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Review

Review on the Microgrid Concept, Structures, Components, Communication Systems, and Control Methods

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Abstract: This paper provides a comprehensive overview of the microgrid (MG) concept, including its definitions, challenges, advantages, components, structures, communication systems, and control methods, focusing on low-bandwidth (LB), wireless (WL), and wired control approaches. Generally, an MG is a small-scale power grid comprising local/common loads, energy storage devices, and distributed energy resources (DERs), operating in both islanded and grid-tied modes. MGs are instrumental to current and future electricity network development, such as a smart grid, as they can offer numerous benefits, such as enhanced network stability and reliability, increased efficiency, an increased integration of clean and renewable energies into the system, enhanced power quality, and so forth, to the increasingly growing and complicated power systems. By considering several objectives in both islanded and grid-tied modes, the development of efficient control systems for different kinds of MGs has been investigated in recent years. Among these control methods, LB communication (LBcom)-based control methods have attracted much attention due to their low expenses, recent developments, and high stability. This paper aims to shed some light on different aspects, a literature review, and research gaps of MGs, especially in the field of their control layers, concentrating on LBcom-based control methods.

Keywords: microgrid; microgrid control; centralized; distributed; hierarchical; wireless communication; low-bandwidth communication; wired communication; communication network

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1. Introduction

Today, due to the increasing power demand, the need for power dependability, reliability and stability requirements, increasing interest in RESs, fossil fuel depletion, and environmental problems, conventional power systems are increasingly becoming complicated and are facing new, serious challenges [1,2]. Several solutions have been introduced to overcome these problems. The most well-known and influential resolutions are DERs, MG, ADM, and ESSs [3–6].

Hereafter, the discussion will be concentrated on MGs, as they are one of the most important solutions for solving existing and upcoming problems in current and future power networks. According to [1,3,7], an MG is a hybrid electric network comprising DERs, local loads, and ESSs for supplying power to specific areas or remote locations, with a primary function of ensuring the system's stability on the occurrence of different network faults. Generally, one of the primary reasons for introducing the MG concept is increasing the RES integration into power grids [8]. Considering the intermittent/variable nature of most RESs, such as PV parks and wind farms, these resources are mostly employed in power grids to provide the required power generation. Their generation can be instantaneously used or stored through ESSs, leading to an overall enhancement in MG performance. In total, to realize a smart grid, the integration of MGs into a power system is regarded as one of the essential technologies providing advantages such as enhanced stability, increased efficiency, higher RES integration, a continuous supply of loads in islanded mode, and so forth, compared to conventional distribution systems. To take advantage of MGs, their integration into the power grid should be performed based on proper and robust engineering to avoid possible adverse effects on the power grid, such as power quality, control, reliability, and problems [1]. For solving the problems of MGs and their integration into the grid, numerous papers have been published to date; most of them are concentrated on developing efficient control methods. Majorly, MGs are controlled based on the hierarchical control strategy, including three control layers named primary, secondary, and tertiary control levels, which can be realized in decentralized, centralized, and distributed control structures. Compared to a low cost with a high redundancy decentralized control structure, the others need communication systems, making them costly and more complicated, with the capability of providing sub-optimal/optimal solutions for MGs. Hence, to use communication-based methods, many investigations have been performed regarding using LB WL and wired communication technologies in MG control systems, which are cheaper and simpler to use with lower power consumption than HB ones. It should be noted that the limited data transfer rate, vulnerability to communication delays and noises, and short coverage of LB technologies are the most critical challenges in using them in MG control methods.

