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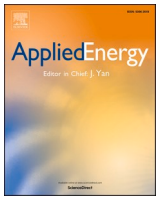

Recent advances on energy management and control of direct current microgrid for smart cities and industry: A Survey

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HIGHLIGHTS

- An overview of microgrids and their fundamentals is offered.
- A comprehensive analysis of the classifications and applications of microgrids.
- An in-depth analysis is conducted on the challenges related to the installation of microgrids.
- An overview of potential future study topics that are worth investigating in the field of microgrids.

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ABSTRACT

Recently, the intent to use microgrid (MG) technology for urban, residential, and industrial applications has significantly increased. Thanks to the integration of shared storage technologies, these power systems allow for higher penetration of distributed renewable generation (DGs) and better mitigation of imbalances between demand and generation. This responds to social and environmental requirements in terms of decarbonizing energy and also contributes to strengthening smart cities. DC (Direct Current) microgrids offer several advantages compared to AC (Alternating Current) type microgrids, like superior efficiency, better control, stability, compatibility with the DC nature of renewables and storage sources, and the absence of reactive and synchronization problems. However, before fully exploiting the potential of microgrids in renewable-powered smart grids, it is necessary to conduct further research and discussion on critical technical and socio-economic challenges. This paper presents a review of the existing state-of-the-art research in DC microgrid development, relevant challenges related to security, communication, power quality, and operation, as well as the appropriate control and energy management strategies to handle them. As control and energy management strategies considerably impact other performance indicators such as operating cost, emissions, and power system safety, this paper offers a perspective on the potential improvement of such management solutions.

1. Introduction

The excessive use of fossil fuels for electricity generation is causing global environmental concerns. Developing and developed countries recognize the need to protect the planet from climate change and are working together to reduce CO2 emissions to 1000 billion equivalents by 2100, aiming to stabilize global warming at 1.5–2 °C. For doing so, a set of actions and measures are expected to be achieved in the coming years in energy, forests, housing, transport, industry, and waste [1]. These programs aim to reach energy decarbonization, mitigate climate change, promote smart cities, and sustain economic development. Indeed, the transition to clean alternative energy generates, in the long run, deep structural changes that lead to the prevention of upcoming environmental and economic crises [2,3]. It's well established in the literature

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that promoting renewable energy is the best way to fight against climate change and reach sustainable development [4,5]. Otherwise, the transition to clean alternative energy is mandatory to prevent upcoming environmental and economic crises. The new energy model is transitioning from the existing power system's reliance on classical fossil-based power resources to an energy mix based mainly on renewable energy resources (RESs) [6]. In this context, smart grid decentralization via management and coordination of local energy systems is an emerging trend in the energy landscape.

The decentralized coordination of distributed energy resources can be achieved through various models, the microgrids (MG) being a relevant example. They enable more localized control and coordination of RES and efficient energy management while operating autonomously or in coordination with the primary grid [7]. Wind, solar, hydro, biomass, geothermal, and marine energy are some examples of RESs characterized as cleaner, smarter, closer, and potentially limitless [8]. These local sources can be integrated at different power and voltage scales into the primary grid through power electronic converters, where they can be defined as distributed generation (DG) systems. In addition, smart cities, representing the next generation of urban cities, require microgrid technology. Smart cities use this technology to increase the effectiveness of various services, including communication, energy, and transportation [9]. On the other hand, microgrids are small-scale energy systems that may function separately or in tandem with the primary grid [10]. Integrating modern control technologies, storage systems, and renewable energy sources enhances the resilience and sustainability of smart cities. They provide environmental sustainability, dependability, and energy efficiency in urban settings [11,12]. However, incorporating new generation sources into the old traditional power grids brings technical and economic challenges to maintaining stability and maximizing financial profitability.

Based on advanced communication and management facilities, the smart grid concept is one of the most promising solutions to these objectives [13]. This technology provides extra options for effective electric power generation, transport, and distribution [14]. Microgrids are becoming more attractive for self-production and self-consumption facilities as a fundamental brick of smart grids. Indeed, MGs based on RESs are installed near final consumers and participate in greenhouse gas emission reduction, minimize transportation losses, and secure the power supply in case of a primary grid fault. Furthermore, this kind of generation, which provides an uninterrupted power supply (UPS), is suitable for rural and isolated areas, islands, military applications, etc. For these reasons, the global microgrid market is expected to rise from $24.6 billion in 2021 to $42.3 billion by 2026, at a compound annual growth rate of 11.4% over 2021–2026 [15]. The prominent market leaders in the microgrids field are ABB (Switzerland), Siemens (Germany), General Electric Company (US), Schneider Electric (France), Bosch (Germany), Honeywell (US), and Eaton Corporation (Ireland).

COVID-19 has significantly influenced the operations of microgrid manufacturers, as well as their suppliers and distributors. Compared to pre-COVID-19 levels, a drop in export shipments, project delays, and poor domestic demand for microgrid hardware are projected to negatively impact and somewhat stagnate demand for the microgrid industry in the short term due to quarantine limitations and the degradation of fund sources [15]. On the other hand, the worldwide recovery process made cleaner electricity systems mandatory following this epidemic. The European Union (EU) emphasized this tendency with the Green Deal program [16]. Furthermore, the United Nations is paving the road for these goals to be met worldwide with goals 7 and 11 of the Sustainable Development Goals (SDG) [17,18].

Indeed, DCMGs have various benefits over AC types. However, it is essential to note that there are several obstacles hindering the promotion of DC microgrids, including:

- Load power sharing and voltage regulation in DC power systems since most installed power conversion systems adopt alternating current.
- Low operating costs and emissions due to the expensive DC protection systems, economical sizing, and operational challenges in DC power systems.
- DC microgrids enable communication and data transmission, whereas extra communication systems are required compared to traditional power systems.
- Energy storage systems' protection against complex operating conditions is required to extend their lifespan and efficiency.
- Communication with the primary grid and prepare the microgrid to switch between grid-connected and isolated modes.
- Grounding systems and protection protocols for DC power systems are immature and expensive. In addition, this paper includes a comparative study between AC and DC microgrids, DC microgrid analysis, and perspectives.

This review article contributes to reviewing current approaches to addressing difficulties in direct current (DC) and alternating current (AC) microgrids, emphasizing their benefits, drawbacks, and practicality. The study investigates the distinctive attributes, operational intricacies, and performance indicators of DC microgrids. The study investigates practical implementations, case studies, and extant literature to comprehend DC microgrid deployment's technical, economic, and regulatory dimensions. Additionally, this study delves into prospective developments and emergent patterns in DC microgrids, discerning possible avenues for advancement and growth. The paper offers stakeholders a comprehensive understanding of the development trajectory of DC microgrids through clarification of existing technologies and ongoing research initiatives. Table 1 presents the main parts covered by the proposed paper compared to other published review papers in the context of DC microgrids.

The rest of this review paper is structured as follows: The microgrid components are provided in Section 2, while their applications and classifications are illustrated in Section 3 and Section 4, respectively. Section 5 presents a comparative study between AC and DC microgrids. Sections 6 and 7 present the configuration and challenges of DC microgrids. Section 8 reports and discusses the rated DC bus voltage classifications. Section 9 provides the control plans, while Section 10 presents the management strategies. The main perspectives on the DCMG's future directions are reported in Section 11.

