhance the efficiency of onshore distribution systems and minimize emissions from offshore and aerospace applications, such as all-electric ships, offshore platforms, and hybrid electrical propulsion aircraft. The current trend towards multi-energy integration has also given rise to multi micro-energy MGs (MMGs). In addition to the structural evolution of MGs, their infrastructure is significantly shaped by advancements in the energy storage sector. To facilitate islanded operations, MGs are inherently designed with ESSs, which can be mechanical, electrical, chemical, thermal, or electrochemical, and may be deployed in either a dispersed or centralized manner [4]. These ESSs are capable of delivering a range of power and energy services to MGs. In grid-tied scenarios, ESSs can be utilized for energy arbitrage, load shifting, and the provision of ancillary services, which not only enhance the reliability of power systems but also provide benefits to MG operators and end users [5].

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2. Microgrid Architectures

Because of their high efficiency in power conversion and transfer, flexibility in connecting to renewable energy sources, and high resilience and dependability in on/off grid operation, a variety of MGs have been playing significant roles in both present and future power systems.

AC, DC, hybrid AC/DC, and MMGs are the different categories of current MGs. Certain component level models and system level models in energy management problem formulations are produced by combining various conversion, distribution, energy storage, and consumption techniques within these architectures.

2.1. DC Microgrids

As seen in Fig.1, the primary benefit of DC MG is its user-friendly power electronics integration feature. In most cases, two-stage energy conversions are needed to connect AC or DC type sources and loads to the AC grid. For example, AC-DCAC or DC-DC-AC for sources and AC-DC-AC or AC-DC-DC for loads could be used. The source and load converter interfaces are connected by an intermediate DC-link. It is clear that the primary benefits and motivators for land-based DC MG are the reduction of equipment cost and conversion loss that can be achieved by utilizing a common DC-link.

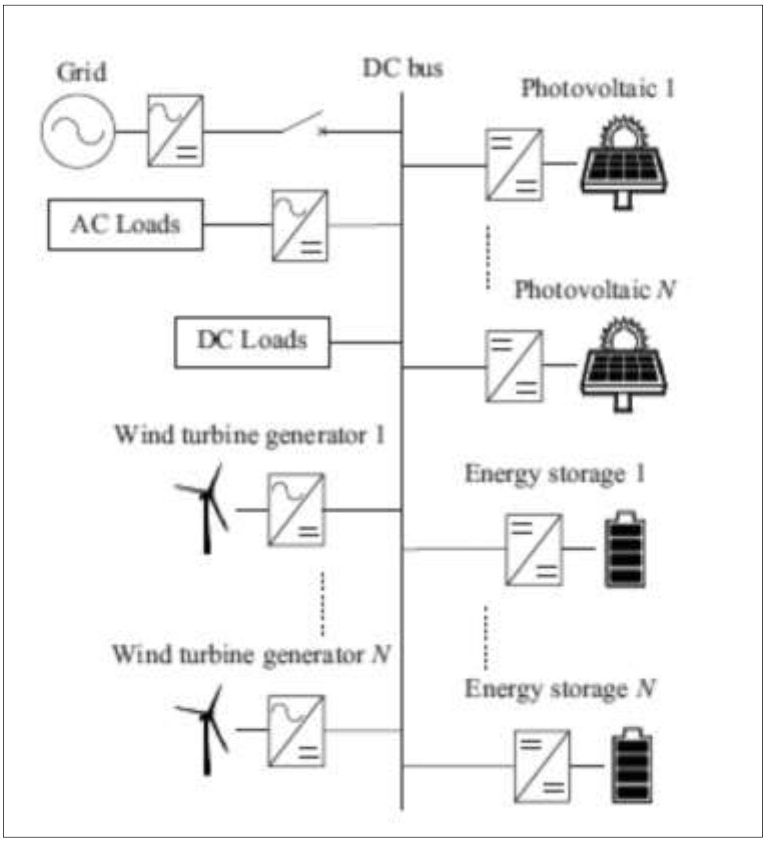

Figure 1 General DC MG architectures

In order to accomplish decentralized control, DGs and ESSs can share power by using a common DC-link voltage as a communication carrier in DC MG. The common DC-bus voltage tolerance band is separated into multiple regions in this control scheme to allow for the differentiation of each converter unit's priorities. Every converter's operating modes are governed by the voltage region's threshold value. During periods of high solar radiation, for instance, the PV converter will switch to DC bus regulation mode and the battery converter will operate at maximum current charging mode if the DC-link voltage exceeds its rated value. In order to control DC bus voltage, the PV converter will transition to maximum power point tracking (MPPT) mode and the battery converter will function in discharging mode if the DC-link voltage falls below its rated value. They are ideal for space-constrained applications such as data centers and electrical propulsion systems for ships and airplanes [6][7].