Several review papers have been published about MGs and their control methods. In [9], a thorough overview is presented, concentrating on control methods introduced for different MGs' hierarchical control levels. In [1], different challenges and issues related to MGs are reviewed. It discusses various topics related to MGs, such as their technical and economic issues, diverse controllers designed for controlling power flow in MGs, their limitations and protection issues, and their future prospects and market integration. In [8], the main advantages and challenges of an AC MG are explained. As an effective solution for AC MGs, the hierarchical control architecture is introduced, and its control levels are discussed in detail [8]. In [10], along with conventional droop control methods, various modified droop controllers are listed and explained briefly. In [11], different primary control techniques used for regulating the voltage and frequency of inverter-based MGs are categorized, reviewed, and also compared with each other in terms of their potential merits and drawbacks. In [12], a comprehensive survey is presented about MGs' different control methods, classified into four main groups: centralized, distributed, hierarchical, and decentralized strategies. It reviews their applicability, operational principles, and performances. It also discusses future trends, research gaps, technical challenges for real-world applications along with their possible solutions, and different integrated technologies for MGs leading to SG. In [13], a solid and informative overview is carried out regarding different structures and control methods of MGs at various hierarchical levels. Initially, by concentrating on grid-supporting, grid-forming, and grid-feeding configurations of power converters, their major operating modes and control methods are analyzed and discussed. Then, the hierarchical control scheme is reviewed. In [14], a survey of control strategies used for achieving the coordinated integration of PEL-interfaced distributed generator (DG) units in islanded MGs is presented, which also includes detailed figures of the strategies. As an effort toward the standardization of AC and DC MGs, Guerrero, J.M. et al. presented a hierarchical control method obtained from electrical dispatching and ISA-95 standards to make MG smart and flexible [15]. In [16], diverse control methods are compared and summarized for reactive and active power sharing in islanded hierarchical controlled MGs. Moreover, it discusses the future research trends on islanded MGs. In [17], a compact discussion is presented for different control techniques and the modeling of MGs. Table 1 summarizes the mentioned review papers along with their main focus. As can be seen, these papers reviewed MG control methods comprehensively; however, none of them focus on wired and WL LBcom-based control methods.

Table 1. Different review papers on the microgrid control topic.

Ref.	**Main Focus**
[18]	Recent developments in the control and optimization of MGs
[19]	A brief study on MGs in terms of the two topics of feasibility and economic studies and control and optimization
[9]	Control methods for different MGs' hierarchical control levels
[1]	Different challenges and issues related to MGs
[10]	Conventional droop control methods and various modified droop controllers
[8]	Hierarchical control architecture and its control levels
[11]	Different primary control techniques used for regulating the voltage and frequency of inverter-based MGs
[12]	Applicability, operational principles, and performances of centralized, distributed, hierarchical, and decentralized strategies
[16]	Diverse control methods for reactive and active power sharing in islanded hierarchical controlled MGs
[14]	Control strategies for the coordinated integration of PEL-interfaced DGs in islanded MGs
[13]	Different structures and control methods of MGs at various hierarchical levels besides grid-supporting, grid-forming, and grid-feeding configurations of power converters in MGs
[15]	Standardization of AC and DC MGs, including a hierarchical control method to make MG smart and flexible
[17]	Different control techniques and modeling of MGs

Besides introducing the MG concept and its related topics, this paper presents a comprehensive review of MG control methods, with a focus on wired and WL LBcom control methods due to their advantages and importance. In Section 2, a thorough introduction is presented about the concept, components, configurations, challenges, advantages, and significant control structures of MGs. Then, Section 3 presents a compact discussion on communication requirements, standards, and challenges in SGs/MGs. In Section 4, wired and WL LBcom technologies are discussed, along with their characteristics. In Section 5, a thorough literature review is given for wired and WL LBcom-based control methods. Finally, Section 6 presents the conclusion, including future trends and suggestions.

2. Microgrid

In this section, a comprehensive introduction to the MG concept and its structures, control system, challenges, and components is given.

It is worth noting that the criteria used for selecting the research papers reviewed in this article are as follows. First, it was attempted to select papers published in high-quality scientific journals and conferences indexed in prestigious databases such as IEEE, IET, Elsevier, Springer, WILEY, and so on. Second, only the papers with new and/or significant contributions and analyses were selected to provide a compact but well-designed summary. As the third criterion, this paper tries to give a good picture of the published works in the area of LBcom-based control methods after presenting a general overview of MGs.