2. Microgrid components

Microgrid (MG) is a multisource system that combines various distributed generators (DGs), including RESs, energy storage systems (ESSs), loads (controllable and non-controllable), and grid equipment such as control and protection systems [24,25]. MG components are defined as follows:

Distributed generators: Distributed generators may include emerging generation technologies such as combined heat and power (CHP) [26], fuel cells (FCs) [27], micro wind turbines, and PV [28]; and classic generators including single-phase, three-phase induction, and synchronous generators [29]. Fuel cell technology is one of the most promising technologies because of its high efficiency, modularity, scalability, and low pollutant emissions. FC technology includes the following types: proton exchange membrane FC (PEMFC), alkaline FC (AFC), phosphoric acid FC (PAFC), molten carbonate FC (MCFC), solid oxide FC (SOFC), and direct methanol FC (DMFC).

Energy storage systems: Energy storage systems (ESSs) are essential components ensuring proper functioning. The primary role of the ESS is to maintain the power balance and energy demand within the MG [30]. They have other tasks, such as enhancing the power quality against load fluctuations or intermittence of RES and supplying the necessary power for a smooth transition from grid-connected to island-based MG

Table 1
comparative study between several review papers and the proposed paper.

Ref		[19]	[20]	[21]	[22]	[23]	Proposed
Market evolution		Yes	No	Yes	No	No	Yes
Architecture		Yes	Yes	Yes	Yes	Yes	Yes
DC vs. AC MGs		No	No	No	No	No	Yes
Classification		No	No	No	No	No	Yes
Applications		Yes	Yes	No	No	Yes	Yes
Rated voltage review		No	No	No	No	No	Yes
Control		Yes	No	Yes	No	No	Yes
Energy management system		No	No	Yes	No	No	Yes
Challenges	Protection	No	Yes	No	Yes	Yes	Yes
	Power quality		Yes		No	No	Yes
	Communication		Yes		No	No	Yes
	Operation		Yes		No	No	Yes
Perspectives		Yes	Yes	No	Yes	Yes	Yes

operation. Batteries, flywheels, and supercapacitors are the energy storage technologies better suited to MGs [31]. Because of their high energy density, batteries can provide superb performance for this application.

MG loads: a microgrid can supply various consumer types such as residential, commercial, and industrial. Generally, commercial and industrial consumers are crucial loads that require high power quality and reliability. Therefore, the microgrid has to manage the loads by accomplishing the following tasks [32]:

- Load monitoring, analytics, and prediction.
- Load balancing and demand response.
- Load shedding for non-crucial loads to fulfill the net import/export power in on-grid mode.
- Stabilize the voltage and frequency in the islanded mode.
- Enhance the power quality and reliability of critical loads.
- Load scheduling and resource planning for the resilient operation.

DG interfacing systems: most DGs require a converter interface to adopt their output power with common bus-compatible power (AC or DC). Furthermore, the power electronic interface includes filters, measurement elements, and protection systems [33]. In particular, the interoperability among monitoring and control devices and microgrids is an open change. At the same time, interoperability is essential to ensure efficient communication and coordination between various monitoring and control devices within the microgrid.

Management and control system/electronic card IC and measurement systems: the management card allows users to control and supervise the source and ESSs. A complete energy management solution includes process data from the control and data acquisition systems, network monitoring, inverters, system automation, and more. In addition, the remote cards are plug-and-play for quick and immediate management system installation.

3. DCMG applications:

Since microgrids can deliver power in a dependable, resilient, and environmentally friendly manner, they have a broad range of applications across various industries. The following are some of the most essential uses of microgrids:

Smart Cities and Urban applications: By integrating with cutting-edge technologies like the Internet of Things (IoT), energy management systems, and demand response processes, MGs aid in the transition of urban infrastructures to smart cities [34]. Intelligent energy systems and reliable electrical networks distinguish smart cities. They enable the integration of renewable energy resources, refueling electric vehicles, increase energy efficiency, facilitate demand-side management, and innovative energy-related value-added services [11]. In the power paradigm, these technological characteristics and information and communication networks are indispensable [35].

Residential applications: MGs can potentially augment energy independence and robustness by installing sophisticated energy management devices, solar panels, and battery storage systems. In addition, with the increased number of DC residential loads, such as laptops and LEDs, DCMGs are becoming more reliable for residential applications. Because of its compatibility with the standards of the Emerge Alliance of buildings, 380-400 V DC bus voltage is used more in this application [21].

Commercial applications: commercial buildings have experienced a significant increase in energy consumption due to their characteristics, including high consumption ratio and building size [36]. MGs have the potential to decrease energy costs and alleviate the hazards linked to power outages. Also, the buildings can play a significant role if they are operated in a coordinated manner as flexibility assets integrated with the microgrids. Research efforts are needed to support the digital transformation of the buildings by proposing technological enablers and interoperability unlocking mechanisms to allow their coordinated operation. As reported in [37], 380 V DC bus voltage is an appropriate choice for these buildings. Zero-net energy (ZNE) buildings are becoming more attractive and using MG technology as a power system [38,39]. Using PV and batteries on the rooftops is also an encouraging solution for deploying the DCMGs in these buildings. In addition, buildings lose 13% of energy annually due to AC/DC conversion [40]. These losses can be eliminated using DCMGs. Its compatibility with residential and commercial buildings makes it an excellent solution for distributing power in urban cities. This can allow the city members to participate in the energy market by exchanging power between them. This can provide economic and technical benefits [41].

Industrial applications: electric motor drives consume >40% of the provided electricity [42]. If the used converters are connected to a DC bus, this enables the utilization of regenerative (braking) power [43]. As a result, the common DC bus configuration can be a cost-effective and energy-efficient option for many industrial applications. Therefore, using DCMGs for this kind of application is a reliable solution. Its DC nature allows for excellent plug-and-play prospects, enabling the attachment or disconnection of DGs or loads in the future without affecting the functioning of the MG [40].

Transportation applications: Most current propulsion systems are based on AC-supplying systems. However, the emerging propulsion technology may present DC-supplying systems as better solutions [44]. Hence, DCMGs are being presented as optimal solutions for future transportation systems such as electric ships [45], more electric aircraft (MEA) [46], advanced electric vehicles (EVs) [47], ships [48,49], and hybrid electric vehicles [50]. MGs-based hybrid power systems (HPSs) are becoming a strategic solution for these applications. Most EVs are based on batteries with other storage systems, such as supercapacitors. Furthermore, hybrid electric vehicle-based fuel cells are increasingly utilized for their advantages, including high power density and alternative storage strategies [51].

Fast charging stations for electric vehicles (EVs): Plug-in electric

vehicles (PEVs) are gaining more and more attention in the context of energy decarbonization [52]. However, they require specific charging stations due to the high consumption rate. On the other hand, a microgrid as an independent power system favors self-consumption, and thus, less stress is applied to the main grid [53]. Moreover, due to their compatibility with the DC nature of charging power, DC microgrids are considered an optimal solution for charging station infrastructures compared with the AC type. Moreover, it is compatible with PV generators commonly used in urban areas.

The microgrid's main applications are illustrated in Fig. 1.

4. Microgrid classification:

4.1. Based on the structure:

ACMGs (Fig. 2.b): power electronics converters connect DGs and ESSs to the AC bus. AC sources that provide variable frequency and variable voltage are connected to the AC bus using AC/AC converters, while controllable AC sources are linked directly to the AC bus. Several sources, such as wind turbines and low-head hydro, may require AC/DC/AC power converters to stabilize the ACMG [54]. On the other hand, DC sources are connected to the AC bus via a DC/AC converter [55]. Furthermore, the ACMGs directly link AC loads, while DC loads require AC/DC power converters.

