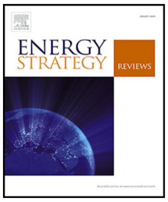
Energy Strategy Reviews 49 (2023) 101127

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr



Microgrids: A review, outstanding issues and future trends

Moslem Uddin [a,*], Huadong Mo [a,*], Daoyi Dong [a], Sondoss Elsawah [a], Jianguo Zhu [b], Josep M. Guerrero [c]

[a] School of Engineering & Information Technology, The University of New South Wales, Canberra, ACT 2610, Australia
[b] School of Electrical and Information Engineering, University of Sydney, Camperdown, NSW 2006, Australia
[c] Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark

ARTICLE INFO

Keywords:
Microgrid
Energy management
Renewable energy
Battery energy storage system

ABSTRACT

A microgrid, regarded as one of the cornerstones of the future smart grid, uses distributed generations and information technology to create a widely distributed automated energy delivery network. This paper presents a review of the microgrid concept, classification and control strategies. Besides, various prospective issues and challenges of microgrid implementation are highlighted and explained. Finally, the important aspects of future microgrid research are outlined. This study would help researchers, scientists, and policymakers to get in-depth and systematic knowledge on microgrid. It will also contribute to identify the key factors for mobilizing this sector for a sustainable future.

1. Introduction

Electricity distribution networks globally are undergoing a transformation, driven by the emergence of new distributed energy resources (DERs), including microgrids (MGs). The MG is a promising potential for a modernized electric infrastructure [1,2]. The term “microgrid” refers to the concept of a small number of DERs connected to a single power subsystem. DERs include both renewable and /or conventional resources [3]. The electric grid is no longer a one-way system from the 20th-century [4]. A constellation of distributed energy technologies is paving the way for MGs [5–7]. It can act as a well-regulated single grid-level entity to provide either islanded or grid-connected operation [8]. It has the potential to improve power quality, boosts energy security for critical loads, and maximize overall system efficiency [9,10]. MGs have gained popularity in recent years as a result of technological improvements in small-scale power generation [11]. Meanwhile, environmental concerns about centralized electric power generation have been a motivating reason behind the development of MGs [12–18].

The MG market is expected to continue growing, despite the fact that the most important feature of MG technology is not effectively expressed in monetary terms: resiliency [19,20]. Various MG deployments or current experiments are taking place around the world to better understand how MGs work [21]. For varied purposes, many technologies and topologies have been investigated. Some of the trials are carried out only for research and development, while others are set up on islands or in remote areas. Since the MG concept is much versatile, the experiment settings and goals can be widely varied [22]. The majority of the world’s MGs are currently located in North America and Asia-Pacific, with the People’s Republic of China providing the majority of the capacity in Asia-Pacific. While there is no central registry, as of the fourth quarter of 2017, a semiannual tracker estimated 1869 MGs with a total capacity of 20.7 gigawatts (GW) [23]. MGs are predicted to grow significantly in the next years, particularly in Asia-Pacific and North America, with annual capacity installation and spending expected to climb fivefold between 2018 and 2027 [24]. MGs are expected to become more popular in areas with inadequate or deteriorating power infrastructure, as well as remote business activities such as mining pits. MGs are likely to become an increasingly important part of the energy sector as current and future challenges arise [25].

The MG has also attracted much attention in global academic communities. Fig. 1 shows the number of MG-related web of science (WoS) articles from 2000 to 2021. These statistics motivate the authors to conduct an in-dept study in this field to clarify the state of knowledge and identify needed research. Several review papers have addressed different aspects of MGs. The basic concept of MGs has been briefly presented in [26,27]. A review has examined the MG technology [28]. Planning, modeling, design and architectures of hybrid renewable MGs have also been reviewed in [29]. A survey has classified MGs into different groups [30]. In [3], existing MGs architectures have also been investigated. AC and DC MGs have been surveyed concisely in [31]. Several review articles have explored MG control strategies [32–34]. Control methods proposed for inverter-based MGs have also been presented [35]. Control strategies for DERs in MGs were investigated and

---

* Corresponding authors.
E-mail addresses: moslem.uddin.bd@gmail.com (M. Uddin), huadong.mo@adfa.edu.au (H. Mo).

https://doi.org/10.1016/j.esr.2023.101127
Received 14 February 2023; Received in revised form 2 July 2023; Accepted 4 July 2023

Table 1
Examples of existing reviews related to MGs.

Ref	Basic concept	Classification	Control	Simulation	Challenge	Future direction
[30]	×	✓	×	×	✓	✓
[43]	✓	✓	✓	×	×	✓
[44]	✓	✓	✓	×	×	×
[45]	✓	×	✓	×	×	✓
[46]	✓	✓	×	×	✓	✓
[47]	✓	×	✓	×	×	×
This review	✓	✓	✓	✓	✓	✓

reported in [36]. Also, control strategies for voltage and frequency regulation in MGs have been discussed [37]. The droop control techniques for MGs can be found in [38]. The literature has also provided reviews on protection schemes for MGs [39–41]. The available techniques for reactive power compensation in MGs have been reviewed and analyzed in [42]. A review on MGs has summarized the experimental MG systems installed in three different regions namely Asia, North America and Europe [7]. A few recent review articles in the existing literature on a similar investigation of MGs are summarized in Table 1 to highlight this article's research scope and significance. Overall, the existing reviews indicate that the information on MGs is scattered throughout the literature. As a result, identifying the key attributes for advancing the global MG projects is tricky for practitioners and policymakers.

Therefore, the purpose of this study is to review the current scenarios of MGs. The paper is organized in a systematic manner to provide a detailed study of MG systems. An attempt has been made to review MGs and identify the key attributes that will help mobilize this sector globally for a sustainable future. This research investigates and outlines many factors that may help researchers, practitioners, and stakeholders get systematic and in-depth understanding about MGs. The feature of this review lies in the discussion of significant challenges and future research directions that are potentially important for MGs. In summary, the importance and the originality of this study are as follows:

- A brief overview of MGs and its basics are presented (Section 3).
- An in-depth review on MGs classification is included (Section 4).
- MG control systems are thoroughly discussed in Section 5. A comprehensive survey of different control aspects of MG is reviewed in detail with respect to the principles behind, their applicability and performances.
- Mathematical modeling is vigorously explained, to provide a deep insight into complex MG systems (Section 6). Simulation case study is also conducted.
- Challenges and issues associated with MG implementation are thoroughly analyzed and explained (Section 7).
- Future work and possible research areas worth exploring for MG are also outlined (Section 8).

2. Review methodology

This review paper aims to provide a comprehensive overview of MGs, with an emphasis on unresolved issues and future directions. To accomplish this, a systematic review of scholarly articles and reports was conducted, allowing for the identification and analysis of critical findings. The following strategy was adopted:

- *Objective and scope*: The primary objective of this review is to evaluate the current state of knowledge regarding MGs, identify outstanding issues, and investigate potential future trends. The literature review includes research articles, conference papers, and technical reports, among others. The scope of this review spans from the initial stages of MG research to the contemporary period.
- *Literature search strategy*: A systematic search was conducted to identify relevant literature from various scholarly databases, including Google Scholar, IEEE Xplore, ScienceDirect, ResearchGate, Scopus, Springer, Web of Science, and ACM Digital Library. The searching keywords are "microgrid", "microgrids", "micro-grid", "nano-grid" and "nanogrid". The search was limited to English-language publications.

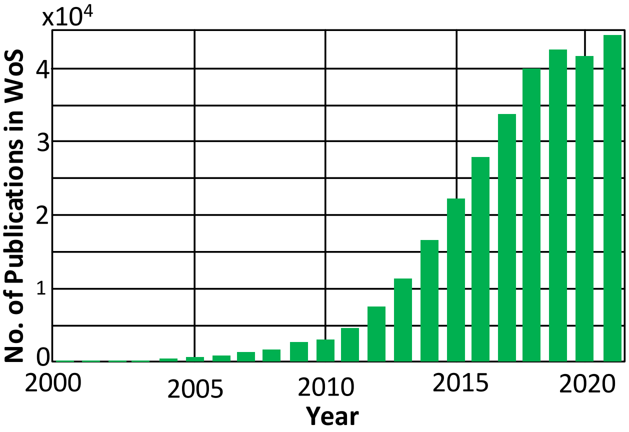


Fig. 1. Annual publications in advance WoS search for MGs.

- *Selection criteria:* The articles were selected based on a set of inclusion and exclusion criteria. The initial screening focused on examining article titles and abstracts to determine their relevancy. Only articles, conference papers, and authoritative reports concentrating on MGs and related topics that have been peer-reviewed were considered for further analysis.
- *Data synthesis and analysis:* Relevant data were extracted from the selected articles, including author(s), publication year, research methodologies employed, significant findings, challenges, and future trends identified. The extracted data were structured so as to facilitate analysis and synthesis.

3. The concept of MGs

3.1. Foundational MG research

The Consortium for Electric Reliability Technology Solutions (CERTS) and the MICROGRIDS project, respectively, initiated a systematic research and development various projects in the United States and Europe [48–50]. CERTS, founded in 1999, is widely regarded as the forerunner of the present grid-connected MG idea [51]. The CERTS MG was suggested as a possible solution to the problems associated with integrating DERs into the grid [52,53]. Initially, the focus was on automated and seamless islanding and grid reconnection, as well as passive control mechanisms [54]. The CERTS MG idea is further tested in both test beds and real-world MG projects [55–57]. By incorporating the renewable sources, reliability improvement was the initial motivation of CERTS rather than reduction of greenhouse gas emissions. Similar technical challenges were explored by the European Union MICROGRIDS project such as energy management, safe islanding and re-connection practices, protection equipment, control strategies under islanded and connected scenarios, and communications protocols [50]. All these issues pioneered in the early investigations are still attracting wide attention [47].

3.2. Basic MG components

Understanding the commonly utilized power generation technologies and applications is critical for evaluating a potential MG project. Table 2 summarized the MG generation options with their advantages and disadvantages.

(a) *Generation:* MG generation system can be consisted of different dispatchable and non-dispatchable generations. There is a range of dispatchable generations such as natural gas generators, biogas generators, and combined heat and power (CHP). Non-dispatchable generations include renewable sources such as solar, wind, hydro, biofuels etc. [3,7,58].

(b) *Energy storage system:* Energy storage system (ESS) performs multiple functions in MGs such as ensuring power quality, peak load shaving, frequency regulation, smoothing the output of renewable energy sources (RESs) and providing backup power for the system [59]. ESS also plays a crucial role in MG cost optimization [58].

(c) *Energy management system (EMS):* EMS ensures the smart management of the MG with the help of energy meters and communication tools. It controls MG generation and load dispatching based on economic and reliability criteria [7,58].

(d) *Loads:* MGs present two major types of loads: (i) critical loads that need to be served under all conditions and (ii) deferrable loads that could be adjusted for MG load balancing and hence, achieving the most economic power generation [3,7,58].

(e) *Controller:* The MG controller supervises the instantaneous operation of the system [7,58].

(f) *Point of common coupling:* The point of Common coupling (PCC) is a crucial component as it acts as the physical connection point between the MG and the main grid. It serves as the interface where electrical energy is exchanged between the MG and the larger power system. The PCC incorporates various equipment and devices to facilitate the connection, power exchange, control, and protection between the MG and the main grid. This includes components such as circuit breakers, protective relays, and synchronization equipment. The isolated MG does not have PCC [7,58].

3.3. Potential benefits of MGs

- *Price stability:* Investment in the grid can reduce risk. It acts as a safety net against the unforeseeable and potentially exorbitant expenses of contingency/emergency energy. It also offers protection from fluctuating electricity bills.
- *Economic benefit:* Depending on local market laws and initiatives, MGs can lower peak load prices, engage in demand response (DR) markets, and provide frequency management services to the larger grid. They can also make money by lowering peak load costs, engaging in DR markets, and offering frequency regulation services to the rest of the grid.
- *Continuous supply:* While the electric system in many developed countries is typically stable, any outage can be costly and hazardous. Extreme weather, ageing, physical attacks, and cyberattacks are all posing rising risks to the nation's electricity infrastructure today [65–67]. Operating in the island mode can ensure a constant supply of electricity (i.e., separating itself from the bulk grid while using on-site generating).
- *Renewable integration:* RESs contribute significantly to supplying some of the world's energy demands. The ongoing global energy crisis has generated unparalleled impetus for RESs. The projected expansion of renewable capacity in the next five years is anticipated to surpass previous expectations. According to the IEA forecast, renewable energy is expected to grow by approximately 2400 GW between 2022 and 2027. This represents a significant acceleration of 85% compared to the growth witnessed in the previous five years. Furthermore, the forecasted growth is nearly 30% higher than what was initially predicted in last year's report, marking the most substantial upward revision to date [68]. As a result, MGs are becoming increasingly important for reaping the benefits of RESs.
- *Increased reliability and resilience:* MGs' capacity to island allows them to continue supplying power to their customers in the case of a power outage. The ability to island can also be significant for isolating faults by separating distribution feeds.
- *Increase power quality:* Systems may necessitate a higher level of electricity than the electric grid can provide. Implementing an MG allows better control over its parameters, which is important for sensitive equipment in healthcare, sophisticated manufacturing, labs, and other institutions.
- *Relationship of the MG to the utility grid:* MGs can be thought of as the essential building element for smart grids. To put it in another way, future utility grids may be a collection of interconnected MGs that manages energy demand and supply at the micro and macro levels.
- *Grid support:* MGs reduce grid "congestion" and peak loads. Also, they offer several grid services including: energy, capacity, and ancillary services.