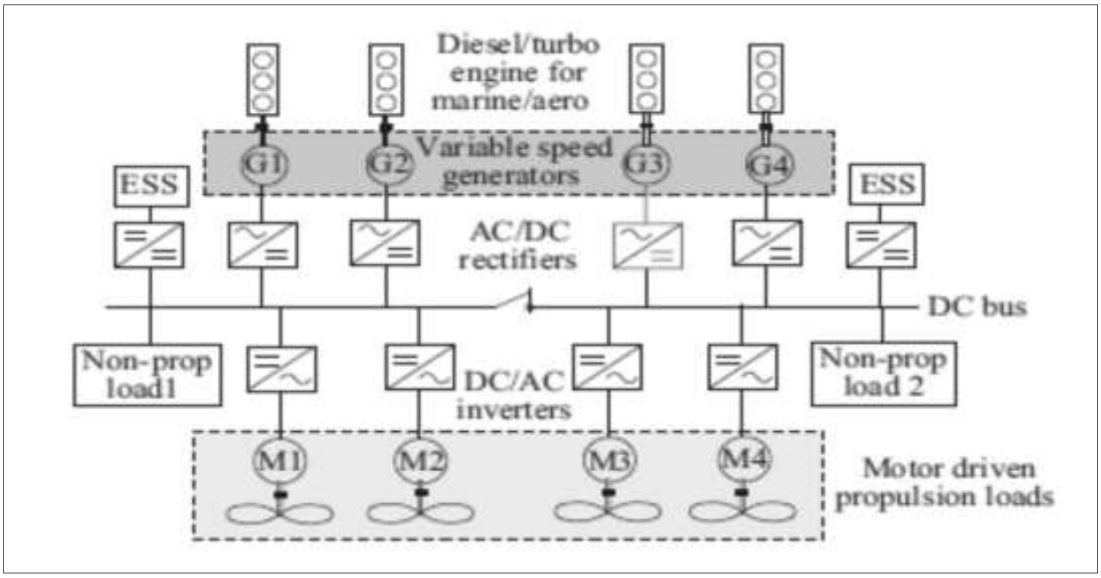

Figure 2 Typical DC MG architectures

2.2. AC Microgrids

Inverter-based power sources will replace synchronous generators (SGs) in AC MGs due to the high penetration of renewable energy generation using power electronics technologies. Nevertheless, many design and analysis theories of AC MGs can be inherited from the conventional power system, which will face fewer challenges for new project implementation. This will present new difficulties like limited fault current capability and decreased system inertia. In AC MGs where inverters and SGs coexist, the inertia support is essential for maintaining system frequency stability. In the AC grid-forming processes that support system voltage and frequency, including black start, ESSs are essential. The following sections will go into greater detail about how to control the inverter as a virtual synchronous generator (VSG) for simple synchronization and system frequency support in AC MG. In the event of a fault, the AC MG system level protection must also appropriately coordinate with the inverters own power semiconductor protection mechanisms [8].

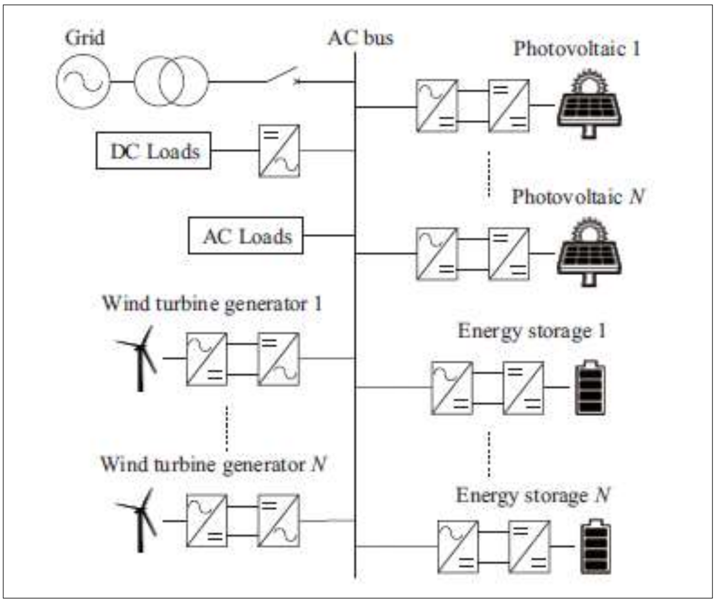

Figure 3 General AC MG architectures

Effective modeling is necessary for MG energy management to address the dynamics of low inertia AC MGs. AC MGs are also used in the electrification of transportation. All-electric, series/parallel hybrid electric (hybrid shaft generator), diesel/turbo-electric, and other MG architectures are the same for marine and aerospace applications.