DCMGs (Fig. 2.a): DC-based DGs and ESSs connect directly to the DC bus, providing DC power. In addition, DC-compatible loads are getting more popular. As a result, the DCMGs will dominate soon. In this case, an AC/DC converter connects the AC sources to the DC bus [8].

Hybrid MGs: This type of MG includes both AC and DC MG features, where the AC sources are connected to the AC bus, and the DC sources are connected to the DC bus. A bidirectional converter connects the AC and DC buses, allowing power to flow between them. Hybrid microgrids (HMGs) comprise several parallel-connected DGs capable of operating in island and grid-connected modes [56]. Therefore, HMGs can be considered a combination of DC and AC MGs [57]. However, the HMGs require a robust management system due to the complex interaction between the AC and DC sides [58].

4.2. Based on operating mode [59]:

Islanded MGs (off-grid mode): due to their independence and lack of connection to the main grid, MGs are able to generate electricity on their own.

Grid-connected MGs (on-grid mode): MGs can be connected to the main grid or function autonomously during grid disruptions or blackouts.

4.3. Based on size [60]:

Mini MGs: designed to serve extremely small communities or individual residences, frequently in remote or rural regions, these microgrids are compact in size.

Medium MGs: these MGs are characterized by their smaller size and are primarily designed to provide electricity to specific towns, colleges, or smaller industrial sites.

Large MGs: these MGs may encompass a substantial geographical expanse and cater to a sizable population or industrial facility.

4.4. Based on application [59]:

Urban MGs: urban areas are equipped with these microgrids in an effort to improve energy resilience, efficiency, and sustainability.

Rural MGs: these MGs are strategically installed in remote or rural regions to supply dependable electricity in the absence of conventional grid infrastructure.

Embedded MGs: these MGs are designed for embedded applications like transportation applications.

MG general classifications are summarized in Fig. 3.

5. AC versus DC MGs:

DC MGs are getting more attractive due to their considerable advantages. The DC nature of several renewable energy sources and electrochemical storage systems reduced conversion stages to power local consumers. In addition, the simplified electrical structure of this MG type implies higher efficiency and more simple control since no synchronization and complex control is needed. Nevertheless, these power systems still suffer from several problems, such as safety and protection tools, existing codes and standards designed for AC systems, and other issues [61,62]. According to the research reported in [63,64], the main characteristics of both DC and AC MGs are reported in Table 2.

6. DCMG Configuration:

The configuration of a DCMG is mainly available in four different topologies: single-bus, multi-bus, multi-terminal, and ring architecture.

Single bus: This type of configuration is the basic one. A single bus is used in this configuration. All the devices, including RESs, ESSs, and loads, connect in parallel, as shown in Fig. 4(a). Power electronics converters must be correctly located to provide system stability and robustness. Because of a single bus, single-point failure may lead to system failure [65].

Ring architecture: As shown in Fig. 4(b), the ring configuration offers a closed arrangement suitable for various applications. In addition, this configuration provides more reliability and security due to the bidirectional power flow. If one busbar connection is damaged, the

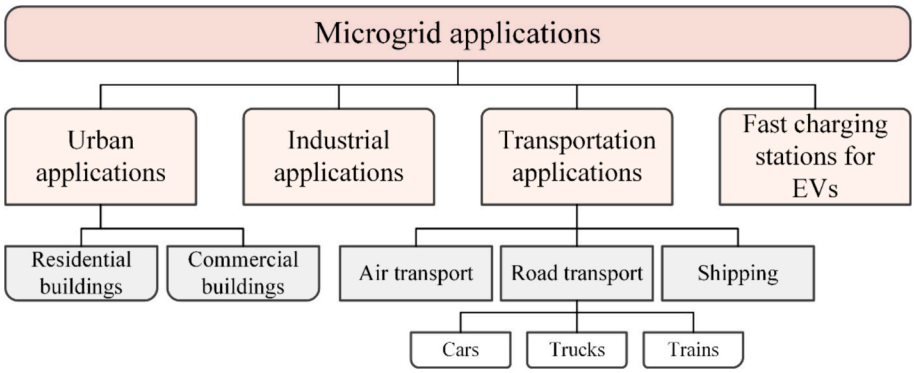


Fig. 1. Microgrid applications

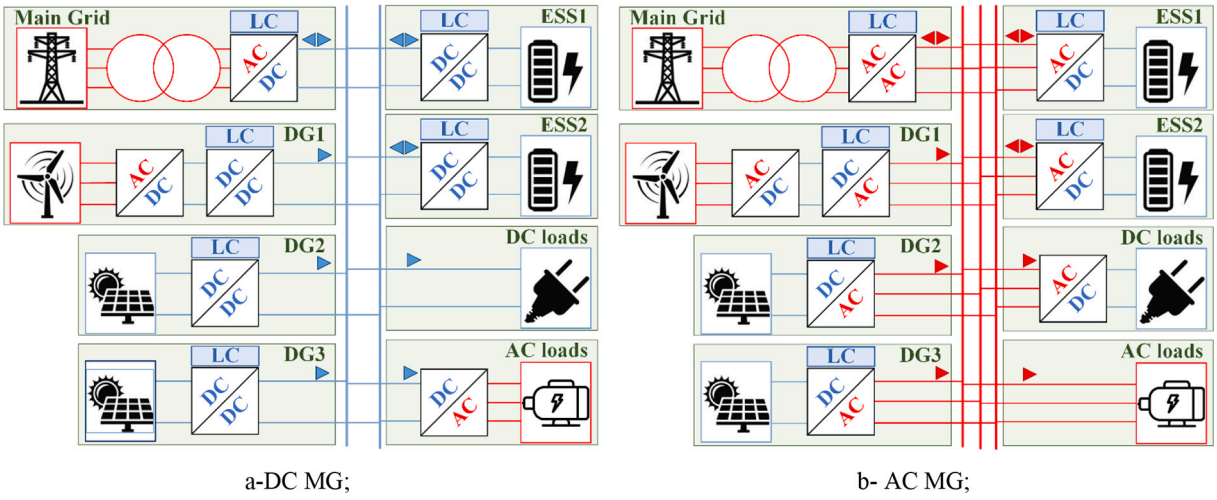


Fig. 2. Microgrid types according to the power type

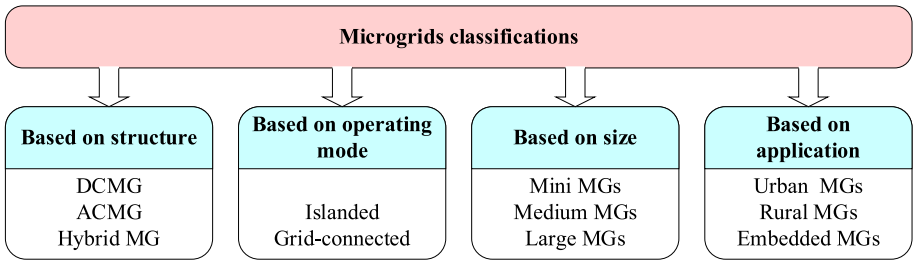


Fig. 3. Microgrid classifications

Table 2
AC vs. DC MG.