3.4. Applications

There are several key MG applications, according to current experience and publications.

3.4.1. Institutional and campus MGs

Institutional and campus MGs are typically comprised of a certain number of buildings in a limited geographical area. Depending on the type of institution, the requirements for power supply quality may differ [69]. Most government and college facilities may be fine with a moderate level of power supply reliability, while research institutes may demand a higher-quality power supply. In this sort of MGs, all buildings and participants often belong to a single entity, and there is a single decision–maker. This structure allows for quick decisions, and the real estate owner can take action if there are evident benefits [70,71].

3.4.2. Commercial and industrial MGs

This type of MGs is similar to the one mentioned above in the case of single ownership. When an MG is developed in an existing commercial or industrial area with multiple participants, the scenario becomes more complicated. When a "commercial–industrial park" is a greenfield project with both premium and normal power supply capabilities, the investor can opt for an MG structure to suit all client requirements. By diversifying their energy sources, taking advantage of time-of-day electricity pricing, and having backup power on hand whenever it is needed, facilities connected to public grids can minimize energy costs and boost self-sufficiency.

3.4.3. Community and utility MGs

Private end-customers in largely residential regions, but occasional business and industrial customers, will form "community and utility" MGs. Urban regions, communities, and rural feeders may all be included. Connected to the large utility grid, such MGs can offer power to urban and rural areas. This sort of MGs can contain a wide range of renewable or fossil-fueled distributed energy supplies. National and international standards and regulations will play a decisive role in the commercial acceptability of this type of MGs. Decisions will take long as compared to other MG structures due to a large number of participants.

Table 2
A summary of MG generation options with their advantages and disadvantages.

MG components	Advantages	Disadvantages
Diesel generator [46,60]	– Quick start-up – High load acceptance – Dispatchable – Low-load operation of 20% possible – Fuel storage – Very good transient response	– Higher fuel cost – Higher emissions
Gas generator [61]	– High fuel efficiency – CHP option – Low emissions – Part load operation of 35% possible	– Slower start-up and limited transient response – Costly fuel storage – Recently, fuel price has experienced significant increases
Solar [62]	– Low maintenance cost – Diverse applications – Reduces carbon footprint	– Reliance on sun – Requires ESS – Capital cost – Requires inverter
Wind [62]	– Location independent – Reduces carbon footprint – Low production costs	– Reliance on wind – Visual/noise pollution
Biogas [62]	– Cost-effective fuel source – Reduces soil/water pollution – Byproduct-fertilizer	– Integration cost – Fuel treatment/filtration – Requires suitable biomass
Battery storage [61,62]	– Carbon savings neutrality – Retrofit-able – Rate optimization/curb – Instantaneous power availability	– Space constraint – Battery life – Limited energy storage
Fuel cell [63,64]	– Low Emissions – Extremely quiet – Useful for CHP application	– Hydrogen extraction is expensive – Expensive infrastructure is required for hydrogen

3.4.4. Island and remote “off-grid” MGs

A community or utility MG is usually fairly similar to an island MG. The key distinction is that there will be no connection to the power grid in most cases. If the distance between the island and the mainland allows it, a cable connection to the utility grid on the mainland may be possible in a few cases. On the other hand, depending on the island’s actual power supply infrastructure, the decision-making process could be quicker. For geographically isolated/remote communities and developing countries, “off-grid” MGs emphasize distributed and diverse power sources. Many remote MGs are being implemented to eventually join a larger grid system as developing world regions continue to improve their electrical infrastructure. Other remote MGs are designed to be self-sufficient to preserve energy security.

3.4.5. Advanced applications

MGs can also be used for the following, in addition to their usual applications:

- *Maritime:* Maritime power systems, such as those installed in ships, ferries, vessels, and other maritime devices, operate in islanded mode at sea and grid-connected mode at port. Therefore, maritime MGs are true commercial microgrids that are affordable and have a prospective market. Maritime MGs are growing increasingly important as ships become more electrical [72,73].
- *Aerospace:* Aerospace MG concept has gained an increased importance in recent years. In several aerospace applications, electrical sources are eventually replacing mechanical, hydraulic, or pneumatic power sources such as airport MGs, e-aircraft/more electric aircraft (MEA) [74].
- *Space:* The reliability of the power system components of a spaceship or satellite is crucial to the success of an extremely costly space mission. Space MGs have emerged as a sustainable solution for meeting the energy requirements of space applications [75].
- *Biological:* Artificial ecosystems can be employed as life support systems (LSSs) to support long-duration human space missions. There is no provision for food production or waste disposal in space. Therefore, an open LSS requires food and waste treatment from Earth. Ecosystems that do not participate in any form of matter exchange with the surrounding environment are referred to as closed ecological systems (CESs). Long-term manned space missions require CESs to minimize Earth support. They include multiple distinct compartments that reproduce the key functions of an ecological system continuously and under regulated settings [76].
- *Water:* As our reliance on electricity has grown over the years, prolonged power outages can have severe effects on affected communities. Additionally, power outages can prevent the operation of water treatment facilities, resulting in a shortage of clean water, which is crucial for recovery efforts following a disaster. The temporary reconfiguration of electricity and water networks into localized networks, such as electric MGs and water micronets, that use local resources to meet local demand apart from the primary power grid and/or water network, is one strategy to deal with this [77,78].

4. Classification of MGs

A detailed literature analysis was conducted to investigate the primary topologies and architectural structures of current MGs to guide designers in adopting inherent safe and robust design options. MGs’ can be categorized into different groups according to their applications, infrastructure, and end-users requirements (as illustrated in Fig. 2).

4.1. Classifying MGs on the basis of control strategies

According to control strategies, there are primarily two types of MG systems [79].

Centralized control MGs: In centralized control MGs, the central controller (CC) provides the required directions to the set points of local controller (LC) by a two-way communication channel. Hence, this control technique has limited capability of reliability and is superfluous.

Decentralized control MGs: The decentralized control MGs usually follow the control technique for a multiagent system. The operation control of these MGs is defined and directed individually. A single controller is not attending here for control purposes. The MGs’ function is flexible, and the communication between the two ends may be maintained using a communication language like Java-Jade.

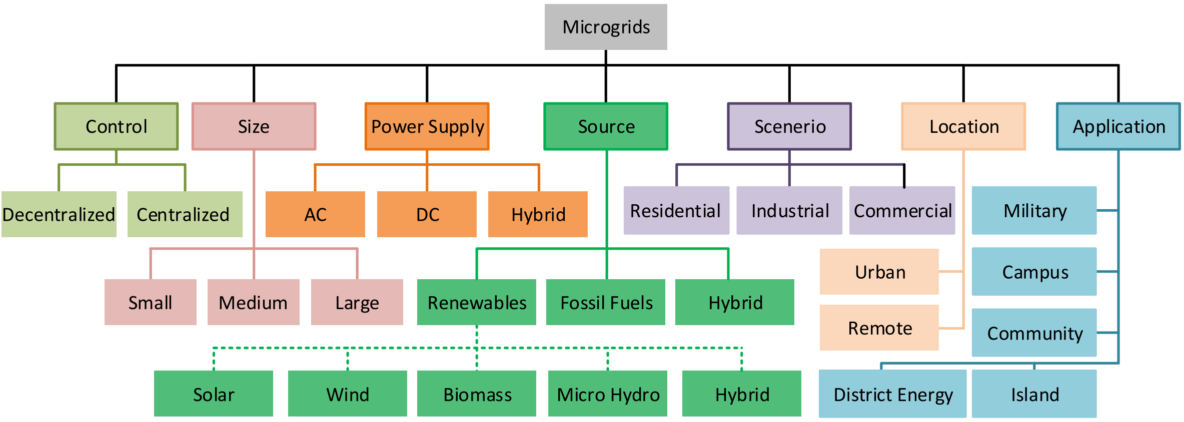


Fig. 2. Classification of MGs.

4.2. *Classifying MGs on the basis of size*

MGs can be categorized into three groups on the basis of their size: small, medium and large scale MGs [44].

4.2.1. *Small scale MGs*

Small scale MGs generate electricity of low capacity using RESs. However, some MGs may utilize diesel generator (DG) sets as a power source alongside or in place of RESs. The generation capacity of a small scale MG can be up to 10 MW [80,81]. Small-scale MGs are capable to supply residential buildings, small regional power grids, island and remote areas.

4.2.2. *Medium scale MGs*

Medium-scale MGs generate electricity of medium capacity using renewable energy resources/oil/coal. The range of generation capacity for a medium scale MG may be $>$ 10 MW $\sim$ 100 MW [80,81]. This type of MGs is capable to feed industrial zones applications.

4.2.3. *Large scale MGs*

Large scale MGs generate electricity of high capacity using oil/coal. The range of generation capacity for a large scale MG may be $>$ 100 MW [80,81]. This type of MGs is capable to feed industrial zones site applications.

4.3. *Classifying MG on the basis of power supply*

In terms of connected power supply, MGs can be divided into three categories: AC, DC, and hybrid MGs [36,82–84].

4.3.1. *AC MGs*

A typical MG system with an AC power supply and connected loads driven by the AC power is defined as an AC MG. This MG can be operated independently or can be connected to the main grid at the PCC. The AC bus connects the power producing sources, storage devices, and other system components to satisfy the AC load demands. These MGs are straightforward to incorporate into present power systems and require no extra control mechanisms. The three varieties of AC MGs are single-phase, grounded three-phase, and ungrounded three-phase [30,85,86]. Besides, this type of MGs may be classified into three categories based on frequency: high-frequency [87,88], low-frequency [89,90] and standard-frequency AC MGs. AC microgrids have been the predominant and widely adopted architecture among the other options in real-world applications. However, synchronizing with the host grid while maintaining voltage magnitude, phase angle, and frequency is challenging. Their efficiency and dependability are also low. Complex architecture and control are required for AC MGs.

4.3.2. *DC MGs*

The concept of DC MGs is to generate and store electricity in DC forms. The supply power of this type of MGs will be followed by DC power and the connected loads will be driven by DC power. This type of MGs is more advantageous than AC MGs because these MGs do not require synchronization, and there are rarely any power quality issues. They do not have any concerns about the power factor improvement. To interface with the existing distribution systems, these MGs use many converters and power electronic devices. In comparison to AC MGs, DC MGs have higher efficiency and a lower conversion process when feeding DC loads. Telecommunication, electric vehicles, marine power systems, and other commercial applications of DC MGs are only a few examples. Mono-polar, bi-polar, and homo-polar MGs are the three different types of DC MGs [91–93]. DC MGs have the advantage of being able to connect DC loads directly to the DC bus. As a result, there are just a few power converters necessary. DC MGs, on the other hand, do not have a standardized voltage. An additional power step is required to generate AC voltage. DC MGs also cannot be reconfigured from the existing grid. Their protection is complicated.

4.3.3. *AC-DC coupled/hybrid MGs*

The connected load will be driven by both AC and DC power sources in this type of MGs. Hybrid MGs feature an AC and DC distribution system. The goal of a hybrid MG is to minimize the number of conversion stages and interface devices while keeping energy prices low [94]. As a result, the system's overall efficiency and reliability can be improved. Hybrid MGs may combine both AC and DC loads, allowing customers to customize their power usage with their own needs. Power electronic converters decouple the AC and DC components of an MG [95–97]. DG units in AC-DC hybrid MGs can be tied directly to the DC and/or AC networks without the need for synchronization [98]. However, this configuration does not necessarily lead to reduced energy losses in the MGs. Energy losses can still occur within the system due to various factors such as converter inefficiencies, transmission losses, and system control limitations. Hybrid MGs, on the other hand, necessitate a sophisticated controller and management system, particularly in an islanded mode. These MGs also exhibit lower reliability compared to AC MGs, primarily attributed to the incorporation of interface power converters in the distribution network for DC-link generation [84]. Nevertheless, a reduction in the number of converter stages leads to an enhancement in the reliability of the interconnected devices.

4.4. *Classifying MGs on the basis of source*

4.4.1. *Renewable MGs*

An MG powered by distributed renewable resources is known as a renewable MG. Renewable MGs usually comprise RESs and batteries [99]. They provide electricity to end-users with lower carbon footprint. Therefore, these MGs are becoming increasingly popular and being deployed across the world. However, the uncertain and intermittent output of RESs increase the complexity of effective operation of the MGs [100]. Also, meeting the time-varying demand presents a pivotal challenge to an isolated MG. ESS is one of the most appealing technologies for enabling maximum utilization of renewable and is extensively used for balancing demand and supply in MGs [101]. However, the critical challenge is to coordinate storage systems, distributed RESs and variable power demand. Therefore, an EMS is crucial for renewable MGs [102].

Renewable MGs can be classified into five subgroups based on renewable sources: solar, wind, biomass, micro-hydro and hybrid MGs.