2.3. Hybrid AC/DC Microgrids

As a combination of AC and DC MGs, hybrid AC/DC MGs can further minimize conversions within MGs, maximizing efficiency and investment cost [9], [10]. For land-based distribution systems, hybrid AC/DC MGs have been the basic design. A. energy integration [11], [12], transport, zero and net-zero buildings, and utility, municipal, and military applications. For hybrid AC/DC MGs to support both AC bus voltage/frequency and DC bus voltage, ESSs are essential to achieving the ability to form both AC and DC sub-grids. It is simple to expand the connection of multiple hybrid AC/DC MGs by implementing a modularized design. as illustrated. A micro power park's (MPP) hybrid AC/DC module, which can be used with variable speed diesel generators and various renewable energy sources, is primarily used as an emergency power source for vital operations in disaster areas and on the battlefield. It can also be used as a smart micro-grid for peacetime deployment in isolated locations and islands. From a technical standpoint, hybrid grids are more efficient than traditional AC grids. This is especially crucial for emergency and remote deployments where the best possible energy use is required. Table I provide a summary of comparisonsfor AC, DC, and hybrid AC/DC MGs.

2.4. Multi Micro-energy Grids

MGs can also communicate with other MGs through integrated energy networks [13], such as transportation networks with electrified vehicles (EVs) [16], fluid networks [14], thermal networks [15], and electrical networks1. These networks have well-defined boundaries. Single-phase or three-phase AC networks [17], DC networks [18], and hybrid AC/DC networks, as previously mentioned, are all types of electrical networks. With the use of heat ventilation air conditioning (HVAC) and micro-turbine technologies, MGs can share gas and thermal resources with other entities that are connected to the same gas and thermal networks. Energy sharing between MGs can be further realized by EVs through spatial movement on transportation networks. The creation of MMGs is the outcome of these interrelated energy networks.

An MMG is a group of MG’s connected by transportation, thermal, gas, or electrical networks. MGs are acknowledged as effective platforms for enhancing the dependability and efficiency of land-based distribution systems, particularly through transactive energy management [19], [17]. In addition to electrifying ships, ports, islands, and offshore platforms, MMGs are also greatly lowering emissions from the shipping and offshore sectors under the International Maritime Organization's greenhouse gas regulations. A promising architecture for representing the interaction between electrified ports and AESs during their cold ironing processes is MMGs [21]. The NMGs can be used to modify the electrical boundaries of each MG using boundary switches.

Table 1 Comparisons for AC, DC and Hybrid AC/DC MGs

Architecture	Advantages	Limitations	Application
DC MGs	1.Because fewer conversion stages are required, renewable energy resources are more favorable. 2.Even though the AC terminals are still present, the true DC loads are growing. The only problem, which is rather simple, is DC voltage stability.	1. Larger DC distribution areas require solid state transformers, which are more expensive and inefficient 2.Devices and protection plans are not yet developed. 3.The DC load ecosystem is still in its infancy. 4. New infrastructure must be constructed.	1. Data centers 2.Zero-emission buildings 3.Charging stations 4.Propulsion systems for ships and aircraft
AC MGs	1.. Simple deployment utilizing the current infrastructure 2.Devices and protection plans are available	1.Issues with cross-coupling effects, frequency and voltage stability, and synchronization	1.When a diesel generator serves as a primary source, e.g. A. islands

	3. It is simple to use a transformer to connect to various voltage levels.	2. Less effective because there are more conversion steps.	2. System for ship propulsion.
Hybrid AC/DC MGs	1.The benefits of both AC and DC MGs are that they are more effective at connecting different sources and loads. 2. The interlinking AC/DC converter allows for flexible operation and control schemes to manage power exchange.	1. Because of the AC-DC bus coupling effect, the stability issue is rather complicated. 2.Plans for protection are intricate	1.Zero-emission buildings 2.Electrification for rural areas 3.Emergency power supply modules

3. Energy storage systems

Energy storage is essential to MGs' dependable and steady operation. Many ESS types are appropriate for MG applications in a variety of conditions, including loads, component failures, DER disturbances, etc. Usually, these energy storage systems (ESSs) are serial combinations of energy conversion systems (PCSs). To ensure the safe and efficient use of energy storage systems (ESSs), it is necessary to accurately model the unique electrical patterns that are admitted by the physical characteristics of energy storage materials. An overview of ESS models and their functions in MG energy management is provided in this section

3.1. Energy Storage Systems for Microgrids.

ESSs can be categorized according to their composition and formations into mechanical, thermal, electrochemical, chemical, and electrical systems. According to their technical attributes and the needs of the MG application, they can be used for various MG types, as indicated in Table III. Usually, requirements are event-driven and encompass both anticipated and unforeseen occurrences. They can be categorized as either short-term or middle-term disruptions within expected events. A. component failure, load fluctuation, and intermittent renewable output necessitate multi-time scale responses, such as primary, secondary, and inertia. For unanticipated circumstances, e.g. In order to support electrical boundary adjustment of MGs during extreme weather events, ESS reconfiguration is necessary.