2.1. MG Definitions

Several definitions have been presented for an MG, of which the most important ones are listed in Table 2. By considering the fact that an MG includes cyber (communication), control, and physical layers, it is obviously seen that all these definitions only considered the physical layer of an MG.

Table 2. Different definitions presented for an MG.

Reference	Definition
[1,3,7]	An MG is basically a typical hybrid electric network comprising DERs, local loads, and ESSs for supplying power to specific areas or remote localities. The main function is to ensure the system's stability under different network faults [1].
IEEE standard 2030.7 [9,20] and the U.S. Department of Energy [1,21]	An MG is a group of interconnected loads and DERs within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. An MG can connect to and disconnect from the grid to enable it to operate in both grid-connected and islanded modes.
[8]	An MG can be considered a small-scale power grid that consists of DERs, loads, and controllers. One of the major advantages of an MG is that it can operate in grid-connected or islanded modes that can generate, distribute, and regulate the power flow to local consumers.
CIGRE [9,22]	Sections of electricity distribution systems containing loads and DERs (such as DGs, storage devices, or controllable loads) that can be operated in a controlled, coordinated way, either while connected to the main power network and/or while islanded

2.2. Different MG Structures

Based on the type of their current and the way of the connection of their buses, MGs can be categorized in several ways. However, according to their current type (direct and alternative), MGs are classified into three major groups: ACMG, DCMG, and HMG [23], which are respectively shown in Figures 1–3. In Table 3, the main characteristics of each type of MG are briefly listed.