- **Solar MGs:** Solar MGs are an attractive renewable energy option since they can be used at any scale and can be scaled up afterwards. As a result, they are widely regarded as a feasible and durable rural electrification option across the world. Since solar MGs rely on the sun for electricity, they function best in places with abundance of sunshine. To deal with gloomy weather, most systems include storage capacity that allows them to run through periods of scant sunshine [103–105]. Solar MGs have the potential to be an environment-friendly energy option. However, the output of solar photovoltaics (PV) is constrained by its fluctuating nature. Therefore, a suitable control technique is imperative. Solar MGs are commonly used to power schools, street lights, homes, businesses, hospitals and irrigation pumps for agriculture.
- **Wind MGs**: A wind MG is an electrical distribution system with a set of interconnected load and wind turbines that operate as a single controlled source within clearly defined electrical boundaries. Wind-based MGs typically employ an ESS to smooth out the supply and store the excess energy for future use in the MGs.
- **Biomass MGs**: An MG powered by biomass is known as a biomass MG. Biomass gasifier systems produce syngas in this MG by incompletely burning biomass, which is then burned in an engine to power a generator [106–108]. Bioenergy MGs are gaining traction in many locations, despite the fact that solar and wind power is more typical MG generation alternatives. As they use biomass gasifiers, which are less expensive than solar PV, their capital requirements are comparatively modest. Biomass gasifiers, on the other hand, are confined to places with a sufficient biomass source. They also require a great amount of feedstock, decent storage procedures, and a fair number of manpower compared to other types of systems. Tar build-up or wet husk can stymie operations on a daily basis. Spark plug failure, battery discharge, and bottle coil failure are all common problems with these systems (an unintentional current to the spark plug). Keeping the husk dry during the monsoon season is another challenge.
- **Micro hydro MGs**: Micro-hydro-based MGs are mainly run-of-the-river projects in which water is redirected from a river or streams through a pipe into a turbine to generate electricity. The cost of energy generation per kWh is quite low. Micro-hydro systems, however, are confined to places with sufficient water supply.
- **Hybrid MGs**: An MG with the capability to provide electricity to a remote site using hybrid renewable sources such as PV, wind, biomass, and micro hydro [109].

4.4.2. *Fossil fuels MGs*

MGs powered by fossil fuel (diesel/natural gas) based generator, which can supply power to the remote areas. They can work in both islanded and grid-connected environments. For many years, energy sources like steam/gas turbines and diesel generators have been the standard for generating local power in an MG. These, however, have a negative influence on both the environment and the economy. The fossil fuels required to power these MGs are expensive to purchase and transport, not to mention that transportation has its own carbon burden. Many communities that employ diesel generators face this problem on a regular basis. MGs are exploring for cleaner options as a result of these impacts [110].

4.4.3. *Hybrid MGs*

A hybrid MG system combines RESs, fossil fuel generators (diesel/gas), and/or batteries to operate in both isolated and grid-connected modes [111]. Fuels-renewable energy hybrid MGs are replacing 100% diesel/natural gas MGs as a more popular option. Hybrid cars substantially lower fuel usage while also being less expensive, more reliable, and less environmentally damaging over their lifetime. However, hybrid systems require fuel-based generators, and hence noise and pollution are inescapable.

4.5. *Classifying MGs on the basis of scenario*

Residential: A typical residential MG consists of an advanced control system (or "controller") that combines customers' electrical demands, regulates distributed resources such as solar PV and energy storage, and coordinates with the distribution networks. A residential MG provides emergency power to key circuits during power outages, reducing a customer's dependency on a centralized electrical supply. The MG controller turns a residence into a flexible, dynamic, and fast-acting network resource that can provide services to electricity distribution and transmission network operators. This types of MGs is designed to serve household customers and will consequently be multi-users, with the MGs being managed by a separate company. It may be rural or urban in nature.

Industrial: The key reasons for implementing an industrial MG are the security and reliability of the power supply. Power outages may disrupt many production processes, resulting in considerable revenue losses and lengthy start-up times. Chip production, the chemical industry, and the paper and food industries are just a few examples. Uninterruptible power supplies are now being installed at some industrial sites if their use is economically justified. The MG architecture may offer additional benefits, such as the ability to combine a reliable power supply with great energy efficiency and the use of renewable energy.

Commercial: Commercial customers often deploy these MGs to serve single users, such as airports, hospitals, data centers, and so on. This type of electricity systems is likewise self-contained and may operate independently of the main grid. They may also be connected to the main grid at times. By diversifying their energy sources, taking advantage of time-of-day electricity pricing, and having backup power on hand whenever it is needed, facilities connected to public grids can minimize energy costs and boost self-sufficiency.

4.6. *Classifying MGs on the basis of location*

Urban MGs: Urban MGs are MGs that have been established in urban areas near utility systems. These MGs are capable of operating in both grid-connected and islanded modes. They conform to all rules, control strategies, and synchronization techniques to maintain the utility grid's system stability and power quality [112]. Hospitals, universities, industries, communities, offices, and shopping malls are among the commercial and residential sectors where urban MGs are implemented.

Remote MGs: Remote MGs are MG systems that are located in remote regions where utility power systems are unavailable due to geographic location. Military installations, hilltop areas, and islands are all instances of remote MGs. Because the utilities are not there, these MGs operate in an isolated manner. Because of the economic, political, and technological challenges, they are rarely installed in comparison to urban MGs [113,114]. Remote MGs provide access to energy outside of the grid. Remote MGs, like island MGs, have traditionally relied on diesel, but are increasingly combining solar and storage.

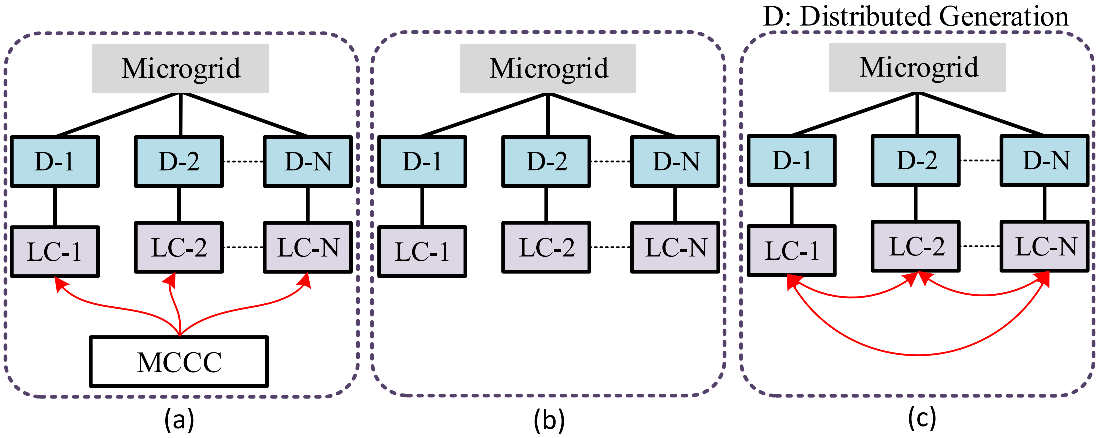


Fig. 3. MG control structures: (a) centralized, (b) decentralized, and (c) distributed.

4.7. Classifying MGs on the basis of application

The MGs may be divided into several groups according to their applications. The following are some of the categories.

- *Military MGs:* Military MGs are small-scale electricity infrastructures that can operate almost autonomously in a military base camp.
- *Campus MGs:* Corporate, university and college campuses are all examples of campus MGs. They are frequently introduced through the use of CHP.
- *Community MGs:* A community MG is a coordinated local grid region served by one or more distribution substations and supported by high penetrations of local RESs and other DERs. They are frequently employed in developed countries to help communities reach renewable energy goals.
- *Island MGs:* They are small-scale MGs that are completely disconnected from the main grid and generate their own electricity.
- *District energy MGs:* District energy MGs provide both electricity and thermal energy for various facilities' heating (and cooling).

5. Microgrid control

MGs' resources are distributed in nature [115]. In addition, the uncertain and intermittent output of RESs increases the complexity of the effective operation of the MG. Therefore, a proper control strategy is imperative to provide stable and constant power flow. MG Central Controller (MGCC) is used to control and manage the MG. MGCC can be installed at a local control center or a distribution substation [116]. Local DG units and distributed ESS devices are controlled by MGCC, which communicates with controllers at lower hierarchical levels. MGs can also be managed using more distributed methods like droop control and agent systems.

In an MG context, a control strategy should meet the following requirements [31,117–119]:

- **Power balance:** Coordination of DG supply and efficient load sharing.
- **Transition:** Islanding to the grid-tied mode or vice versa is a seamless transition between MG modes of operation.
- **Protection:** Monitoring of energy flow and important equipment, as well as grid fault management.
- **Power transmission:** Exchange of power between the main grid and the MG.
- **Optimization:** Determines the best MG dispatch plan in order to maximize economic advantage. In addition, depending on the MG's conditions, it ensures enhanced energy efficiency.
- **Synchronization:** For optimal power transmission, the MG must be synchronized with the power network.
- **Stability:** The MG's voltage and frequency are regulated as it operates in various modes. Furthermore, both the AC- and DC-sides of the MG benefit from a robust and reliable power network.

5.1. Control techniques

A detailed classification of the MG control methods that are frequently utilized in MG operations can be found in Fig. 3 [120–124].

5.1.1. Centralized control techniques

Centralized control management allows for easy deployment and real-time monitoring of the entire system. Within the framework of centralized control, a single individual CC serves as the primary controller. In MG systems, CC manages the operation of different DG units. A LC is used by each DG unit, which can interact with the CC directly. Recent computation technologies help CC to monitor and analyze the data received from the LC in real-time operation [125]. The implementation of centralized control is rather straightforward. It has also demonstrated excellent response in the operation of the MG system. However, many concerns remain unresolved, particularly when working with a large-scale hybrid system [126]. CC failures impact the entire system's functionality. In addition to this, the control technique has a low degree of flexibility and expandability [44,127].

5.1.2. Decentralized control techniques

In recent years, decentralized control has been extensively developed to maximize the autonomy of the micro sources and loads in MGs. The key aspects of this control technique are to maintain stability, cost-effective operation, and reliability [128]. The control decision is made by relying on the local measurement and it requires limited local connections [129]. Furthermore, high-performance computer units and a high level of connection are not required [125]. However, global optimum solutions for the whole MG system cannot be guaranteed.

5.1.3. Distributed control

Some information is shared among controllers so that each has some understanding of the behavior of the others, so improving the overall performance [130]. Table 3 summarized the different control methods with their advantages and disadvantages.

Table 3

A summary of MG control methods options with their advantages and disadvantages [131].

Control method	Advantages	Disadvantages
Centralized	– Global optimal solutions	– Require communication infrastructure – Significant computational burden is involved – Reduced scalability – Communication network affect stability
Decentralized	– No communication infrastructure is required – Reduced computation complexity – Enhanced scalability – Higher reliability	– No global optimal solution
Distributed	– Reduced computation complexity – Enhanced scalability – Better reliability	– Sub-optimal solutions – Require communication infrastructure – Communication network affect stability

5.2. Advancements in MG control systems

Recent advancements in control and supervision systems for MGs have been driven by the increasing incorporation of RESs, the need for enhanced grid flexibility, and the growing complexity of MG operations. The primary aim of these technological advancements is to improve the performance, reliability, and efficiency of MGs, ensuring seamless integration of DERs, and effective management of grid operations. Some notable advancements in control and supervision systems for MGs include:

- *Intelligent EMS*: Advanced EMS solutions utilize artificial intelligence, machine learning, and optimization algorithms to efficiently manage the generation, storage, and consumption of energy within microgrids [132–134]. These systems continuously monitor and forecast energy demand and generation, dynamically optimize energy dispatch, and enable real-time decision-making to achieve optimal operational performance.
- *Advanced ESS management*: To optimize the utilization and effectiveness of ESS in microgrids, sophisticated control strategies have been developed. These strategies involve intelligent scheduling and control of ESS based on real-time capacity demand, renewable energy availability, and grid conditions [135–137]. This facilitates the efficient balancing of energy, peak reduction, load shifting, and grid support.
- *Grid-forming inverter control:* Grid-forming inverters have attracted attention due to their ability to independently regulate the voltage and frequency of MGs, eliminating the dependence on the main grid [138]. This feature is particularly significant as RESs become more prevalent. Advanced control algorithms for grid-forming inverters enhance grid stability, strengthen MG resilience, and enable seamless transitions between grid-connected and islanded modes [139–141].
- *DR integration*: Control systems in microgrids are incorporating DR mechanisms to allow consumers to actively participate in load management. Advanced DR algorithms and communication protocols enable real-time interaction between the MG operator and end-users, which facilitates load shedding or load shifting during peak demand periods and optimizes overall energy consumption [142,143].
- *Cyber-physical security:* It is crucial to ensure the cybersecurity and resilience of MG control systems as they grow more networked and dependent on digital communication and control technologies [144,145]. To defend against cyber threats, control and supervisory systems are integrating advanced security features like encryption, authentication protocols, anomaly detection, and intrusion prevention systems [146–148].

6. Modeling and simulation studies

6.1. Mathematical modeling of MG

This subsection discusses detailed mathematical model of MG components, which can be used for optimum capacity planning.