	DC MG	AC MG
Number of converters	Medium	High
Transmission efficiency	High: no loss associated with the reactive power	Low: the reactive power increases the transmission losses
Stability margin	High: easy	Low: complexed
Synchronization	Not required	Required
Power supply reliability	High reliability with smooth transient	A seamless transition is challenging to ensure after a grid fault
Control	Simple due to the absence of frequency, reactive power, or phase unbalance problems	Complex control process due to voltage and frequency regulation and the unbalanced compensation in three-phase systems.
Load compatibility	Low but promising for future loads	High due to domination of the AC loads
Protection system	Complex and costly	Simple and affordable
Devices compatibility	No	Yes
skin effect	Not existed	Yes

opposite direction of the current flow will hold power. Therefore, this configuration provides excellent robustness [66].

Multi-bus: This kind of configuration combines several single-bus MGs, as illustrated in Fig. 4(c). Each microgrid in a multi-bus DCMG system absorbs or provides electricity to or from its neighbors [67]. This structure makes it easier to isolate a DC MG in the event of a breakdown. Furthermore, the communication lines between DGs transmit control signals to enhance the performance and stability of the DC microgrid [68].

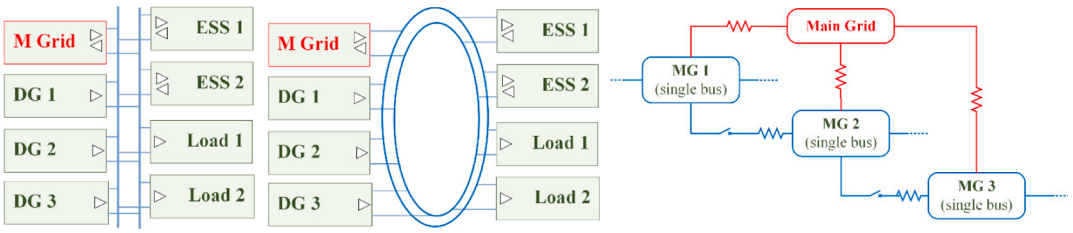
According to [22,69], the characteristics of each one are presented in Table 3.

7. DCMG Challenges

Many problems occur due to the various features and topologies of the DC microgrid, causing the system to fail to work consistently and, therefore, necessitating further development to meet these obstacles. As illustrated in Fig. 5, DCMG issues can be classified into four categories: protection, communication, power quality, and operational.

Protection issues: some issues are common in DCMGs and DCMGs, such as the restricted fault current contribution of inverter-based DG in islanded mode or the incapacity of single-setting overcurrent relays to protect dual-mode microgrids [70]. However, two additional problems regarding DCMG protection should be taken into account.

- **Grounding:** typically, two types of faults may occur on DCMGs that may damage the MG: pole-to-pole (PP) faults associated with the low impedance and pole-to-ground (PG) faults associated with the high impedance. These faults can be prevented by respecting the grounding norms [71,72]. In addition, the grounding has extra benefits, such as improving personnel safety by decreasing the touch voltage [73,74]. According to the international standard IEC60364–1 [75,76], three grounding types are expressed by two letters: TN, TT, and IT. The first letter describes the connection type, symbolized by T (direct connection) or I (no point is connected). The second letter represents the connection mode between the ground and the electrical device, and it has two symbols: T (local direct connection to ground) or N (the MG provides the grounding, either as a separate protected earth wire or in combination with the neutral conductor). Although detecting faults in a TN system is straightforward due to the low grounding resistance, personnel safety cannot be



a- Single bus configuration. b- Ring configuration. c- Multi-bus configuration

Fig. 4. Microgrid structures.

Table 3
DCMG Topology Characteristics.

Topology	Explanation	Advantages	Reliability	Application
Single bus	All the sources are connected to a single line	- High dynamic stability. - Improved ESS reliability. - Improved voltage regulation	+ +	Residential Commercial Transportation
Multi-bus	Multiple Single bus MGs connected in series and parallel	- High controllability of power flow. - A possible connection between LV and MV MGs. - UPS.	+	Commercial Auxiliary grid
Multi-terminal	A structure that provides the power flow in multiple directions	- UPS. - Reliable operation	+ +	Commercial Industrial
Ring	Closed-loop topology	Bidirectional load supplying	+ +	Industrial

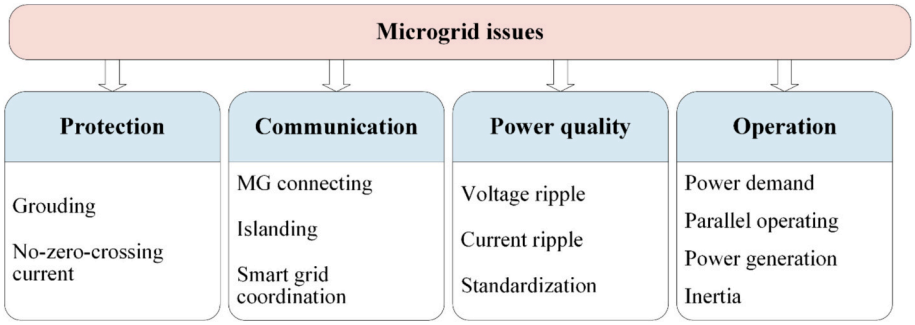


Fig. 5. DC Microgrid's main issues

assured as the touch voltage may exceed the permitted limit. On the other hand, IT systems are good candidates for maximizing human safety because of their low fault currents, but fault detection in such systems is difficult [77]. As a result, developing an optimal grounding model that satisfies human safety criteria and fault detection is difficult.

- **No zero-crossing current:** the functioning of circuit breakers (CBs) in both AC and DC networks is associated with arc phenomena. Because AC CBs rely on the natural interruption of AC currents, they can generally discern an arc within half a cycle after tripping. However, because DC currents have no natural zero-crossing point, interruption of currents is a significant issue that poses a substantial safety risk to personnel and causes contact corrosion that will reduce their lifespan [78,79]. Moreover, the fault current levels are commonly very high because of the low impedance of DC systems.

Communication issues: communication is a critical issue in achieving the reliability and efficiency of the system since it has a substantial impact on the MG design, including topology, operating mode, control, protection, and energy management systems. MG has adopted several communication methods, including wireless and optical fiber, to ensure stable and effective MG operations. In addition, the communication system delivers voltage and current information to manage the MG operating mode [80].

Power quality issues: due to the combination of nonlinear load and renewable DG output, power quality problems such as voltage fluctuations, harmonics, reactive power compensation, and frequency deviations will become more significant in MGs. DCMGs have low power quality issues compared to AC and hybrid types. The main power quality problems in DCMGs focus on reducing the voltage and current ripple. Ripple control may be achieved by increasing the capacitors in the DC bus [81]. However, operating DCMG in islanded and on-grid modes can lead to other power quality problems [82]. These problems include:

- **Voltage transient from AC grid:** According to [83], the transient over-voltage in these circumstances reaches 194% of the standard voltage and is balanced off at 111% of the standard voltage. This might be a very unsafe level for other devices using a similar DC bus.
- **Harmonics and Electromagnetic Interference compatibility:** The high operating frequency of many DC-DC converters might produce electromagnetic interference. Moreover, the converter's capacitor can produce multiple resonance frequencies and increase the impedance of the bus cable [84].
- **Inrush currents:** the power electronic converters are equipped with electromagnetic interference filters. However, the inrush current that passes through these filters will produce voltage fluctuations in the DC bus and ultimately affect the operation of other devices connected to the common DC bus [85].