3.1.1. Mechanical ESSs

The bi-directional conversion of electrical and mechanical energy in mechanical energy storage systems (ESSs), such as kinetic and potential ESSs, enables the energy storage function. Flywheel ESSs transfer kinetic energy to an electrical machine rotor. First employed as an uninterruptible power supply (UPS) for critical users, flywheel ESSs have multiple life cycles, quick response times, and minimal environmental effects. Later, they were integrated into MGs to withstand short- and middle-term disruptions. Another example of a potential energy storage system (ESS) that is appropriate for large-scale, long-term energy storage is compressed air and pumped hydro. The most advanced energy storage methods, pumped hydro ESSs, have been used for power systems since 1882. In 2022, an MG was installed in a sewage treatment plant in Wuhan, China. In terms of MGs, mountainous regions with abundant run-of-river resources could potentially receive pumped hydro ESS deployments [56], e.g. 3. the Chinese provinces of Guizhou and Yunan. Compressed air energy storage systems (CAESs) are a safe, effective, and economical way to achieve energy storage. With fewer construction restrictions than pumped hydro ESSs, they can be used for MGs near caves. 3. seas and oceans [23]. An innovative method for quick and large-scale energy storage that is gaining popularity is gravity energy storage.

3.1.2. Thermal ESSs

Thermal ESSs typically take the form of sensible heat, latent heat, and thermo-chemical sorption. Building MGs is a good fit for the latent heat ESSs because of their high energy density and efficiency at a steady temperature [22]. In everyday life, sensible heat ESSs are widely used with both solid and liquid media. Thermo-chemical sorption energy storage systems (ESSs) are promising methods for storing energy in MMGs due to their higher energy density.

3.1.3. Electrical ESSs

Electrical ESSs differ from other ESSs in that they store energy in an electric field by separating charges or magnetic fields by flux. The two most common electrical ESSs are super-capacitors (SCs) and superconducting magnetic ESSs. SCs have a long lifespan, high power capacity, and high efficiency. They can respond quickly to external systems with low energy capacity and are appealing options for hybridizing with other ESSs and improving power quality. Higher efficiency, a longer life cycle, and millisecond scale response make superconducting magnetic ESSs suitable for military MG applications and applications requiring rapid power.

3.1.4. Electrochemical ESSs

An electrochemical storage system stores energy by converting electricity and chemical energy in both directions. The chemical reactions that occur in such a system are likely to shorten its lifespan. Electrochemical storage systems have two primary subtypes: flow batteries and secondary batteries. Due to their wide operating temperatures, low memory effect, high energy density, and power density, secondary batteries are currently leading the portable energy storage market. Mobile MGs have made extensive use of them. A. AESs, electric cars, etc. Redox flow batteries (RFBs) are a type of flow battery that admits high power, high efficiency, and high life cycle stability. Grid-scale applications are appropriate for RFBs [24].

3.1.5. Chemical ESSs

In chemical ESSs, energy that is stored as chemical fuels can be easily transformed into electrical energy. ESSs based on hydrogen are widely used and accessible. Hydrogen-based fuel cells (FCs), which use a combination of hydrogen and oxygen to generate electricity, are highly efficient and carbon-free. They are suitable for mobile MGs since they can produce heat and electricity at the same time for automobiles, construction MGs, and MMGs

4. Conclusion

Energy storage devices and near-by renewable energy sources are propelling the microgrid's shift to a low-carbon future. Renewable energy resources zero inertia and unpredictable nature necessitates innovative architectures, energy storage use, energy management models, and management solution techniques. Interoperability between electricity and other energy systems in local areas, including both grid-tied and isolated applications, is being improved by hybrid AC/DC, multimicro-energy grids. Energy management models have incorporated the multiphysics properties of energy storage systems under uncertainty. With the right reformulation, these models can be further resolved using deep reinforcement learning algorithms, mathematical programming, and adaptive dynamic programming, all of which take into account the mathematical characteristics of uncertainties. Under various energy market economics, hierarchical energy management schemes are supporting a variety of distributed and decentralized energy management schemes. Future research must examine the issues raised by dynamic-captured models, resilience, stability constraints, market operation, and effective computation techniques.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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