6.1.1. PV modules

The PV panel's output power is affected by meteorological conditions such as net sun irradiation and solar panel temperature. As a result, these variables are interdependent as the following [149]:

$$P_{PV}(t) = P_{PV}^{rated}\left(\frac{R(t)}{R_{stnd}}\right)\left[1+\alpha_p(T_{amb}-T_{ref})\right]. \tag{1}$$

where P_{PV}^{rated} refers to the nominal output of the solar cell, R_{stnd} denotes the solar irradiation under the typical standard conditions. The value of 1 kW/m^2 is a standard condition typically applicable to the northern parts of the Earth, while closer to the equator, the solar irradiation under standard conditions is generally higher, around 2 kW/m^2. $R(t)$ is the solar radiation at time t and α_p is the temperature coefficient of output. T_{amb} stands for the ambient temperature, and T_{ref} is the standard temperature of a solar panel, which is 27° Celsius.

6.1.2. Wind turbine

The wind turbine's output power (P_w) is a function of the air density (ρ), turbine swept area (A_{wt}), turbine efficiency (η_{wt}) and wind velocity (V_w). It is possible to calculate P_w by [150]:

$$P_w = \rho\left(\frac{1}{2}\right)A_{wt}\times V_w^3\times\eta_{wt} \tag{2}$$

6.1.3. Diesel generator

In MGs, a DG can act as a backup supply, turning on when the battery bank's minimum permissible depth of discharge (DoD) is reached. It can be calculated based on its fuel consumption (FC) in litres per kilowatt-hour (L/kW) [151] as:

$$FC(t) = A_G P_{DG}(t) + B_G P_{DG}^r \tag{3}$$

where P_{DG} is the generated power in kW and P_{DG}^r refers to the rated power in kW of DG. The two coefficients A_G and B_G represent the fuel curve slope (L/h/kW^{out}) and fuel curve interception (L/h/kW^{rated}) of DG, respectively.

6.1.4. Battery energy storage system (BESS)

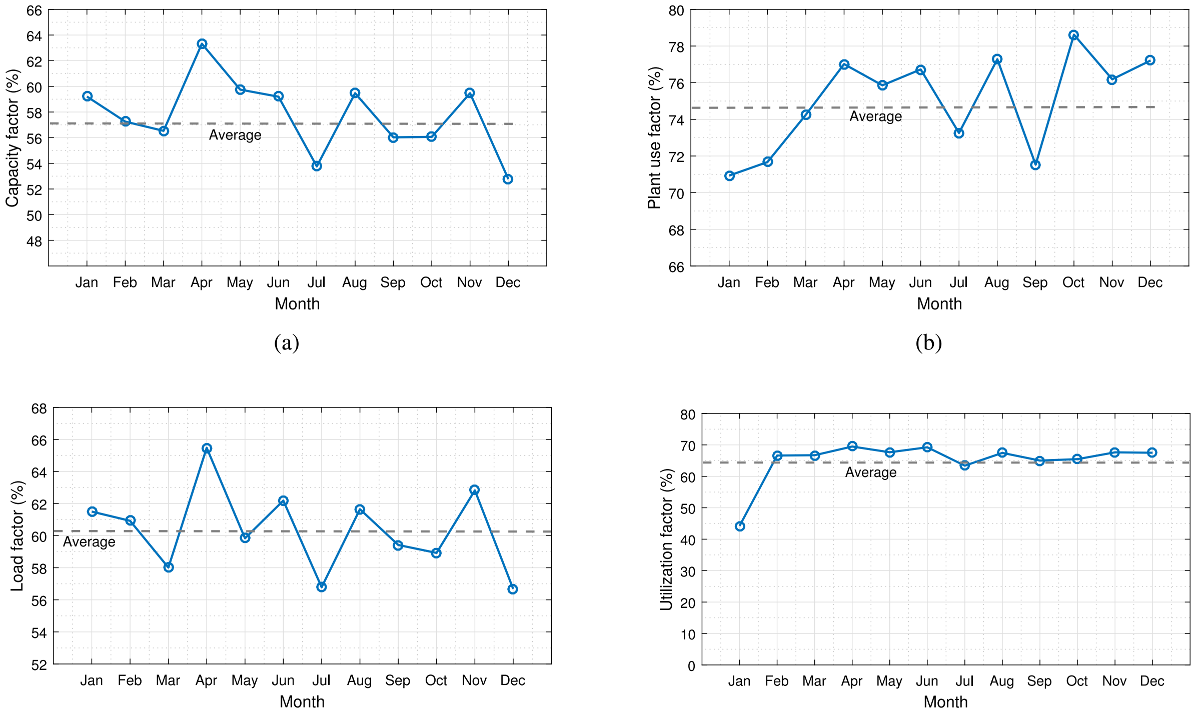
The behavior of the battery can be represented as the state of charge (SOC) in percentage that is related to the battery energy level, $BL(t)$, at time t as follows [152]:

$$SOC(t) = \frac{BL(t)}{BL_{caps}}\times 100\% \tag{4}$$

subjected to

$$SOC_{min} < SOC(t) < SOC_{max}$$

where $BLcaps$ is the battery's initial nominal capacity of battery; SOC_{min} is the minimum limit of the battery, and SOC_{max} is the maximum limit of the battery SOC. The limits require to be set for minimizing the influence on battery ageing, hence extending the battery life [153].



(a) (b)

(c) (d)

Fig. 4. Monthly variation of MG performance indices: (a) capacity factor, (b) plant use factor, (c) load factor and (d) utilization factor.

6.1.5. Power converter modeling

The power converter chosen for an MG should be able to accommodate the maximum expected AC load. Therefore, the converter size (P_{conv}) can be selected based on the maximum load demand (P_{peak}) and inverter efficiency (η_{inv}) as given by [154]:

$$P_{conv} = \frac{P_{peak}}{\eta_{inv}} \tag{5}$$

6.2. Simulation case study

MGs face great challenges to meet demand with unpredictable daily and seasonal variations. Therefore, energy management (EM) for MGs has attracted much attention in global academic and industrial communities. In this study, an isolated campus MG has been considered as a case study for illustrating concepts of peak shaving-based EM [155]. The test MG is powered by two conventional gas turbine generators (GTG), time-varying loads, and battery storage. The maximum power output of each GTG is 4.2 MW, whereas the maximum power output of the BESS is 400 kW. Actual load statistics are from the campus MG system, representing a typical working day. The statistical data of installed capacity, generation and loads are used to analyze the MG's performance under variable load conditions. Statistical analysis results are depicted in Fig. 4. Key observations from the results are:

- The capacity factor for the test MG ranged from 52.77% to 63.32% against the industry best practice 50%–80%.
- The plant utilization factor had an average value of 75.04%. The low plant utilization factor reflects a poor ratio between the actual and projected energy productions.
- Average load factor was 60.35%, which is low compared to the industry standard of 80% or more.
- The highest level of utilization factor (UF) recorded was 67.65%. The UF fluctuated throughout the year and it was never close to the optimal practice, which is 80%.

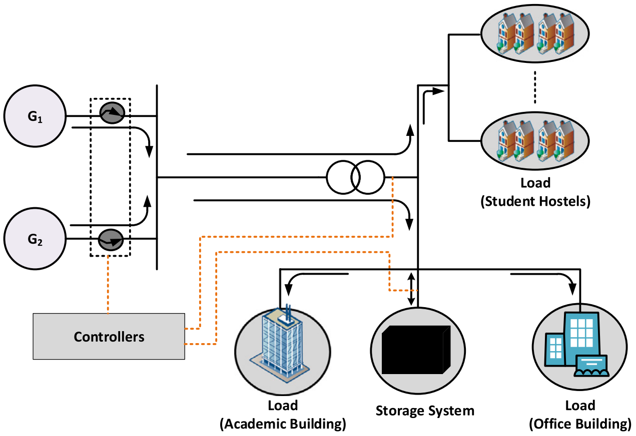
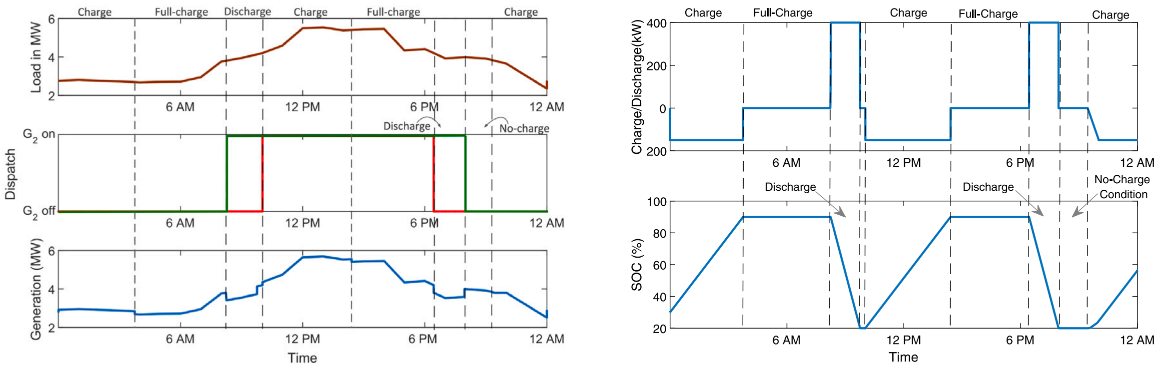


Fig. 5. Proposed structure of test MG.

The findings of the statistical data-based study show that the test MG's performance is considerably below ideal. The significant disparity between the peak and average peak loads caused the test MG to underperform. In practice, the introduction of battery storage-based EMS can improve the MG's performance significantly. Since the electrical demand fluctuates throughout the day, the supply–demand mismatch is more likely to happen. BESS is expected to supply the essential amount of energy into the power system during the low load demand. Fig. 5 illustrates the simplified structure of the proposed model for the test MG.

Fig. 6(a) shows the hourly demand or the load profile of the test MG for a working day. Two major peaks are observed: the day and evening peaks. The evening peak is observed at about 6:20 PM, which is slightly higher than the optimum capacity of G_1. Typically, G_2 is operated along with G_1 to meet this evening peak. However, as can be seen from the simulation results illustrated in Fig. 6(a), the



(a)

(b)

Fig. 6. Simulation results for case MG: (a) EM results (power) with dispatch of generator G_2, and (b) charge–discharge (kW) behavior of BESS and SOC.

battery energy control system can precisely maintain the instantaneous power balance. The required power from BESS to meet the peak load is determined by the battery energy control system. Meanwhile, the controller allows BESS to absorb power from the gas turbine generation system during the off-peak hours and stores it for later use (during the peak load demand). As a result, the campus MG's dynamic performance is improved significantly.

The BESS can offer more cost-effective generator operation. It will decrease the cost of energy production. Without BESS, there will be several on-off generator operations, which will make it more expensive. In addition, without BESS, generators operate at exceedingly low loads in the evening. This also adds to the cost of energy generation. Generator dispatch results are illustrated in Fig. 6(a). The short inspection reveals that G_1 must function throughout the day whereas G_2 works for a particular amount of time in order to power the associated loads. The availability of stored energy yields minimal operational hours for G_2. Reduced use of traditional generators will improve the system economics and lessen the environmental impact.

The charge–discharge and SOC results of the BESS are depicted in Fig. 6(b). The simulation results show that the BESS follows the considered energy management approach. During the periods of low demand, such as when MG is operating in the evening peak, the battery unit supplies the system with the necessary amount of power. During the day's peak demand, the GTG generation is sufficient to meet the demand. As a result, during the daytime peak period, the BESS unit is not required to engage with the system for supplying the stored energy. The BESS unit absorbs the power from the system after the discharging process, particularly during the low demand periods. To prevent overcharging and underdischarging, the minimum level of charge for a battery storage is regarded to be 20%, while the maximum is 90%. The simulation results demonstrate that BESS performed as planned.

The following are the key insights of this simulated case study:

- Using battery storage, the current EM method can minimize the challenges related with the fluctuating demand. BESS can minimize the peaks in demand profile optimally, and maximize the economic benefits.
- The EM may regulate the BESS' charging/discharging process to ensure optimal functioning of the MG.
- The EM can ensure that the conventional generators are utilized to their full potential, which can result in economic benefits for the MG.

7. Challenges and issues

Despite the potential benefits, MG development has a number of challenges and limitations, as explained. The fundamental challenges of MGs can be classified under four groups as illustrated in Fig. 7.