Operational issues: power-sharing between various DGs under

different operating conditions is a significant issue regarding the performance of MG. The main objective of the MG is to supply the users with high-quality power, so the response to the power demand must be considered [86]. Moreover, integrating various DG types with different characteristics may lead to stability problems. Hence, controlling the parallel operation of the DGs is a crucial step [63]. The power generation of each DG has its characteristics and limitations that must be included, such as the dynamics, capacity, and nature of the DG [27]. As the permeability of power electronic devices with low inertia compared with power systems based on generative machines [87,88] increases, the conventional power system's rotating reserve capacity and rotational inertia will diminish. Furthermore, the microgrid exhibits inadequate anti-disturbance capabilities and stability when operating in islanding mode [89]. As a result, many researchers have developed design methods for virtual synchronous generators (VSGs) that let inverters using VSG control strategies mimic the working characteristics of synchronous generators. This makes it easier for microgrids and power systems to work together smoothly and improves the stability of microgrids [90].

Social issues: social acceptance is one of the most significant social problems [91–94]. It includes community acceptance, sociopolitical acceptance, and market acceptance. At the community level, social acceptability is significantly influenced by member behavior and active participation in initiatives. Other social issues can be faced during the evolution of DCMG, such as decision-making and investment challenges, especially for the local communities, due to a lack of resources and capacity and stakeholder contact, participation, and coordination issues [95,96].

8. Rated DC bus voltage classifications:

Another critical aspect to be tackled is the voltage levels for DCMGs. The compatible voltage ranges are necessary to adapt the i-AFE converter architecture to current DC load standards [97]. The IEC publication [98] summarizes the primary rated voltages utilized in direct current applications, as illustrated in Fig. 6.

In houses and offices, there are many DC loads. However, it is required to protect safety from electric shocks, making using extra-low DC voltage (ELDCV) levels appealing. Furthermore, several industrial systems use ELDCV to facilitate servicing and repair. Many crucial DC loads in telecommunications, for example, are powered by 12, 24, or 48 V. Large currents and long distances result in substantial power losses, which inherently restricts ELDCV buses in terms of power processing and distance. As a result, ELDCV buses should only be used across short distances and at modest power levels (>1 kW). Low DC voltage (LDCV) values between 350 and 450 V are often employed in data centers, racks, servers, and other industrial applications. The amount of electricity handled can be increased thanks to these LDCV levels [99,100]. The primary challenge for the high DC voltage levels (HDCV) (600–900 V and 1–1.5 kV) relates to safety and protection needs. These voltage ranges are not typical for residential-scale microgrids due to the potential risk of damage to end users [100].

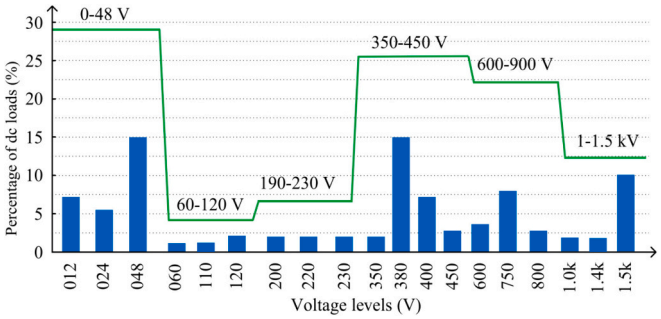


Fig. 6. DC bus voltage levels for existing applications [98].

9. DCMG Stability and Control Strategies:

Usually, each DC-DC converter is built to provide strong stability margins and reach certain performance levels while working independently. Nevertheless, the interaction between the many DC-DC converters in the network might impact the overall performance and possibly result in instability. In addition, unlike constant impedance and current loads, which typically do not affect stability, constant power loads (CPLs) might result in network instability owing to their negative impedance characteristics. DCMGs often have stability problems when they have CPLs, which happen when filters with low impedance do not match up with strictly regulated power converters [101]. Additionally, electronic loads and speed-regulated motor systems can produce destabilizing effects [102]. Therefore, ensuring network stability is essential to a DCMG. This can be achieved using feedback control mechanisms to regulate voltage and current at the converters' local control level [103].

Averaging and linearization are the most common methods for modeling and analyzing switching power converters in DCMGs. This method provides small-signal models valid for frequencies up to half of the switching frequency but provides accurate analysis around the quiescent operating point [104]. The impedance-based approach simplifies the dynamic analysis and design of DC MGs by defining straightforward stability criteria for every individual subsystem through convenient impedance specifications [105]. However, the stability results for impedance criteria rely heavily on selecting the point in the system, which is broken into load and source subsystems [106]. They provide only sufficient stability conditions and assume unidirectional power flow, making them inapplicable to systems where ESSes are used on the load side [107]. The system should be well-tuned before applying a filter, and a full-order state-space approach can be used as an alternative.

Designing a control strategy for the DCMG should include a list of controlling objectives, such as guaranteeing stability and reliability, enhancing global performance and efficiency, protecting the MG elements, and managing the power flow within the MG. This is achievable by implementing a proper control strategy. The literature review classifies control strategies into three categories [108]: centralized, decentralized, and distributed. An illustrative classification of various types is presented in Fig. 7.

9.1. *Centralized control strategies:*

To establish centralized control in DCMGs, a central controller (MGCC) system and a digital communication network link the CC with the power sources and loads, as shown in Fig. 8(a). The MG central controller (MGCC) receives data from the DG units and sends command signals back to each unit for centralized control strategies. For small-scale DCMGs can be directly controlled via master-slave control strategies [109,110]. In the case of larger-scale MGs, hierarchical control is favored on account of its autonomy and dependability [111,112]. Local converter control is utilized as a primary control level in hierarchical control. Secondary and tertiary control levels regulate DC voltage, control power flow, and grid-interactive control objectives such as unit commitment and global optimization, which are coordinated functions. The hierarchical control structure has been introduced as one of the most successful control strategies [111,113]. Its structure is based on primary, secondary, and tertiary levels [111,114]. The primary control is decentralized control, which mainly includes voltage loop and current regulation loops, DG MPPT control, and state of charge estimation for each storage unit. It has a fast dynamic response to real-time regulation [115,116]. Secondary control is associated with voltage correction and load-sharing performance improvement. It is concerned with controlling the DC bus voltage [117,118]. The tertiary control level can schedule the