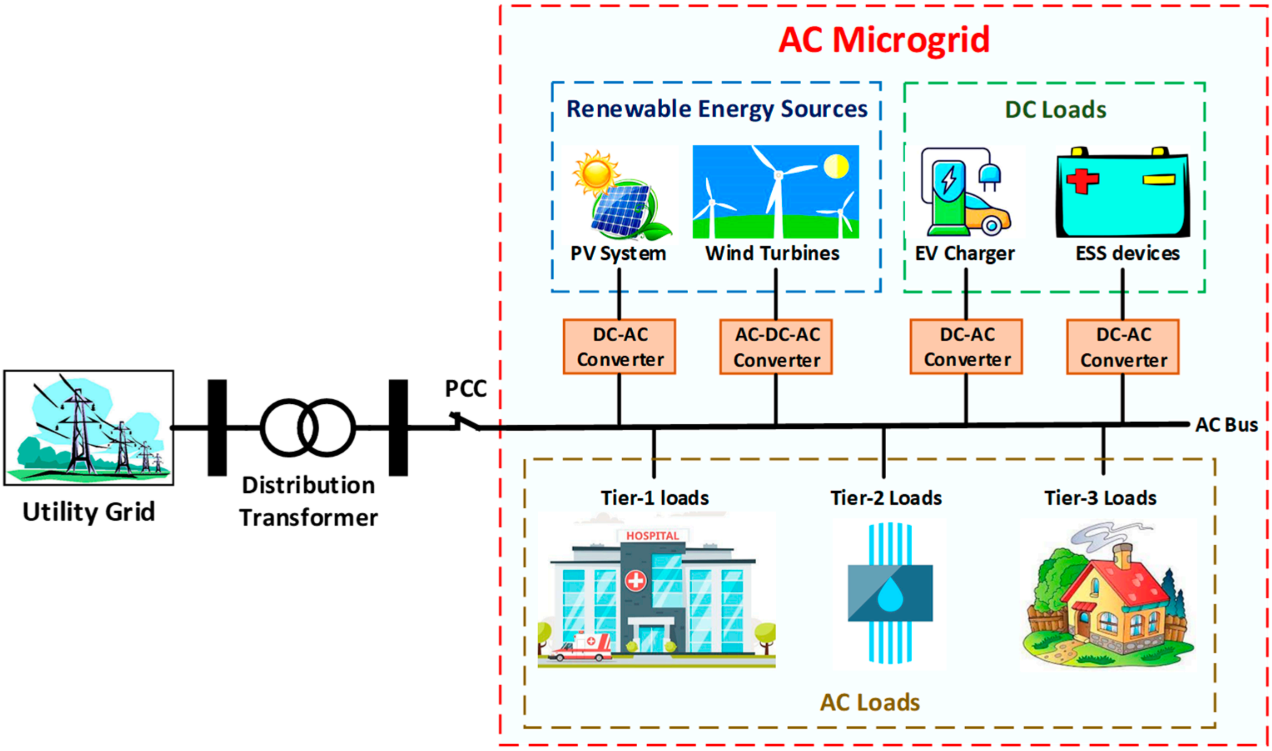


Figure 1. Simple diagram of a typical ACMG.

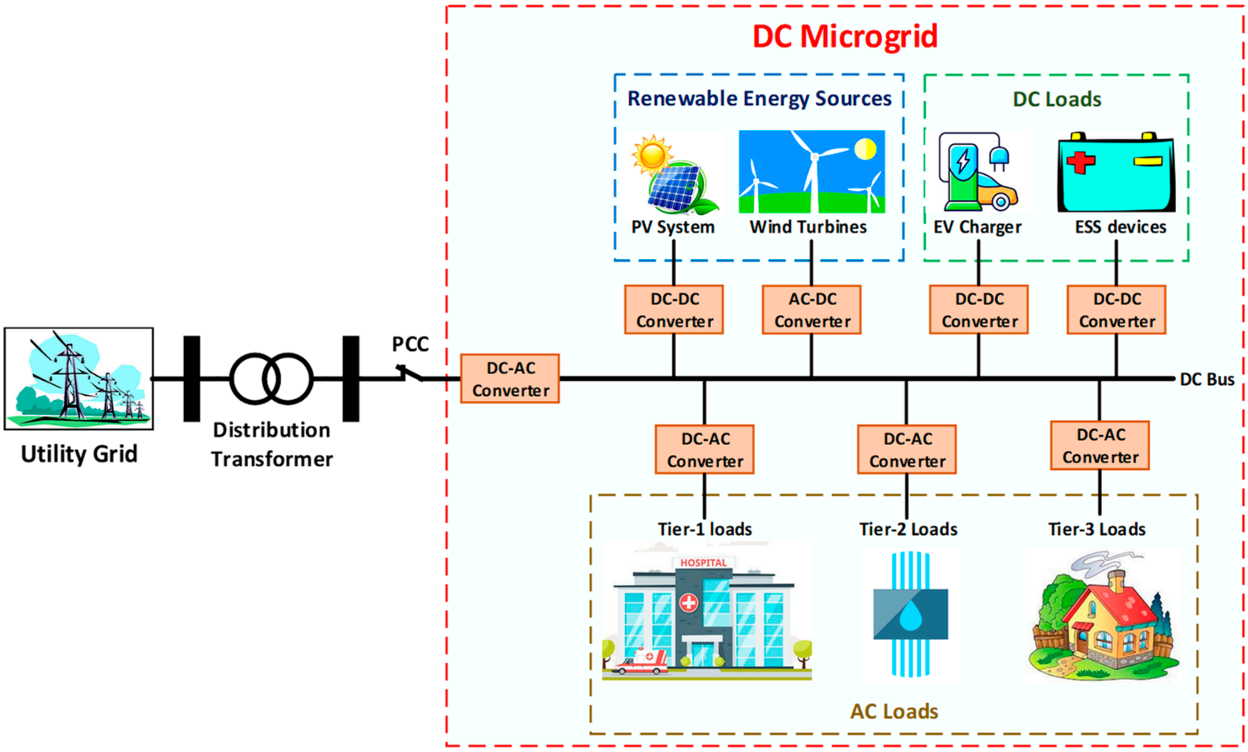


Figure 2. Simple diagram of a typical DCMG.