7.1. Technical challenges in MGs

7.1.1. Operation and management

Operation and management: The following are the major management and operational issues that an MG experiences:

- *Issues during start-up of island mode:* The system's frequency and voltages can be affected by the drastic intake of current during the earliest stages of island mode start-up. This may cause the generators to trip and shut down during the initiation phase. To address this, an investigation of energy generation methods in island mode is required, as well as the development of specialized controls suitable for MG operations.
- *Energy management:* In general, energy regulation includes several fine-tuning parameters. After that, the parameters need to be simulated for finding the best solutions. Finding an ideal value in MGs is a challenging task because of the varied ambiguity and unspecific instances, as well as the well-identified specific event [156–158].
- *Appropriate design:* MGs, particularly renewable energy-based MGs, have a different design, modeling, and planning requirements than conventional fuel-based systems, with which most people are already aware [159–162]. One of the major factors that reduces the longevity of MGs is poor design. The design of renewable MGs necessitates a thorough understanding of the available energy supplies as well as the demands of the users [163]. It is also important to consider how changes in available energy resources and demand can affect energy supply availability and reliability. As a result, proper MG design remains a challenge.
- *Identifying the MG's modes of operation:* Each integrated power source versus load scenario in the MG should be identified and specified for situations such as temporary switching or emergency shedding. As an MG consists of loads and generators with varying operational natures and behaviors, this phase becomes critical and challenging [43,164].
- *System security:* To keep the system secure, contingency planning and emergency actions (such as demand-side management, load shedding, islanding, or unit shutdown) are needed. Under contingency scenarios, generation should be rescheduled economically to accommodate system loading and load-end voltage/frequency. System security should be maintained in an MG

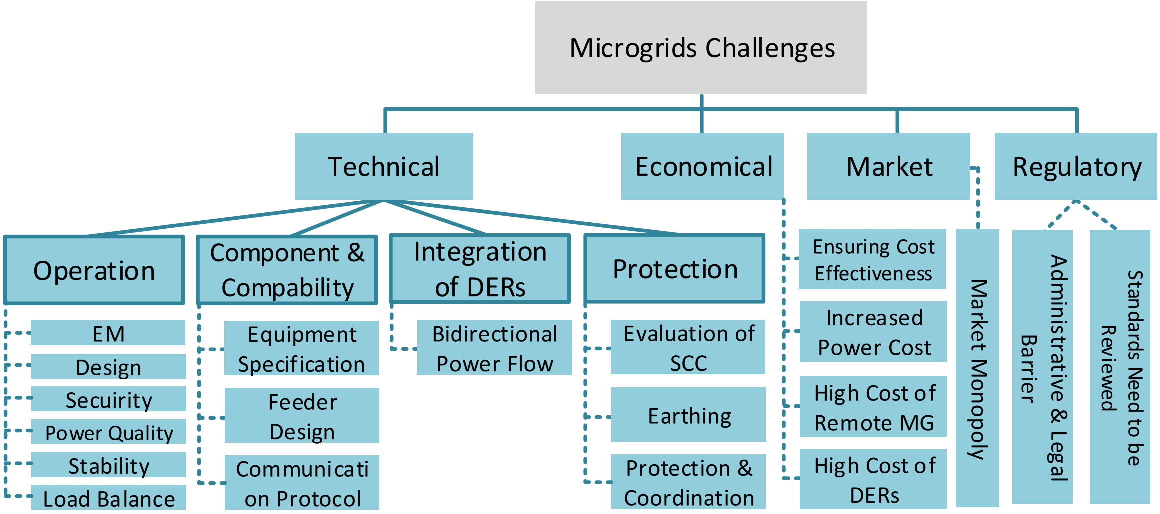


Fig. 7. Challenges of MG implementation.

through emergency operations and contingency planning, such as load shedding, distributed source management, islanding, and unit shutdown.

- *Maintaining power quality:* To ensure power quality, MG's active and reactive power balance should be maintained on a short-term basis.
- *Supervisory control and data acquisition:* The CCs and MCs of MG should incorporate SCADA-based metering, control, and protection capabilities. Provisions should be established for system diagnostics through state estimation functions.
- *Analysis on control system:* To get the most out of an MG, it is critical to have a good design and functional analysis. The mode of operation and configurations of the MG are essential while designing the MG control system. To successfully handle the operating scenario, the control system should incorporate each promising control strategy [32,165].
- *Load flow analysis:* Load flow should be analyzed in every MG operating condition and configuration to determine current flow and voltage levels. The challenge is listing relevant loads and determining their critical levels. Additionally, stating the times of variable load profiles may add to the complexity [166,167].
- *Balancing between generation and load in island mode:* This is one of the most typical issues that MGs encounter. It is necessary to maintain a continual balance between load and power generation. Instability in the island system can be caused by sudden or significant changes in loads.
- *Analysis on system stability:* As MG stability is crucial, it is critical to forecast, monitor, and estimate the transient events that occur as a result of both common and unusual disruptions. MGs are composed of various power sources and components. It is challenging to maintain system stability while employing inertia-based generators, static converter-based PV, wind, and energy storage devices [168,169]. Furthermore, there are other sorts of converters, such as those based on power electronic devices and virtual synchronous generators. To maintain system stability, manufacturers and designers should conduct a comprehensive study and close connection of equipment [170,171].

7.1.2. Component and compatibility

- *Equipment specifications:* The specifications and single-line diagrams of the system are the most important factors to consider while planning power system studies. As a result, the fundamentals for illuminating and demonstrating the MG's operating behavior are essential [172–174].
- *Designing feeders for MG:* Feeders are now developed based on robust sources of power generation and delivery, as per the existing power system. However, there is a challenge when the demand for feeders in MGs remains unfulfilled [43,175,176].
- *Telecommunication infrastructures and communication protocols:* Complete energy management, protection, and control necessitate telecommunication infrastructures and communication protocols [177].

7.1.3. Integration of DERs

When an MG is connected to the main grid, power flows between the main grid and MG are bidirectional. Voltage rise concerns arise as a result of the addition of a large number of distributed generators to the grid, which is one of the biggest technological challenges [178]. As solar PV is intermittent, it typically causes short-term voltage changes, which disrupt the operation of power regulation and protection systems and, as a result, shorten the equipment's life. [179].

- *Bidirectional power flows:* The presence of DG units at low voltage levels in the network may produce reverse power flows, posing challenges with protection coordination, undesirable power flow patterns, fault current distribution, and voltage control.

7.1.4. Protection

The following are the major protection issues that an MG may experience:

- *Evaluation of short-circuit current:* Short-circuit current (SCC) limits are typically calculated using the maximum and minimum levels caused by power system faults. The difficulty originates from the widely variable SCC between operating configurations as a result of different power sources and loads [168,180,181].
- *Earthing:* Neutral earthing is a vital and difficult issue in MGs in terms of the protection plan. This is because the MG shifts between power sources, uses numerous power sources (such as spinning machines and converters), and interfaces with the main grid. The installation of earthing is governed mostly by local grid regulations, but the distribution and maintenance of neutral earthing may bring particular issues [182].

- *Analysis on protection and coordination:* Due to the obvious changing and low SCC, protection research is necessary. The MG configuration should include effective protection equipment and personnel safety, as well as coordinated and sequenced protection device operation. In MGs, the traditional protection plan may not be easy or successful, necessitating innovation and compromise [164,183,184].

7.2. Economic challenges

MG investments remain substantial. Some of its components, including fuel cells, energy storage technologies, smart grid infrastructure, and grid management software, are not yet commercially viable without some form of financial assistance.

Ensuring economic operation: Generation schedules, economic load dispatch, and efficient power flow operations should all be used to achieve a cost-effective operation. The economic operation of the MG should be ensured by economic load dispatch, generator scheduling, and optimal power flow operations.

Increased power generation cost: The implementation of a hybrid system will result in an overall increase in complexity, and there is a possibility that the cost of producing electricity would go up as a result.

Fixed cost reimbursement: Infrastructure expenses are factored into utility tariffs. Individual users will purchase less power from the utility if they are encouraged to generate their own electricity. Some will also generate additional electricity for selling to the utilities. Customers who use net metering will remain connected to the grid, and they may be benefited from this infrastructure without having to pay for its fixed expenses. As a result, consumers who do not adopt net metering will face the consequences of infrastructure expenditures. Utilities are also concerned that as more individuals opt for net metering, they may be unable to afford the massive infrastructure upgrades that a modern, clean grid necessitates [185].

Additional cost for the remote MG: The MG installation in rural places makes maintenance difficult and increases transportation costs.

High costs of DERs: MGs have a significant disadvantage in terms of installation costs. This can be mitigated by securing some type of government subsidy to promote investment. For the sake of satisfying environmental and carbon capture targets, this should be done at least temporarily. A global goal has been set to increase renewable green power output and cut carbon emissions by 50% by 2050.

7.3. Market challenges

Market monopoly: If MGs are permitted to distribute energy autonomously to priority loads during any interruption of the main grid, the key question is who will be responsible for energy supply pricing during the outage. Since the main grid would be disconnected and the electrical market would lose control over energy prices, MGs may sell energy at a very high price, taking advantage of market monopoly. As a result, to support the long-term development of MGs, proper market infrastructure should be established and implemented.

7.4. Regulatory challenges

Standards need to be reviewed: MG is a relatively new industry. Standards and protocols for micro source integration and participation in traditional and deregulated power markets, as well as recommendations for safety and protection, should be developed. To properly combine MGs with active distribution networks, standards such as G59/1 and IEEE 1547 should be reviewed and restructured. Also, research is needed to review IEEE 2030.7-2017– IEEE Standard for the Specification of Microgrid Controllers.

Administrative and legal barrier: In most countries, there is no standard legislation or regulation that regulates the operation of MGs. Some governments are promoting the development of green electricity MGs, although standard regulations have yet to be drafted for future implementation.

8. Future research areas in MGs

The MG is an exciting research field in power engineering. Various research challenges have been addressed with great attention in recent MG studies. However, it still has several critical areas that need to be addressed. Both AC and DC MGs leave open research areas that should be considered when considering future improvements. This paper highlights some of the most critical aspects for future MG research.

- *Modeling:* In future MGs, power sources, ESSs, and loads will all desire to function as plug-and-play units, which will increase its complexity. To avoid this growing complexity, future MGs will necessitate an MG system redesign.
- *Mode of operation:* Another topic of future research could be to investigate and design a system that allows MGs to seamlessly transition from grid-connected to autonomous operation.
- *Protection:* Fixed relay settings are commonly used in classic distribution network protection mechanisms. For MGs, this protection mechanism may be insufficient. As a result, more study is required to develop a protection strategy capable of ensuring the MG's safe operation in all modes and transitions.
- *Control:* When the operating elements of the MG have varying characteristics, an efficient technique for controlling system parameters is necessary for standalone mode.
- *Energy management:* Coordination of renewable sources, storage systems, and load is not straightforward/trivial. Therefore, a strategy is imperative to maintain the power delivered by the renewable sources, generators, and ESS for achieving an economical use of the power sources.
- *Generation-load stability:* An efficient control strategy is required for the MGs operating in standalone mode for maintaining an equalization between generation and load
- *Storage units:* It will be critical in the future to investigate the potential use of ESS with diverse features to maintain the MG's inertia.
- *Integration of electric vehicles:* Electric vehicles (EVs) are growing significantly. Therefore, a greater focus on EV incorporation with MGs could produce interesting findings for power system development.
- *Integration of nuclear energy and RESs:* Future research can focus on the integration of nuclear energy and RESs to achieve a balanced and sustainable energy mix. This entails studying hybrid energy systems, devising strategies for integrating nuclear power and intermittent renewables into the MG, and exploring energy storage technologies that can effectively harness the benefits of both nuclear and RESs [186,187].
- *Co-ordination among multiple MGs:* To allow multi-MGs to coordinate and collaborate, reliable signaling and communication infrastructure should be established. This will help MGs in achieving a balanced operation and a continuous supply of energy to loads.
- *Communication channel:* In MGs, smart metering and network control are required to be integrated.
- *Policy and standards:* It is necessary to have a universally accepted set of standards, regulations, and processes in order to foster and support the successful incorporation of MGs all over the world.

9. Conclusion

This work was set out to present the overview of MGs. Due to the potential importance of MGs, this survey explores the key technologies used in MGs. This review also classifies MGs into seven groups according to their applications, infrastructure, and end-users requirements. Further, MG control strategies are reviewed to provide an insight into these techniques. There is no doubt that the emergence of MGs leads to a more environmentally sound future and better power supply services. However, there are still many certain significant aspects for improvement. A number of research issues and challenges have been identified for MGs. Future research areas to address the identified issues and challenges have been outlined. The state-of-the-art information of MGs provided in this review would draw attention to the investigators, experts, and researchers for MGs. In this paper, however, essential communication systems for MG implementation have not been reviewed. Therefore, further research could also be conducted to highlight the current status of MG communications research.

CRediT authorship contribution statement

Moslem Uddin: Conceptualization, Methodology, Software, Drafting. **Huadong Mo:** Supervision, Knowledge, Review & editing. **Daoyi Dong:** Supervision, Knowledge, Review & editing. **Sondoss Elsawah:** Supervision, Knowledge, Review. **Jianguo Zhu:** Knowledge, Review & editing. **Josep M. Guerrero:** Knowledge, Review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Huadong Mo reports financial support was provided by University of New South Wales.

Data availability

Data will be made available on request.

Acknowledgments

The authors acknowledge University of New South Wales (UNSW), Australia for providing the financial supports to perform this research.

References

[1] A. Aderibole, H. Zeineldin, M. Al Hosani, A critical assessment of oscillatory modes in multi-microgrids comprising of synchronous and inverter based distributed generation, IEEE Trans. Smart Grid (2018).

[2] M. Jafari, Z. Malekjamshidi, D.D.-C. Lu, J. Zhu, Development of a fuzzy-logic-based energy management system for a multiport multioperation mode residential smart microgrid, IEEE Trans. Power Electron. 34 (4) (2018) 3283–3301.

[3] L. Mariam, M. Basu, M.F. Conlon, A review of existing microgrid architectures, J. Eng. 2013 (2013).

[4] G.S. Thirunavukkarasu, M. Seyedmahmoudian, E. Jamei, B. Horan, S. Mekhilef, A. Stojcevski, Role of optimization techniques in microgrid energy management systems—A review, Energy Strategy Rev. 43 (2022) 100899.

[5] M. Grimley, J. Farrell, Mighty Microgrids (Energy Democracy Initiative), Institute for Local Self-Reliance, 2016.