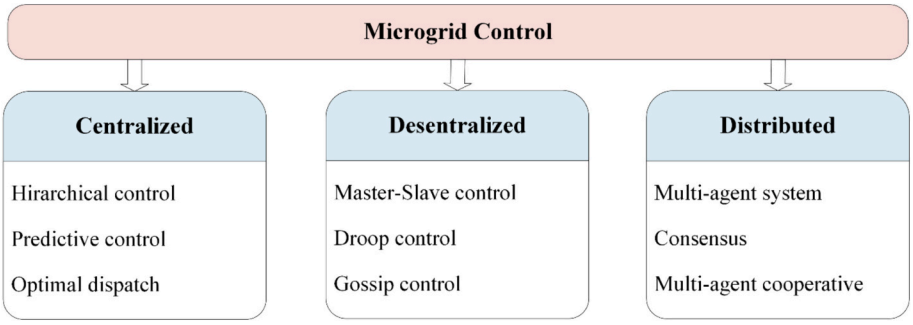


Fig. 7. DC Microgrid's main category control strategies

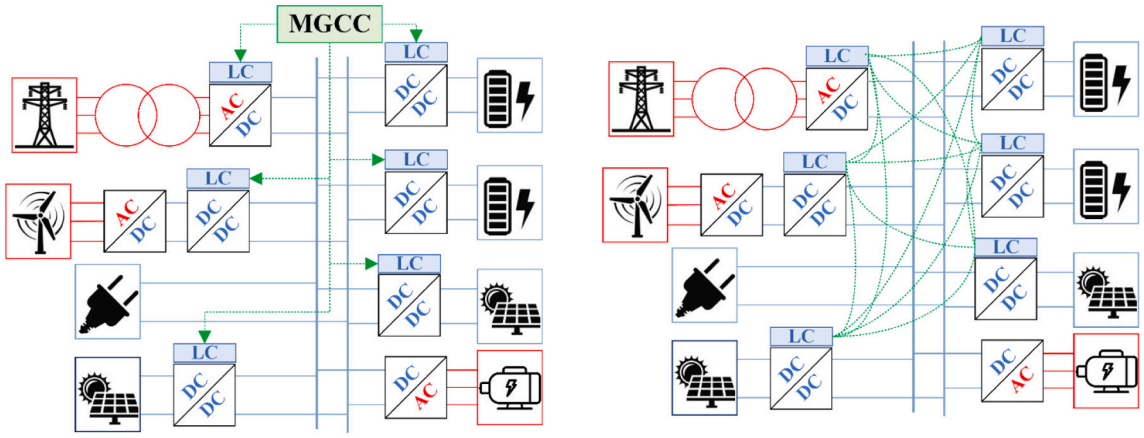


Fig. 8. Microgrid control strategies.

MG operating mode, the exchanged energy, the load prediction, and response, forecast the DG production, evaluate the power quality, and optimize the global performance. All of these tasks are provided by the energy management strategy implemented at the MGCC level [119]. However, this technique has several disadvantages regarding the decentralized topology, including single-point failure, less battery life, and weak scalability [103].

9.2. *Decentralized control strategies:*

Each DG unit generates its control signal in the case of decentralized control strategies. Droop control strategy, power line signaling (PLS), and distributed DC bus signaling (DBS) are the most common decentralized control strategies [120]. Lately, the decentralized management of microgrids has focused on using blockchain or other distributed ledgers to facilitate peer-to-peer exchanges among prosumers or energy assets [121–124]. In such approaches, the blockchain will store immutable energy transactions based on digitally signed energy-related data acquired by intelligent devices installed at the prosumers' sites. At the microgrid level, the blockchain network is established, and the prosumer, as a network peer, maintains the blockchain and receives notifications from peer nodes when new energy transactions are generated. Prosumers can trade energy among themselves to increase their profits or contribute to microgrid objectives, such as balancing demand and supply, reducing energy exchanges with the primary grid, and increasing local renewable energy usage. Smart contracts implement the control logic in these cases. Similarly, demand response programs can be implemented in microgrids using blockchain overlays. Intelligent contracts will monitor the demand response process for correctness, compliance, and control according to predefined rules. These can encode, execute, and enforce arbitrary agreements between entities, be they humans or machines, which provide a transparent, verifiable, and secure framework for, e.g., following the demand signal and trading energy flexibility. The droop control strategy is the most used strategy. However, determining the droop parameters is problematic because the current sharing, accuracy, and system stability depend on the droop parameters [125,126]. Moreover, with limited communication, full control cannot be possible. These control strategies offer several benefits, such as simplicity and autonomy from digital communication technology, but the absence of information from other units inherently constrains their performance. Furthermore, considering that the efficacy and dependability of these approaches are unfailingly contingent on the interpretation of the voltage in the common DC bus, the precision of voltage sensors is crucial.

9.3. *Distributed control strategies*

Distributed control is a control approach in which no central and local controllers (LCs) interact only with each other. Distributed control strategies may perform duties comparable to centralized methods using digital communication. Fig. 8(b) shows the distributed topology. They collect and analyze data using consensus-based algorithms or direct means, which improves dependability by eliminating any single point of failure [127,128]. The distributed control technique may effectively regulate voltage fluctuations while fulfilling tertiary-level goals like load sharing or economic dispatch [129]. Distributed control provides a level of information awareness that is similar to centralized control. This allows for achieving goals such as sharing output current, autonomous voltage restoring, power sharing, improving global efficiency, and balancing state of charge (SoC) [130,131]. One primary benefit of this technique is that it allows the system to retain complete functionality even if certain communication links fail, as long as the communication

network remains connected. Distributed control is, therefore, impervious to singular points of failure [120]. Nevertheless, its primary drawback is the intricacy of its analytical performance analysis, particularly in nonideal settings. Moreover, thorough mathematical analysis continues to be difficult, particularly under nonideal conditions such as communication delays, measurement noise, and inadequate electrical control systems. Therefore, this type is not achievable for large-scale MGs.

Table 4 compares centralized, decentralized, and distributed MG control strategies.

10. DCMG Management system

Each microgrid has a management system (MS) that includes monitoring, control systems, and electronic interfaces. In addition, it tacks on voltage level control, power balancing, load sharing, and shedding [86]. According to the implemented energy management strategy (EMS) in the control system, the MG operates in islanding (off-grid) mode without connection with the primary grid or in grid-connected (on-grid). In grid-connected operating mode, the MG exchanges power with the primary grid by absorbing or injecting it. The locally generated power will supply the loads if the MG operates in islanding mode. The management system architecture is illustrated in **Fig. 9**.

The MS tasks are presented in Fig. 10, including forecasting, analyzing, and optimizing tasks and real-time controlling tasks. These tasks are executed based on data optimization variables (DG generation), load power, storage, meteorological conditions, and electricity market prices [132,133].

According to [134], the specific functions of the MS can be listed in Table 5.

The energy management strategy (EMS) is a multi-objective strategy that responds to technological, financial, and environmental problems. The principal purposes are to improve system reliability, energy scheduling, and operation in both on-grid and islanded modes. Therefore, developing the energy management strategy (EMS) can enhance the operation of the MG. This topic is gaining more attention due to its enormous impact on the performance of the MG. The MGCC and the LCs control and coordinate the whole MG operation using a communication network known as information and communication technology (ICT) [135].

In the literature, the EMS can be classified into three major categories: rule-based, artificial intelligence, and optimization-based strategies [27,51]. There are two subcategories for rule-based strategies: deterministic and Boolean logic strategies. Furthermore, there are two subcategories for optimization-based strategies: online and offline. Finally, artificial intelligence can be classified into three subcategories: fuzzy logic, neural network, and machine learning strategies. These categories and subcategories are presented in Fig. 11.