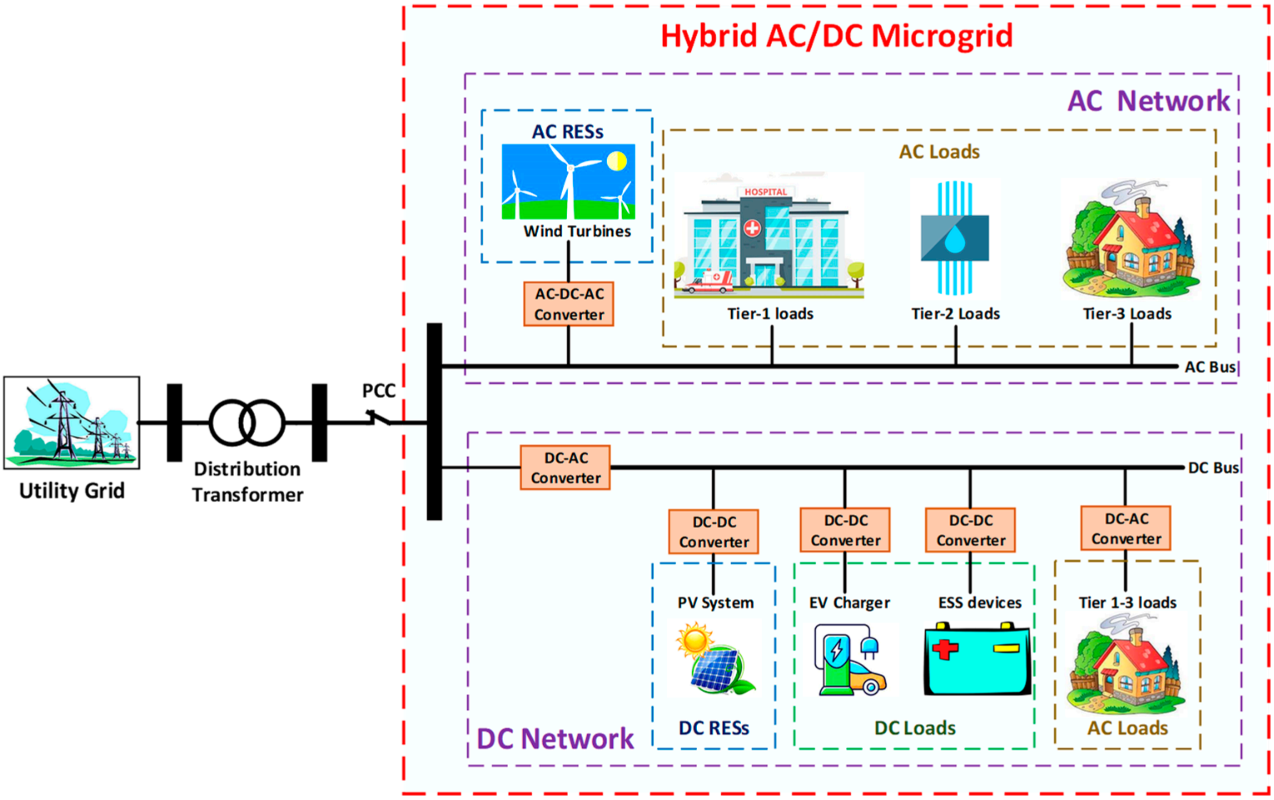
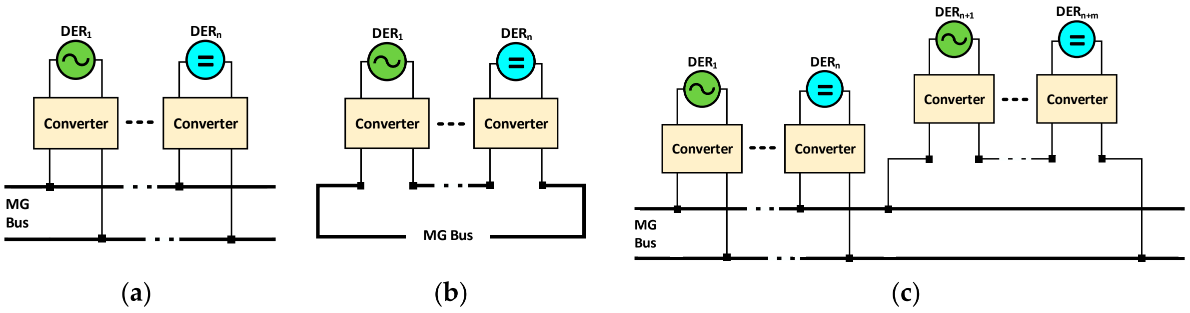