[6] T.-T. Nguyen, H.-J. Yoo, H.-M. Kim, A flywheel energy storage system based on a doubly fed induction machine and battery for microgrid control, Energies 8 (6) (2015) 5074–5089.

[7] N. Lidula, A. Rajapakse, Microgrids research: A review of experimental microgrids and test systems, Renew. Sustain. Energy Rev. 15 (1) (2011) 186–202.

[8] X. Gong, F. Dong, M.A. Mohamed, O.M. Abdalla, Z.M. Ali, A secured energy management architecture for smart hybrid microgrids considering PEM-fuel cell and electric vehicles, IEEE Access 8 (2020) 47807–47823.

[9] N. Hatziargyriou, H. Asano, R. Iravani, C. Marnay, Microgrids, IEEE Power Energy Mag. 5 (4) (2007) 78–94.

[10] Y. Gui, B. Wei, M. Li, J.M. Guerrero, J.C. Vasquez, Passivity-based coordinated control for islanded AC microgrid, Appl. Energy 229 (2018) 551–561.

[11] M. Jafari, Z. Malekjamshidi, J. Zhu, Copper loss analysis of a multiwinding high-frequency transformer for a magnetically-coupled residential microgrid, IEEE Trans. Ind. Appl. 55 (1) (2018) 283–297.

[12] C. Wouters, Towards a regulatory framework for microgrids—The Singapore experience, Sustainable Cities Soc. 15 (2015) 22–32.

[13] L. Ye, H.B. Sun, X.R. Song, L.C. Li, Dynamic modeling of a hybrid wind/solar/hydro microgrid in EMTP/ATP, Renew. Energy 39 (1) (2012) 96–106.

[14] S. Mizani, A. Yazdani, Optimal design and operation of a grid-connected microgrid, in: Electrical Power & Energy Conference (EPEC), 2009 IEEE, IEEE, 2009, pp. 1–6.

[15] R.J. Vijayan, S. Ch, R. Roy, Dynamic modeling of microgrid for grid connected and intentional islanding operation, in: Advances in Power Conversion and Energy Technologies (APCET), 2012 International Conference on, IEEE, 2012, pp. 1–6.

[16] V.S. Bugade, P. Katti, Dynamic modelling of microgrid with distributed generation for grid integration, in: Energy Systems and Applications, 2015 International Conference on, IEEE, 2015, pp. 103–107.

[17] H. Dagdougui, L. Dessaint, G. Gagnon, K. Al-Haddad, Modeling and optimal operation of a university campus microgrid, in: Power and Energy Society General Meeting (PESGM), 2016, IEEE, 2016, pp. 1–5.

[18] M. Göransson, N. Larsson, D. Steen, et al., Cost-benefit analysis of battery storage investment for microgrid of Chalmers university campus using μ-OPF framework, in: PowerTech, 2017 IEEE Manchester, IEEE, 2017, pp. 1–6.

[19] W. Ajaz, Resilience, environmental concern, or energy democracy? A panel data analysis of microgrid adoption in the United States, Energy Res. Soc. Sci. 49 (2019) 26–35.

[20] M. Sandelic, S. Peyghami, A. Sangwongwanich, F. Blaabjerg, Reliability aspects in microgrid design and planning: Status and power electronics-induced challenges, Renew. Sustain. Energy Rev. 159 (2022) 112127.

[21] E. Hossain, E. Kabalci, R. Bayindir, R. Perez, Microgrid testbeds around the world: State of art, Energy Convers. Manage. 86 (2014) 132–153.

[22] D. Kanakadhurga, N. Prabaharan, Demand side management in microgrid: A critical review of key issues and recent trends, Renew. Sustain. Energy Rev. 156 (2022) 111915.

[23] G. Insights, Microgrid deployment tracker identifies 2,179 new projects, 2020, [Online]. Available: https://guidehouseinsights.com/news-and-views/microgrid-deployment-tracker-identifies-2179-new-projects. [Accessed 10 April 2022].

[24] E. Wood, What's driving microgrids toward a $30.9b market? 2019, [Online]. Available: https://microgridknowledge.com/microgrid-market-navigant/. [Accessed 10 April 2022].

[25] T.M. Guibentif, F. Vuille, Prospects and barriers for microgrids in Switzerland, Energy Strategy Rev. 39 (2022) 100776.

[26] A. Banerji, D. Sen, A.K. Bera, D. Ray, D. Paul, A. Bhakat, S.K. Biswas, Microgrid: A review, in: 2013 IEEE Global Humanitarian Technology Conference: South Asia Satellite (GHTC-SAS), IEEE, 2013, pp. 27–35.

[27] S. Lenhart, K. Araújo, Microgrid decision-making by public power utilities in the United States: A critical assessment of adoption and technological profiles, Renew. Sustain. Energy Rev. 139 (2021) 110692.

[28] B. Hartono, Y. Budiyanto, R. Setiabudy, Review of microgrid technology, in: 2013 International Conference on QiR, IEEE, 2013, pp. 127–132.

[29] S.M. Dawoud, X. Lin, M.I. Okba, Hybrid renewable microgrid optimization techniques: A review, Renew. Sustain. Energy Rev. 82 (2018) 2039–2052.

[30] S. Chandak, P.K. Rout, The implementation framework of a microgrid: A review, Int. J. Energy Res. 45 (3) (2021) 3523–3547.

[31] J.J. Justo, F. Mwasilu, J. Lee, J.-W. Jung, AC-microgrids versus DC-microgrids with distributed energy resources: A review, Renew. Sustain. Energy Rev. 24 (2013) 387–405.

[32] K. Rajesh, S. Dash, R. Rajagopal, R. Sridhar, A review on control of ac microgrid, Renew. Sustain. Energy Rev. 71 (2017) 814–819.

[33] S.P. Bihari, P.K. Sadhu, K. Sarita, B. Khan, L. Arya, R. Saket, D. Kothari, A comprehensive review of microgrid control mechanism and impact assessment for hybrid renewable energy integration, IEEE Access (2021).

[34] N. Ali, D. Kumar, State-of-the-art review on microgrid control strategies and power management with distributed energy resources, in: Advances in Smart Grid Automation and Industry 4.0, Springer, 2021, pp. 749–756.

[35] M.H. Andishgar, E. Gholipour, R.-a. Hooshmand, An overview of control approaches of inverter-based microgrids in islanding mode of operation, Renew. Sustain. Energy Rev. 80 (2017) 1043–1060.

[36] B.M. Eid, N. Abd Rahim, J. Selvaraj, A.H. El Khateb, Control methods and objectives for electronically coupled distributed energy resources in microgrids: A review, IEEE Syst. J. 10 (2) (2014) 446–458.

[37] S.M. Malik, X. Ai, Y. Sun, C. Zhengqi, Z. Shupeng, Voltage and frequency control strategies of hybrid AC/DC microgrid: a review, IET Gener. Transm. Distrib. 11 (2) (2017) 303–313.

[38] U.B. Tayab, M.A.B. Roslan, L.J. Hwai, M. Kashif, A review of droop control techniques for microgrid, Renew. Sustain. Energy Rev. 76 (2017) 717–727.

[39] A. Dagar, P. Gupta, V. Niranjan, Microgrid protection: A comprehensive review, Renew. Sustain. Energy Rev. 149 (2021) 111401.

[40] S.S. Rath, G. Panda, P.K. Ray, A. Mohanty, A comprehensive review on microgrid protection: Issues and challenges, in: 2020 3rd International Conference on Energy, Power and Environment: Towards Clean Energy Technologies, IEEE, 2021, pp. 1–6.

[41] S.A. Gopalan, V. Sreeram, H.H. Iu, A review of coordination strategies and protection schemes for microgrids, Renew. Sustain. Energy Rev. 32 (2014) 222–228.

[42] M. Gayatri, A.M. Parimi, A.P. Kumar, A review of reactive power compensation techniques in microgrids, Renew. Sustain. Energy Rev. 81 (2018) 1030–1036.

[43] A. Cagnano, E. De Tuglie, P. Mancarella, Microgrids: Overview and guidelines for practical implementations and operation, Appl. Energy 258 (2020) 114039.

[44] G. Shahgholian, A brief review on microgrids: Operation, applications, modeling, and control, Int. Trans. Electr. Energy Syst. (2021) e12885.

[45] E. Planas, A. Gil-de Muro, J. Andreu, I. Kortabarria, I.M. de Alegría, General aspects, hierarchical controls and droop methods in microgrids: A review, Renew. Sustain. Energy Rev. 17 (2013) 147–159.

[46] A. Hirsch, Y. Parag, J. Guerrero, Microgrids: A review of technologies, key drivers, and outstanding issues, Renew. Sustain. Energy Rev. 90 (2018) 402–411.

[47] S. Parhizi, H. Lotfi, A. Khodaei, S. Bahramirad, State of the art in research on microgrids: A review, IEEE Access 3 (2015) 890–925.

[48] D.T. Ton, M.A. Smith, The US department of energy's microgrid initiative, Electr. J. 25 (8) (2012) 84–94.

[49] C. Marnay, S. Chatzivasileiadis, C. Abbey, R. Iravani, G. Joos, P. Lombardi, P. Mancarella, J. von Appen, Microgrid evolution roadmap, in: 2015 International Symposium on Smart Electric Distribution Systems and Technologies, EDST, IEEE, 2015, pp. 139–144.

[50] N. Hatziargyriou, N. Jenkins, G. Strbac, J.P. Lopes, J. Ruela, A. Engler, J. Oyarzabal, G. Kariniotakis, A. Amorim, et al., Microgrids–large scale integration of microgeneration to low voltage grids, in: CIGRE C6-309, 2006, pp. 1–8.

[51] J.A.P. Lopes, A.G. Madureira, C.C.L.M. Moreira, A view of microgrids, Wiley Interdiscip. Rev.: Energy Environ. 2 (1) (2013) 86–103.

[52] R.H. Lasseter, P. Paigi, Microgrid: A conceptual solution, in: 2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No. 04CH37551), Vol. 6, IEEE, 2004, pp. 4285–4290.

[53] C. Marnay, O.C. Bailey, The CERTS Microgrid and the Future of the Macrogrid, Technical Report, Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), 2004.

[54] P. Piagi, R.H. Lasseter, Autonomous control of microgrids, in: 2006 IEEE Power Engineering Society General Meeting, IEEE, 2006, pp. 8–pp.

[55] R.H. Lasseter, J.H. Eto, B. Schenkman, J. Stevens, H. Vollkommer, D. Klapp, E. Linton, H. Hurtado, J. Roy, CERTS microgrid laboratory test bed, IEEE Trans. Power Deliv. 26 (1) (2010) 325–332.

[56] E. Alegria, T. Brown, E. Minear, R.H. Lasseter, CERTS microgrid demonstration with large-scale energy storage and renewable generation, IEEE Trans. Smart Grid 5 (2) (2013) 937–943.

[57] R. Panora, J.E. Gehret, M.M. Furse, R.H. Lasseter, Real-world performance of a CERTS microgrid in Manhattan, IEEE Trans. Sustain. Energy 5 (4) (2014) 1356–1360.

[58] S. Chowdhury, P. Crossley, Microgrids and Active Distribution Networks, The Institution of Engineering and Technology, 2009.

[59] M. Uddin, M.F. Romlie, M.F. Abdullah, S. Abd Halim, T.C. Kwang, et al., A review on peak load shaving strategies, Renew. Sustain. Energy Rev. 82 (2018) 3323–3332.

[60] M.F. Akorede, H. Hizam, E. Pouresmaeil, Distributed energy resources and benefits to the environment, Renew. Sustain. Energy Rev. 14 (2) (2010) 724–734.

[61] B. Ponstein, An introduction to microgrids, 2019, [Online]. Available: https://www.mtu-solutions.com/au/en/technical-articles/2019/an-introduction-to-microgrids.html. [Accessed 16 May 2022].

[62] E. Planas, J. Andreu, J.I. Gárate, I.M. De Alegría, E. Ibarra, AC and DC technology in microgrids: A review, Renew. Sustain. Energy Rev. 43 (2015) 726–749.

[63] A. Kirubakaran, S. Jain, R. Nema, A review on fuel cell technologies and power electronic interface, Renew. Sustain. Energy Rev. 13 (9) (2009) 2430–2440.

[64] S. Mekhilef, R. Saidur, A. Safari, Comparative study of different fuel cell technologies, Renew. Sustain. Energy Rev. 16 (1) (2012) 981–989.

[65] H. Mo, G. Sansavini, M. Xie, Cyber-Physical Distributed Systems: Modeling, Reliability Analysis and Applications, John Wiley & Sons, 2021.

[66] J. Xu, B. Liu, H. Mo, D. Dong, Bayesian adversarial multi-node bandit for optimal smart grid protection against cyber attacks, Automatica 128 (2021) 109551.

[67] H. Mo, G. Sansavini, Impact of aging and performance degradation on the operational costs of distributed generation systems, Renew. Energy 143 (2019) 426–439.

[68] I.E. Agency, Renewables 2022 - executive summary, 2023, [Online]. Available: https://www.iea.org/reports/renewables-2022/executive-summary. [Accessed 21 May 2023].