Rule-based Strategies: These methods are defined mainly by the operating mode. They are simple to integrate with a real-time controller to control power flow in a hybrid power system. The rules are defined using designer intelligence or mathematical models and generally without previous information about the load profile [136]. Deterministic rule strategies, also known as static logic threshold techniques [137], formulate rules with specific goals such as grid independence, cost savings, and diminished emissions. Look-up tables [138], filter-based control (FBC) [139], wavelet transform [140,141], load follow control (LFC) strategy [142], and state machine control (SMC) strategy [143–145] are the most common deterministic rule strategies. Due to their minimal complexity, FBC, SMC, and wavelet-based EMS are the simplest techniques for allocating the power reference via frequency division. Nevertheless, it is unstable in the case of large input variations. Furthermore, it is incapable of responding to complex and changing operational circumstances. Linear programming (LP) [146] and mixed-integer linear programming (MILP) are two different approaches used to manage power flow on DCMGs [147–149]. Furthermore, designers have utilized rule-based strategies in numerous DCMGs. It is possible to benefit from integrating new communication systems like the internet of things (IoT) to design more advanced strategies. Authors in [150] provided a DMS based on MILP for an IoT-enabled grid. Nonetheless, the effectiveness of these strategies heavily depends on the designer's knowledge and engineering experience. Therefore, determining the power system's optimal operating point is complicated.

Artificial intelligence-based strategies: EMSs in this category are developed based on artificial intelligence (AI) approaches like fuzzy logic (FL), neural networks (NN), and machine learning (ML).

FL-based management strategies: Incorporating fuzzy logic (FL) into the EMS provides soft switching between rules, improved stability, and performance. FL is simple to build and offers a high level of resilience. One of the main advantages of FL is its ability to be modified and altered, which increases the degree of flexibility of EMS. Conventional FL [151,152], type 2 FL [153], predictive FL [154], and adaptive FL [155,156] are examples of FL-based EMSs. These strategies are insensitive to model errors and have robust techniques for dealing with system disruptions; nonetheless, they need an accurate design and faster microcontrollers.

NN-based management strategies: these methods include ANN [157], recursive neural network (RNN) [158], and ANFIS [159,160]. These methods can perform better; nevertheless, they require a database to train these systems.

ML-based management strategies: Reinforcement learning (RL) [161,162]. Multi-agent systems (MAS) [163–165] and deep learning approaches [166,167] are the most used strategies in this subcategory. Since there has not been enough study done in this relatively new sector, training the EMS based on a previously obtained database, which is not constantly obtainable, becomes a problem. This poses a problem due to insufficient research in this relatively new sector. Furthermore, there is no guarantee that it will function with data other than that used for the training process.

Optimization-based strategies: they aim to minimize/maximize the objective function. The objective function might include emissions, costs, energy savings, device deterioration, and global efficiency [168].

Offline optimization: Dynamic Programming (DP) [169–171], Nonlinear Programming (NLD) [172,173], Stochastic Dynamic Control Strategy (SDP) [174], and Genetic Algorithm (GA) [175,176] are the most widely utilized to manage the power flow in the DCMG. The authors in [177] developed an Improved Butterfly Optimization algorithm for managing the scheduling of household appliances and battery charging and discharging. The algorithm aims to minimize energy costs, reduce carbon emissions, and optimize peak-to-average energy usage. Similar work has been reported in [178] to discover the optimal scheduling of home appliances using an optimized EMS based on the Bald Eagle Search algorithm. In [179], a multi-objective optimization algorithm using the Improved Cockroach Swarm Algorithm has been used to reduce operating costs, maximize user comfort, and handle peak-to-average ratio. All load profiles must exist. Hence, a large amount of data is involved. This makes their implementation extremely difficult.

Online optimization: in these strategies, the objective function

Table 4
Comparison of MG control strategies.

Metric	Centralized	Decentralized	Distributed
Number of users	Single	Multiple	Multiple
Flexibility	+	+++	+
Optimization	+++	+	++
Evolution	+	+++	++
Communication	+++	+	+++
Installation cost	+++	+	++
System failure	++	−	−
Data acquisition	From all elements	Local data	Local and neighboring data

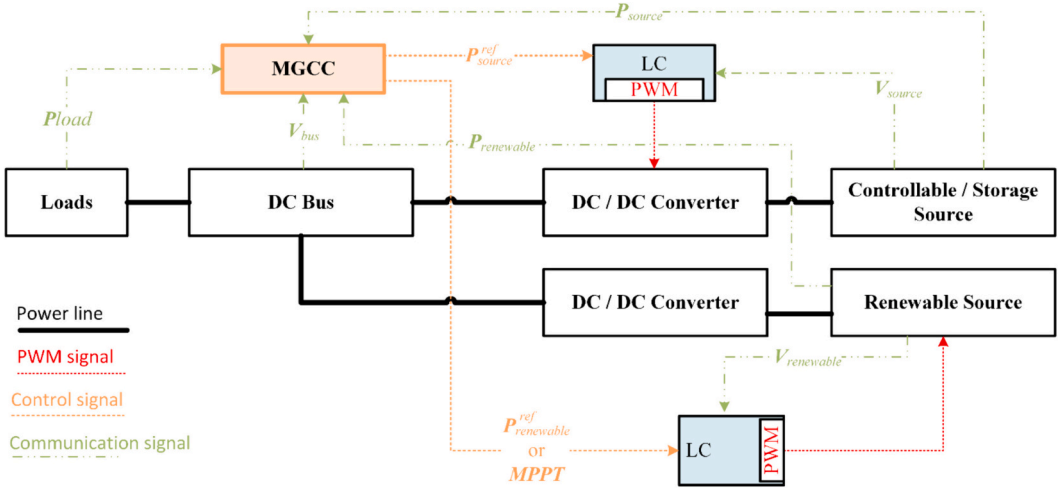


Fig. 9. management system structure for DC Microgrid.

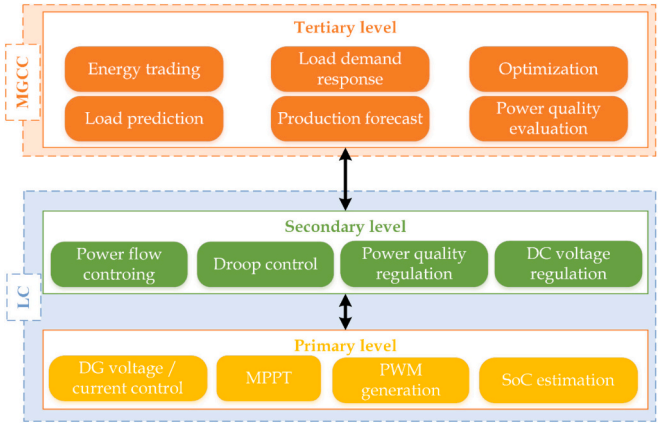


Fig. 10. Microgrid tasks with a time scale.

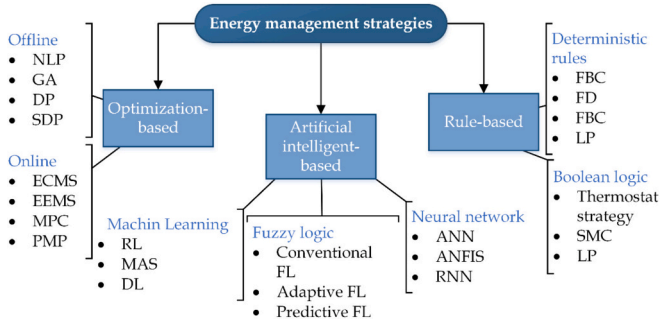


Fig. 11. Energy management strategies

Table 5
DCMG functions.