Figure 3. Simple diagram of a typical HMG.

Table 3. Main characteristics of different types of MGs.

Type	Features
ACMGs	• Usually, a common AC bus exists, connecting its different components. • They can be easily integrated into conventional AC power systems, providing more controllability and flexibility for them compared to other kinds of MGs. • DC/AC converters must be used as an interface between DC components and the AC common bus, decreasing the total efficiency dramatically [24–26].
DCMGs	• Generally, a common DC bus exists, connecting its different components. • They are connected to the main grid through a DC/AC power converter. • In terms of operation principles, DC and AC MGs are similar. • Compared to ACMGs, DCMGs provide reduced power conversion losses since fewer power conversion stages are needed, resulting in a higher efficiency, lower cost, and smaller size. • They provide better stability than AC ones since no reactive power exists in DCMGs [24,27–29]. • They are better options for DER integration [24,27–29]. • Their most popular structures are the bipolar, monopolar, and homopolar structures [25,30].
HMGs	• They are obtained by combining both ACMGs and DCMGs in the same distribution system. • Both AC and DC components can be directly integrated into them. • They benefit from all the advantages of ACMGs and DCMGs, such as the least number of interface devices, facilitated DR integration, fewer conversion stages, decreased power losses, lower overall costs, and higher reliability. • In HMGs, AC and DC components can be respectively connected to AC and DC parts. Hence, no synchronization is required for generation and storage units [31–33].

In terms of the DERs' connection way, MGs can be categorized into three main types: parallel, cascaded (series), and hybrid cascaded–parallel MGs [34–37]. These MG structures are respectively shown in Figure 4a–c [38]. The hybrid cascaded-parallel MG is among the most recent structures that can support high-power operation and be employed for integrating LV sources such as cascaded solar panels and battery cells [38]. Besides the aforementioned classifications, it is noteworthy that MGs also can be classified into LV, MV, and HV systems in terms of their voltage level.



(**a**) (**b**) (**c**)

Figure 4. Simple diagrams of different MG structures in terms of DERs connection types: (**a**) Parallel structure; (**b**) Cascaded structure; (**c**) Hybrid parallel–cascaded structure.

2.3. Different Components of an MG

MGs are composed of different components such as loads, DGs/DERs, ESSs, PEL-based interfaces (converters), and so forth. In Table 4, the different components of an MG are briefly explained.

Table 4. Main characteristics of different components of an MG.

Type	Characteristics and Features
Loads	• In terms of different factors, loads can be classified as follows: ➢ Power: AC and DC loads. ➢ Linearity: linear and non-linear loads. ➢ Location: local and common loads. ➢ Operating conditions and load management schemes: Tier-1, Tier-2, or Tier-3 loads [39]. ❖ Tier-1: The most critical loads such as hospitals that should never be shed at all. ❖ Tier-2: Such as hot water heating and pool filters which can be shed in the short term to decrease load peaks. ❖ Tier-3: Such as commercial facilities with backup generators and residential customers that can only be shed in emergencies to protect MG stability and to prevent a blackout.
ESSs	• ESSs are used for backing up the power supply by storing different DERs' extra generation. • They are used for improving MGs' total stability and performance. • ESSs enable DERs to operate at a fixed output while providing load-fluctuations-based demand [40].
DERs/DGs	• In terms of dispatchability, DERs are classified as dispatchable and non-dispatchable ones. Unlike dispatchable units, non-dispatchable DERs cannot be fully controlled since they generally are intermittent resources like RESs whose outputs are based on weather conditions and are difficult to control [41]. • In terms of generated power, DERs can be classified into AC sources, such as wind turbines, and DC sources, such as PV systems.
Power Converters	• In MGs, rather than installing power conditioning devices for transferring the energy between DC and AC networks, PEL-based interfaces' employment is preferred [42]. • In Section 2.5, a brief discussion about power converters is presented.