[69] L. Hadjidemetriou, L. Zacharia, E. Kyriakides, B. Azzopardi, S. Azzopardi, R. Mikalauskiene, S. Al-Agtash, M. Al-hashem, A. Tsolakis, D. Ioannidis, et al., Design factors for developing a university campus microgrid, in: 2018 IEEE International Energy Conference, ENERGYCON, IEEE, 2018, pp. 1–6.

[70] W. Leal Filho, A.L. Salvia, A. Do Paco, R. Anholon, O.L.G. Quelhas, I.S. Rampasso, A. Ng, A.-L. Balogun, B. Kondev, L.L. Brandli, A comparative study of approaches towards energy efficiency and renewable energy use at higher education institutions, J. Clean. Prod. 237 (2019) 117728.

[71] Y. Huang, H. Masrur, R. Shigenobu, A.M. Hemeida, A. Mikhaylov, T. Senjyu, A comparative design of a campus microgrid considering a multi-scenario and multi-objective approach, Energies 14 (11) (2021) 2853.

[72] Z. Jin, G. Sulligoi, R. Cuzner, L. Meng, J.C. Vasquez, J.M. Guerrero, Next-generation shipboard dc power system: Introduction smart grid and dc microgrid technologies into maritime electrical netowrks, IEEE Electrif. Mag. 4 (2) (2016) 45–57.

[73] Z. Jin, M. Savaghebi, J.C. Vasquez, L. Meng, J.M. Guerrero, Maritime DC microgrids-a combination of microgrid technologies and maritime onboard power system for future ships, in: 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), IEEE, 2016, pp. 179–184.

[74] L. Tarisciotti, A. Costabeber, L. Chen, A. Walker, M. Galea, Current-fed isolated DC/DC converter for future aerospace microgrids, IEEE Trans. Ind. Appl. 55 (3) (2018) 2823–2832.

[75] A. Lashab, M. Yaqoob, Y. Terriche, J.C. Vasquez, J.M. Guerrero, Space microgrids: New concepts on electric power systems for satellites, IEEE Electrif. Mag. 8 (4) (2020) 8–19.

[76] C. Ciurans, N. Bazmohammadi, J.C. Vasquez, G. Dussap, J.M. Guerrero, F. Godia, Hierarchical control of space closed ecosystems: Expanding microgrid concepts to bioastronautics, IEEE Ind. Electron. Mag. 15 (2) (2021) 16–27.

[77] G.J. Falco, W.R. Webb, Water microgrids: the future of water infrastructure resilience, Procedia Eng. 118 (2015) 50–57.

[78] M. Soshinskaya, W.H. Crijns-Graus, J. van der Meer, J.M. Guerrero, Application of a microgrid with renewables for a water treatment plant, Appl. Energy 134 (2014) 20–34.

[79] K. Ullah, Q. Jiang, G. Geng, S. Rahim, R.A. Khan, Optimal power sharing in microgrids using the artificial bee colony algorithm, Energies 15 (3) (2022) 1067.

[80] J. Hu, T. Zhang, S. Du, Y. Zhao, An overview on analysis and control of micro-grid system, Int. J. Control Autom. 8 (6) (2015) 65–76.

[81] N. Singh, I. Elamvazuthi, P. Nallagownden, G. Ramasamy, A. Jangra, Routing based multi-agent system for network reliability in the smart microgrid, Sensors 20 (10) (2020) 2992.

[82] X. Wang, J.M. Guerrero, F. Blaabjerg, Z. Chen, A review of power electronics based microgrids, Int. J. Power Electron. 12 (1) (2012) 181–192.

[83] S. Chakraborty, M.D. Weiss, M.G. Simoes, Distributed intelligent energy management system for a single-phase high-frequency AC microgrid, IEEE Trans. Ind. Electron. 54 (1) (2007) 97–109.

[84] E. Unamuno, J.A. Barrena, Hybrid ac/dc microgrids—Part I: Review and classification of topologies, Renew. Sustain. Energy Rev. 52 (2015) 1251–1259.

[85] M.A. Hossain, H.R. Pota, W. Issa, M.J. Hossain, Overview of AC microgrid controls with inverter-interfaced generations, Energies 10 (9) (2017) 1300.

[86] S. Chandak, P. Bhowmik, P.K. Rout, Robust power balancing scheme for the grid-forming microgrid, IET Renew. Power Gener. 14 (1) (2020) 154–163.

[87] S. Chakraborty, M.G. Simoes, Experimental evaluation of active filtering in a single-phase high-frequency AC microgrid, IEEE Trans. Energy Convers. 24 (3) (2009) 673–682.

[88] R. Barzegarkhoo, M. Farhangi, S.S. Lee, R.P. Aguilera, Y.P. Siwakoti, J. Pou, Nine-level nine-switch common-ground switched-capacitor inverter suitable for high-frequency AC-microgrid applications, IEEE Trans. Power Electron. 37 (5) (2021) 6132–6143.

[89] P. Cheng, H. Kong, J. Ma, L. Jia, Overview of resilient traction power supply systems in railways with interconnected microgrid, CSEE J. Power Energy Syst. 7 (5) (2020) 1122–1132.

[90] F. Sangoleye, J. Johnson, A. Chavez, E.E. Tsiropoulou, L. Marton, C.R. Hentz, A. Yannarelli, Networked Microgrid Cybersecurity Architecture Design Guide-A New Jersey TRANSITGRID Use Case, Technical Report, Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2022.

[91] J.G. Ciezki, R.W. Ashton, Selection and stability issues associated with a navy shipboard DC zonal electric distribution system, IEEE Trans. Power Deliv. 15 (2) (2000) 665–669.

[92] A.T. Elsayed, A.A. Mohamed, O.A. Mohammed, DC microgrids and distribution systems: An overview, Electr. Power Syst. Res. 119 (2015) 407–417.

[93] D. Salomonsson, A. Sannino, Low-voltage DC distribution system for commercial power systems with sensitive electronic loads, IEEE Trans. Power Deliv. 22 (3) (2007) 1620–1627.

[94] M. Abuhilaleh, L. Li, J. Zhu, M. Hossain, Distributed control and power management strategy for an autonomous hybrid microgrid with multiple sub-microgrids, in: 2018 Australasian Universities Power Engineering Conference, AUPEC, IEEE, 2018, pp. 1–6.

[95] F. Nejabatkhah, Y.W. Li, Overview of power management strategies of hybrid AC/DC microgrid, IEEE Trans. Power Electron. 30 (12) (2014) 7072–7089.

[96] H. Xiao, A. Luo, Z. Shuai, G. Jin, Y. Huang, An improved control method for multiple bidirectional power converters in hybrid AC/DC microgrid, IEEE Trans. Smart Grid 7 (1) (2015) 340–347.

[97] L. Che, M. Shahidehpour, A. Alabdulwahab, Y. Al-Turki, Hierarchical coordination of a community microgrid with AC and DC microgrids, IEEE Trans. Smart Grid 6 (6) (2015) 3042–3051.

[98] S. Charadi, Y. Chaibi, A. Redouane, A. Allouhi, A. El Hasnaoui, H. Mahmoudi, Efficiency and energy-loss analysis for hybrid AC/DC distribution systems and microgrids: A review, Int. Trans. Electr. Energy Syst. 31 (12) (2021) e13203.

[99] L. He, S. Zhang, Y. Chen, L. Ren, J. Li, Techno-economic potential of a renewable energy-based microgrid system for a sustainable large-scale residential community in Beijing, China, Renew. Sustain. Energy Rev. 93 (2018) 631–641.

[100] D.W. Gao, Energy Storage for Sustainable Microgrid, Academic Press, 2015.

[101] J. He, X. Wu, X. Wu, Y. Xu, J.M. Guerrero, Small-signal stability analysis and optimal parameters design of microgrid clusters, IEEE Access 7 (2019) 36896–36909.

[102] R. Hao, Q. Ai, T. Guan, Y. Cheng, D. Wei, Decentralized price incentive energy interaction management for interconnected microgrids, Electr. Power Syst. Res. 172 (2019) 114–128.

[103] M. Nasir, H.A. Khan, A. Hussain, L. Mateen, N.A. Zaffar, Solar PV-based scalable DC microgrid for rural electrification in developing regions, IEEE Trans. Sustain. Energy 9 (1) (2017) 390–399.

[104] S. Numminen, P.D. Lund, Evaluation of the reliability of solar micro-grids in emerging markets–issues and solutions, Energy Sustain. Dev. 48 (2019) 34–42.

[105] V. Mehra, R. Amatya, R.J. Ram, Estimating the value of demand-side management in low-cost, solar micro-grids, Energy 163 (2018) 74–87.

[106] A.H.A. Bakar, B. Ooi, P. Govindasamy, C. Tan, H. Illias, H. Mokhlis, Directional overcurrent and earth-fault protections for a biomass microgrid system in Malaysia, Int. J. Electr. Power Energy Syst. 55 (2014) 581–591.

[107] P.Y. Liew, P.S. Varbanov, A. Foley, J.J. Klemeš, Smart energy management and recovery towards Sustainable Energy System Optimisation with bio-based renewable energy, Renew. Sustain. Energy Rev. (2021).

[108] Y. Kuang, Y. Zhang, B. Zhou, C. Li, Y. Cao, L. Li, L. Zeng, A review of renewable energy utilization in islands, Renew. Sustain. Energy Rev. 59 (2016) 504–513.

[109] P.S. Kumar, R. Chandrasena, V. Ramu, G. Srinivas, K.V.S.M. Babu, Energy management system for small scale hybrid wind solar battery based microgrid, IEEE Access 8 (2020) 8336–8345.

[110] D. Schnitzer, D.S. Lounsbury, J.P. Carvallo, R. Deshmukh, J. Apt, D.M. Kammen, Microgrids for Rural Electrification, United Nations Foundation, New York, NY, USA, 2014.

[111] C. Wang, Y. Liu, X. Li, L. Guo, L. Qiao, H. Lu, Energy management system for stand-alone diesel-wind-biomass microgrid with energy storage system, Energy 97 (2016) 90–104.

[112] S. Chandak, P. Bhowmik, P.K. Rout, Load shedding strategy coordinated with storage device and D-STATCOM to enhance the microgrid stability, Prot. Control Mod. Power Syst. 4 (1) (2019) 1–19.

[113] M. Hossain, H. Pota, M. Hossain, A. Haruni, Active power management in a low-voltage islanded microgrid, Int. J. Electr. Power Energy Syst. 98 (2018) 36–47.

[114] A. Vinayagam, A.A. Alqumsan, K. Swarna, S.Y. Khoo, A. Stojcevski, Intelligent control strategy in the islanded network of a solar PV microgrid, Electr. Power Syst. Res. 155 (2018) 93–103.

[115] A. Dimeas, A. Tsikalakis, G. Kariniotakis, G. Korres, Microgrids control issues, Microgrids (2013) 25–80.

[116] N. Hatziargyriou, Microgrids: Architectures and Control, John Wiley & Sons, 2014.

[117] R. Zamora, A.K. Srivastava, Controls for microgrids with storage: Review, challenges, and research needs, Renew. Sustain. Energy Rev. 14 (7) (2010) 2009–2018.

[118] D.E. Olivares, A. Mehrizi-Sani, A.H. Etemadi, C.A. Cañizares, R. Iravani, M. Kazerani, A.H. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke, et al., Trends in microgrid control, IEEE Trans. Smart Grid 5 (4) (2014) 1905–1919.

[119] A. Bidram, A. Davoudi, Hierarchical structure of microgrids control system, IEEE Trans. Smart Grid 3 (4) (2012) 1963–1976.

[120] M.S. Mahmoud, N.M. Alyazidi, M.I. Abouheaf, Adaptive intelligent techniques for microgrid control systems: A survey, Int. J. Electr. Power Energy Syst. 90 (2017) 292–305.

[121] H. Zhao, M. Hong, W. Lin, K.A. Loparo, Voltage and frequency regulation of microgrid with battery energy storage systems, IEEE Trans. Smart Grid 10 (1) (2017) 414–424.

[122] J.M. Guerrero, J. Matas, L.G.D.V. De Vicuna, M. Castilla, J. Miret, Wireless-control strategy for parallel operation of distributed-generation inverters, IEEE Trans. Ind. Electron. 53 (5) (2006) 1461–1470.

[123] J.M. Guerrero, J. Matas, L.G. de Vicuna, M. Castilla, J. Miret, Decentralized control for parallel operation of distributed generation inverters using resistive output impedance, IEEE Trans. Ind. Electron. 54 (2) (2007) 994–1004.

[124] S. Sen, V. Kumar, Microgrid control: A comprehensive survey, Annu. Rev. Control 45 (2018) 118–151.

[125] M. Roslan, M. Hannan, P.J. Ker, M. Mannan, K. Muttaqi, T.I. Mahlia, Microgrid control methods toward achieving sustainable energy management: A bibliometric analysis for future directions, J. Clean. Prod. (2022) 131340.

[126] M. Warnier, S. Dulman, Y. Koç, E. Pauwels, Distributed monitoring for the prevention of cascading failures in operational power grids, Int. J. Crit. Infrastruct. Prot. 17 (2017) 15–27.

[127] S. Mehta, P. Basak, A comprehensive review on control techniques for stability improvement in microgrids, Int. Trans. Electr. Energy Syst. 31 (4) (2021) e12822.