Reliability	Efficiency	Sustainability	Security
- Alarming - Voltage regulation - Reserve management - Grid mode transition - Load Shaving - Black start recovery - Power quality evaluation	- Optimal economic dispatch - Simple or autonomous operation - Demand management - Energy trading - Ancillary services - Protect the energy storage systems	- Emission reducing - Renewable (wind speed and solar radiation) forecasting - Maximum power production from renewables	- Enhancement of the security architecture - Cyber vulnerability evaluation - Access restriction - Lifecycle extension - Information security governance

depends only on the actual states of the system [180]. They have more restricted processing and higher real-time performance. The storage devices' SoC is considered, but global optimization is not possible [50]. The equivalent consumption minimization strategy (ECMS) [181,182], model predictive control (MPC) [183,184], Pontryagin's minimal principle (PMP) [185], and the external energy maximization strategy (EEMS) [181,186] are examples of these techniques.

Table 6 presents the main advantages and shortcomings of each category.

Based on [187–189], several published works in DCMG energy management strategies are presented in Table 7.

11. Perspectives and future works:

Compared to ACMGs, DCMGs offer several technical advantages, including better harmonic mitigation, easier integration of renewable energy sources, no frequency or reactive power management difficulties, and direct connection to DC loads. Nevertheless, DC microgrids also face particular technical challenges that need to be addressed by researchers, system engineers, and developers in both control and management strategies. The most challenging problems in the coming years can be listed as follows:

- Accurate system modeling: increasing the accuracy of the DCMG model will provide better opportunities to evaluate its behavior and improve its performance. However, the model's accuracy may be decreased because of several factors, such as parametric variation, element degradation, and unexpected operation conditions. In this context, the Digital Twins is a promising research field for building replicas of microgrids and energy assets that can play a valuable role in improving the accuracy and effectiveness of DCMG modeling by integrating data-driven models and physics-informed ones.
- Advanced control strategies: several strategies may be developed or incorporated to provide simultaneous power-sharing and efficient DC bus voltage management.
- The high penetration of renewables into DCMGs diminishes their total inertia, which reduces their voltage controllability. Although certain solutions have been proposed to deal with such a

Table 6
The main advantages and weaknesses of each category.

Category		Advantages	Shortcomings
Rule-based strategies		- They're resilient, easy to design, and simple to implement. - They are extensively used for managing the power flow in hybrid power systems (HPS) such as MGs-based EVs.	- Due to the dependency on human experience and the consequences, they cannot be robust or flexible under complicated operating situations. - Determining the optimal control point is challenging.
Artificial intelligence-based strategies		- It has superior robustness and high efficiency in real-time. - It can solve complex and nonlinear problems. - It can provide reasonable power-sharing.	- Complex implementation. - Weak dynamic characteristics due to the firmness of the control rule.
Optimization-based strategies	Offline	- Very excellent performance. - They can be utilized to compare and evaluate the performance of other strategies.	- Knowing the load profile, complicated processing, and vast amounts of data is necessary.
	Online	- It has superior real-time performance, and each point of operating work is optimum. - Extended power source lifespan.	- It requires a high-processing controller and huge storage devices.

Table 7
The main advantages and shortcomings of each category.

MG composition	EMS	Objectives	Ref
Standalone PV/WT/FC/ Battery	Linear Programming	- Power balance - PEMFC protection	[190]
Grid-connected PV/wind/ battery	Linear Programming	- Power balance - Power quality	[191]
Standalone PV/WT/FC/ Battery	FL-based DE algorithm	- Power balance - Cost reduction	[192]
Standalone PV/WT/FC/ Bioethanol reformer	SMC	- Power balance - Bio storage	[193]
Standalone PV/FC/Battery	MPC	- Power balance - Renewable optimization	[194]
Standalone PV/WT/micro hydropower/ Diesel/ Battery	MAS	- Power balance - Demand side control	[195]
Standalone PV/WT/FC/ Battery	ANN	- Power balance - Renewable forecasting	[196]
Standalone PV/WT/Battery	FL	- Battery management	[197]
Grid-connected PV/FC/ Battery	Bald eagle search algorithm (BES)	- Power balance - Cost reduction - Power quality	[37]
Standalone PV/FC/ Supercapacitor	Differential Flatness-Based Control	- Power balance - Power quality	[198]
Grid-connected PV/Battery	MILP	- Cost reduction	[199]
PV/Micro-Turbine/FC/ Battery	PSO	- Power balance - Cost reduction	[200]
Battery/Supercapacitor	LQR with SSA	- Power balance - Power quality	[51]
WT/PV/MT/FC/Battery	Firefly algorithm (FA)	- Cost reduction	[201]

circumstance, more research should be done in this area, considering that the DCMG is becoming a 100% converter-based system. Virtual synchrony generators (VSGs) may receive more attention for this problem.

- Several nonlinear loads, such as constant power loads (CPL), indicator motors, and EVs, may reduce the stability margin. Therefore, power system instability is highly possible. Consequently, it is crucial to investigate the effect of these loads deeply and incorporate them into control strategies.
- Integrating DCMGs with the energy markets by providing coordination mechanisms to trade and exchange energy over local energy markets aims to construct win-win business and financial models for all the stakeholders involved in the value chain and incentivize efficient energy utilization and microgrid stability.
- Integrating DC microgrids with grid-interactive buildings enables effective coordination between building energy management systems and the microgrid, exploiting their flexibility for improving interoperability and creating synergies among DC microgrids, multi-carrier energy networks, buildings, and non-energy sectors.
- Researchers are expected to extend studies on large-scale MGs' communication systems to build robust, secure, and efficient communication environments. These environments are crucial for the efficient and coordinated operation of the microgrids, as they provide data on various operational parameters, performance, and grid conditions.
- The decentralized energy management of a multi-energy grid and energy communities: consumer engagement frameworks are needed to unlock the necessary socio-economic potential for microgrid management, ensuring that consumers and local communities play an active role in grid management via demand response, peer-to-peer energy trading and fair allocation of incurred costs and benefits.
- More research is required for ESS lifespan extension while controlling the power balance and regulating DC bus voltage.
- Establish new standards such as voltage standardization, protection, safety, and power quality for all aspects of DCMGs. These new standards may improve the readiness level of this technology for practical implementation.
- Social problems related to the consumer's opinion on the EMS's decisions. The EMS can cut off the loads in some cases. These loads, considering the EMS, are optional. However, they are not for some consumers. More social studies are required to adapt EMS's decisions to consumers' preferences.
- The contractual commitments between market participants should be made more explicit through improved regulatory and policy obstacles.

Based on these perspectives, our future works can focus on the following points:

- Design sophisticated optimization techniques for DCMGs to improve energy management, optimize efficiency, and reduce costs. These algorithms should consider elements such as integrating renewable energy, exploiting energy storage, controlling the demand side, and the grid's stability.
- Explore novel energy storage technology, including batteries, supercapacitors, and flywheels, for DC microgrid systems in terms of size, location, and management techniques.
- Explore new converter designs, control algorithms, and protective systems to enhance the stability and dependability of the power grid.
- Real-world experiments of DCMG energy management strategies under various environmental conditions with the assistance of real-world emulators such as RT-Lab.

CRediT authorship contribution statement

Seydali Ferahtia: Writing – original draft, Methodology, Investigation, Conceptualization. **Azeddine Houari:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization. **Tudor Cioara:** Writing – review & editing, Validation, Investigation. **Mohammed Bouznit:** Writing – review & editing, Validation, Methodology. **Hegazy Rezk:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis, Data curation, Conceptualization. **Ali Djerioui:** Writing – review & editing, Visualization, Validation, Supervision, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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