2.4. Advantages and Challenges of MGs

Over conventional distribution systems, MGs provide several advantages which are summarized in Table 5 [1,8].

Table 5. Main advantages of MGs over conventional distribution systems.

Advantage	Explanation
Enhanced stability	• Due to MGs' unique characteristics, main grid stability can be increased by integrating MGs into the system.
Increased efficiency	• Decreased power losses of transmission and distribution lines result in increased efficiency.
Higher RESs integration	• MGs facilitate the integration of low-carbon technologies such as RESs into the power system, resulting in decreasing global warming and pollution.
Continuous supply to loads in islanded mode	• Unlike conventional distribution systems, MGs can provide a continuous and independent supply of all micro sources (MSs) to loads during their autonomous/islanded mode.
Supporting the main grid	• MGs can support the local power grid and facilitate the generation increase, leading to improving the system's reliability and power quality.
Plug-and-play capability	• MGs can switch either to grid-tied or islanded modes.
Back-up supply source	• Under the main grid's power supply failure, MGs can play the role of a backup supply source.

Table 5. *Cont.*

Advantage	**Explanation**
Maintaining the energy supply and V-f stability of loads in failures	• In the case of any fault in the main grid, MGs can maintain the energy supply and stability of the voltage and frequency for all local loads by operating in the islanded mode [8].
Bidirectional power flow path	• By integrating MGs into a distribution feeder, the concept of unidirectional power flow (from the substation to the load designed for conventional distribution systems) can be changed to a bidirectional structure.

Despite the advantages, careful and precise engineering is required to integrate MGs into the power systems since MGs consist of diverse components such as DERs (FC, PV systems, gas turbines, micro turbines, and wind power). Without such engineering design, MGs' penetration may have adverse effects on the whole system in terms of several operational aspects, such as power quality, control, operational safety, restoration time, reliability, protection, etc. [1]. For an MG, the most critical technical and economic issues are listed in Table 6 [1]. Generally, in islanded mode, the most significant challenges can be named as ensuring the system stability and reliability and meeting the customer power demand without any interruption [8].

Table 6. Main technical and economic issues and challenges of MGs.

Issue/Challenge	**Explanation**
Power Imbalance	• By changing the MG's mode from grid-tied to islanded mode, due to the slow dynamic response and low inertia of MSs, power imbalances happen. ➢ FACTS [43–45] and ESSs can be considered as applicable solutions for solving this problem. ➢ For islanding an MG, PEL-based devices with a high acceleration and accurate sensing ability must be employed. ➢ An islanded MG should be re-connected to the grid only by considering synchronization issues [12]. • Load changes and DG failures can also cause power imbalances in MGs.
Harmonics	• In a power system, harmonics can have diverse impacts on system reliability and stability. • In MGs, several PEL devices are employed, which are the main harmonic sources in power systems. • These harmonics can cause many problems, such as threatening ESSs' safety [46]. • Active and passive power filtering techniques are used to mitigate harmonics in power systems [47].
Stability and power quality	• For the stability and power quality issues of a power system, including MGs and DERs, three main reasons can be named [48]: (a) Lower network inertia causing decreased angular stability leading to frequency and voltage instabilities. (b) Low-frequency power oscillations caused by changing the power-sharing ratio between DERs. (c) Reduced voltage stability caused by decreased energy distribution support. • The feasible solutions for these problems are enhancing the quality of supply decentralization, having an accurate ratio between demand and supply, and reducing the generation and transmission outages and downtimes [49].
ESS	• Despite the ability of DERs, such as RESs, to provide clean and free/low-cost energy, it is still challenging to manage their produced energy without any interruption/curtailment [50]. • ESSs are widely used as an effective approach to solving these problems. • By using ESSs, many advantages can be achieved, such as decreased fluctuations, a higher power factor for the whole system, regulated frequency and voltage, and overcoming RESs' intermittent nature.