[128] D. Zheng, W. Zhang, S. Netsanet, P. Wang, G.T. Bitew, D. Wei, J. Yue, Microgrid Protection and Control, Academic Press, 2021.

[129] H. Pourbabak, T. Chen, W. Su, Centralized, decentralized, and distributed control for energy internet, in: The Energy Internet, Elsevier, 2019, pp. 3–19.

[130] E. Espina, J. Llanos, C. Burgos-Mellado, R. Cardenas-Dobson, M. Martinez-Gomez, D. Sáez, Distributed control strategies for microgrids: An overview, IEEE Access 8 (2020) 193412–193448.

[131] A. Mohammed, S.S. Refaat, S. Bayhan, H. Abu-Rub, AC microgrid control and management strategies: Evaluation and review, IEEE Power Electron. Mag. 6 (2) (2019) 18–31.

[132] P. Asef, R. Taheri, M. Shojafar, I. Mporas, R. Tafazolli, SIEMS: A Secure Intelligent Energy Management System for Industrial IoT applications, IEEE Trans. Ind. Inform. 19 (1) (2022) 1039–1050.

[133] D. El Bourakadi, A. Yahyaouy, J. Boumhidi, Intelligent energy management for micro-grid based on deep learning LSTM prediction model and fuzzy decision-making, Sustain. Comput.: Inform. Syst. 35 (2022) 100709.

[134] R. Torkan, A. Ilinca, M. Ghorbanzadeh, A genetic algorithm optimization approach for smart energy management of microgrids, Renew. Energy 197 (2022) 852–863.

[135] F. Liu, Q. Liu, Q. Tao, Y. Huang, D. Li, D. Sidorov, Deep reinforcement learning based energy storage management strategy considering prediction intervals of wind power, Int. J. Electr. Power Energy Syst. 145 (2023) 108608.

[136] R. Sreelekshmi, R. Lakshmi, M.G. Nair, AC microgrid with battery energy storage management under grid connected and islanded modes of operation, Energy Rep. 8 (2022) 350–357.

[137] G. Ma, J. Li, X.-P. Zhang, Energy storage capacity optimization for improving the autonomy of grid-connected microgrid, IEEE Trans. Smart Grid (2023).

[138] A. Tuckey, S. Round, Grid-Forming Inverters for Grid-Connected Microgrids: Developing "good citizens" to ensure the continued flow of stable, reliable power, IEEE Electrif. Mag. 10 (1) (2022) 39–51.

[139] Á. Borrell, M. Velasco, M. Castilla, J. Miret, R. Guzmán, Collaborative voltage unbalance compensation in islanded AC microgrids with grid-forming inverters, IEEE Trans. Power Electron. 37 (9) (2022) 10499–10513.

[140] Q. Lin, H. Uno, K. Ogawa, Y. Kanekiyo, T. Shijo, J. Arai, T. Matsuda, D. Yamashita, K. Otani, Field demonstration of parallel operation of virtual synchronous controlled grid-forming inverters and a diesel synchronous generator in a microgrid, IEEE Access 10 (2022) 39095–39107.

[141] L.S. Araujo, D.I. Brandao, Self-adaptive control for grid-forming converter with smooth transition between microgrid operating modes, Int. J. Electr. Power Energy Syst. 135 (2022) 107479.

[142] B. Dey, S. Misra, F.P.G. Marquez, Microgrid system energy management with demand response program for clean and economical operation, Appl. Energy 334 (2023) 120717.

[143] D. Yousri, H.E. Farag, H. Zeineldin, E.F. El-Saadany, Integrated model for optimal energy management and demand response of microgrids considering hybrid hydrogen-battery storage systems, Energy Convers. Manage. 280 (2023) 116809.

[144] Z.-L. Li, P. Li, J. Xia, Z.-P. Yuan, Cyber-physical-social system scheduling for multi-energy microgrids with distribution network coordination, Int. J. Electr. Power Energy Syst. 149 (2023) 109054.

[145] M. Aslani, J. Faraji, H. Hashemi-Dezaki, A. Ketabi, A novel clustering-based method for reliability assessment of cyber-physical microgrids considering cyber interdependencies and information transmission errors, Appl. Energy 315 (2022) 119032.

[146] S. Ma, Y. Li, L. Du, J. Wu, Y. Zhou, Y. Zhang, T. Xu, Programmable intrusion detection for distributed energy resources in cyber–physical networked microgrids, Appl. Energy 306 (2022) 118056.

[147] S.M. Khalil, H. Bahsi, H. Ochieng'Dola, T. Korõtko, K. McLaughlin, V. Kotkas, Threat modeling of cyber-physical systems-A case study of a microgrid system, Comput. Secur. 124 (2023) 102950.

[148] I. Sowa, A. Monti, Distributed consensus control supported by high reporting rate meters in inverter-based cyber-physical microgrids, IEEE Access (2023).

[149] A. Seifi, M.H. Moradi, M. Abedini, A. Jahangiri, An optimal programming among renewable energy resources and storage devices for responsive load integration in residential applications using hybrid of grey wolf and shark smell algorithms, J. Energy Storage 27 (2020) 101126.

[150] A. Raouf, K.B. Tawfiq, E.T. Eldin, H. Youssef, E.E. El-Kholy, Wind energy conversion systems based on a synchronous generator: Comparative review of control methods and performance, Energies 16 (5) (2023) 2147.

[151] R. Hidalgo-Leon, F. Amoroso, J. Urquizo, V. Villavicencio, M. Torres, P. Singh, G. Soriano, Feasibility study for off-grid hybrid power systems considering an energy efficiency initiative for an island in Ecuador, Energies 15 (5) (2022) 1776.

[152] M.A. Hossain, H.R. Pota, S. Squartini, F. Zaman, K.M. Muttaqi, Energy management of community microgrids considering degradation cost of battery, J. Energy Storage 22 (2019) 257–269.

[153] M.J.M. Al Essa, Management of charging cycles for grid-connected energy storage batteries, J. Energy Storage 18 (2018) 380–388.

[154] D. Emad, M. El-Hameed, A. El-Fergany, Optimal techno-economic design of hybrid PV/wind system comprising battery energy storage: Case study for a remote area, Energy Convers. Manage. 249 (2021) 114847.

[155] M. Uddin, M.F. Romlie, M.F. Abdullah, Performance assessment and economic analysis of a gas-fueled islanded microgrid—a Malaysian case study, Infrastructures 4 (4) (2019) 61.

[156] S.K. Rathor, D. Saxena, Energy management system for smart grid: An overview and key issues, Int. J. Energy Res. 44 (6) (2020) 4067–4109.

[157] M. Faisal, M.A. Hannan, P.J. Ker, A. Hussain, M.B. Mansor, F. Blaabjerg, Review of energy storage system technologies in microgrid applications: Issues and challenges, IEEE Access 6 (2018) 35143–35164.

[158] S. Monesha, S.G. Kumar, M. Rivera, Microgrid energy management and control: Technical review, in: 2016 IEEE International Conference on Automatica (ICA-ACCA), IEEE, 2016, pp. 1–7.

[159] A. Kumar, P. Mohanty, D. Palit, A. Chaurey, Approach for standardization of off-grid electrification projects, Renew. Sustain. Energy Rev. 13 (8) (2009) 1946–1956.

[160] H. Zerriffi, Distributed rural electrification in China, in: Rural Electrification, Springer, 2011, pp. 111–135.

[161] D. Akinyele, J. Belikov, Y. Levron, Challenges of microgrids in remote communities: A STEEP model application, Energies 11 (2) (2018) 432.

[162] D.G. Photovoltaics, E. Storage, IEEE Guide for Array and Battery Sizing in Stand-Alone Photovoltaic (PV) Systems, 2008.

[163] S. Chen, T. Liu, F. Gao, J. Ji, Z. Xu, B. Qian, H. Wu, X. Guan, Butler, not servant: A human-centric smart home energy management system, IEEE Commun. Mag. 55 (2) (2017) 27–33.

[164] H. Wang, Z. Yan, M. Shahidehpour, X. Xu, Q. Zhou, Quantitative evaluations of uncertainties in multivariate operations of microgrids, IEEE Trans. Smart Grid 11 (4) (2020) 2892–2903.

[165] Y. Yoldaş, A. Önen, S. Muyeen, A.V. Vasilakos, İ. Alan, Enhancing smart grid with microgrids: Challenges and opportunities, Renew. Sustain. Energy Rev. 72 (2017) 205–214.

[166] U.H. Ramadhani, M. Shepero, J. Munkhammar, J. Widén, N. Etherden, Review of probabilistic load flow approaches for power distribution systems with photovoltaic generation and electric vehicle charging, Int. J. Electr. Power Energy Syst. 120 (2020) 106003.

[167] G. Artale, G. Caravello, A. Cataliotti, V. Cosentino, D. Di Cara, S. Guaiana, N. Nguyen Quang, M. Palmeri, N. Panzavecchia, G. Tinè, A virtual tool for load flow analysis in a micro-grid, Energies 13 (12) (2020) 3173.

[168] G. San, W. Zhang, X. Guo, C. Hua, H. Xin, F. Blaabjerg, Large-disturbance stability for power-converter-dominated microgrid: A review, Renew. Sustain. Energy Rev. 127 (2020) 109859.

[169] S. Sarangi, B.K. Sahu, P.K. Rout, Distributed generation hybrid AC/DC microgrid protection: A critical review on issues, strategies, and future directions, Int. J. Energy Res. 44 (5) (2020) 3347–3364.

[170] M. Farrokhabadi, C.A. Cañizares, J.W. Simpson-Porco, E. Nasr, L. Fan, P.A. Mendoza-Araya, R. Tonkoski, U. Tamrakar, N. Hatziargyriou, D. Lagos, et al., Microgrid stability definitions, analysis, and examples, IEEE Trans. Power Syst. 35 (1) (2019) 13–29.

[171] Y. Wu, Y. Wu, J.M. Guerrero, J.C. Vasquez, J. Li, AC Microgrid Small-Signal Modeling: Hierarchical control structure challenges and solutions, IEEE Electrif. Mag. 7 (4) (2019) 81–88.

[172] A.P. Chandrayan, Multi-agent based intelligent distributed control of a hardware-in-the-loop microgrid test-bed, 2015.

[173] G. Joos, J. Reilly, W. Bower, R. Neal, The need for standardization: The benefits to the core functions of the microgrid control system, IEEE Power Energy Mag. 15 (4) (2017) 32–40.

[174] A.J. Aristizábal, J. Herrera, M. Castañeda, S. Zapata, D. Ospina, E. Banguero, A new methodology to model and simulate microgrids operating in low latitude countries, Energy Procedia 157 (2019) 825–836.

[175] J. Jung, M. Villaran, Optimal planning and design of hybrid renewable energy systems for microgrids, Renew. Sustain. Energy Rev. 75 (2017) 180–191.

[176] J. Zhou, J. Zhang, X. Cai, G. Shi, J. Wang, J. Zang, Design and analysis of flexible multi-microgrid interconnection scheme for mitigating power fluctuation and optimizing storage capacity, Energies 12 (11) (2019) 2132.

[177] J. Xu, Q. Sun, H. Mo, D. Dong, Online routing for smart electricity network under hybrid uncertainty, Automatica 145 (2022) 110538.

[178] R. Tonkoski, D. Turcotte, T.H. El-Fouly, Impact of high PV penetration on voltage profiles in residential neighborhoods, IEEE Trans. Sustain. Energy 3 (3) (2012) 518–527.

[179] A. Sharma, M. Kolhe, U.-M. Nils, A. Mudgal, K. Muddineni, S. Garud, Comparative analysis of different types of micro-grid architectures and controls, in: 2018 International Conference on Advances in Computing, Communication Control and Networking, ICACCCN, IEEE, 2018, pp. 1200–1208.

[180] L. Wang, B. Feng, Y. Wang, T. Wu, H. Lin, Bidirectional short-circuit current blocker for DC microgrid based on solid-state circuit breaker, Electronics 9 (2) (2020) 306.

[181] X. Zhang, Z. Li, Sliding-mode observer-based mechanical parameter estimation for permanent magnet synchronous motor, IEEE Trans. Power Electron. 31 (8) (2015) 5732–5745.

[182] D. Jayamaha, N. Lidula, A. Rajapakse, Protection and grounding methods in DC microgrids: Comprehensive review and analysis, Renew. Sustain. Energy Rev. 120 (2020) 109631.

[183] S. Hossain-McKenzie, E.C. Piesciorovsky, M.J. Reno, J.C. Hambrick, Microgrid Fault Location: Challenges and Solutions, Sandia National Laboratories, Albuquerque, NM, USA, 2018.

[184] P. Barra, D. Coury, R. Fernandes, A survey on adaptive protection of microgrids and distribution systems with distributed generators, Renew. Sustain. Energy Rev. 118 (2020) 109524.

[185] B. States, The main benefits and challenges of microgrids for utilities, 2021, [Online]. Available: https://solutions.borderstates.com/benefits-of-microgrids/. [Accessed 8 April 2022].

[186] D. Michaelson, J. Jiang, Integration of small modular reactors into renewable energy-based standalone microgrids: An energy management perspective, IEEE Power Energy Mag. 20 (2) (2022) 57–63.

[187] D. Michaelson, J. Jiang, Review of integration of small modular reactors in renewable energy microgrids, Renew. Sustain. Energy Rev. 152 (2021) 111638.