Table 6. *Cont.*

Issue/Challenge	Explanation
Topological changes	• Besides intermittent RESs, the continuous connection and disconnection of MSs, loads, and ESSs can cause topological changes in MGs [51]. • MGs can be installed in diverse locations such as houses, farms, buildings, etc. • Based on requirements, various kinds of MGs can be designed and established to meet consumer and/or system demands.
Environmental issues	• Due to problems such as global warming, increased carbon emissions, increased high-quality power demand, and the depletion of fossil fuels, countries are obliged to increase the share of environment-friendly DERs, such as RESs, in their networks. • Several studies have been performed on different MSs to compare their harmful emissions [1].
Economic aspects	• In an MG, essential variables for governing are the reactive and active powers of DERs and the current/voltage of the interface bus of CSI/VSI [52]. • By controlling these variables properly, optimal operation, power distribution, RESs integration, and economical operation are achieved in MGs. • In grid-tied mode, by controlling the output of the MG, losses incurred from feeders and transformers can be controlled. • Since the total life span of MGs depends on the proper utilization of ESSs, an optimized energy approach must be designed for them [53]. • In [54], the most critical parameters resulting in an optimal cost of MGs are presented.
Protection issues	• A protection system must provide a quick and robust response to all faults for either grid-tied or isolated MGs. • In the case of any fault in the main grid, the protection system should be able to quickly detect it and easily isolate the MG to ensure its components' protection. • In the case of any fault in the MG, protection systems should be able to quickly detect it and easily isolate the faulty part of the MG from the rest.
Communication system	• For the proper operation of an MG, and by considering that MGs are small-sized grids mainly established in remote areas, it is required to establish a cost-effective, robust, and reliable communication system with suitable coverage, security, and latency. • In terms of communication technology, communication systems can be categorized into WL and wired systems. • In terms of data rate capability, LB- and HB-com systems are mainly used in MGs.
Control system	• For controlling MGs, hierarchical control methods are commonly employed due to equipment diversity, unique challenges, and complicated relations among the components. • Despite MGs' advantages, a careful and precise control system is required for MGs to provide a robust, proper, and stable operation. • In terms of communication systems, MGs' control systems can be classified as communication-based and -free controllers. • In terms of the controlling structure, it can be grouped into centralized, decentralized, and distributed methods.
RESs integration	• Besides the RESs' benefits (being low-cost and clean sources), most of them have a variable, non-dispatchable, and intermittent nature. For achieving higher/optimum RES integration into MGs, these problems must be considered in designing control systems and by using some other solutions such as ESSs.

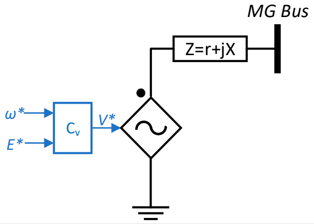
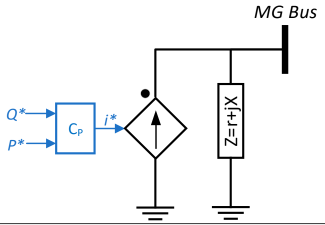
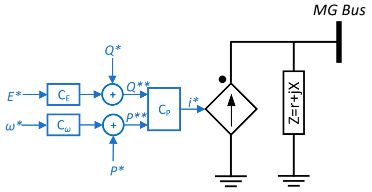
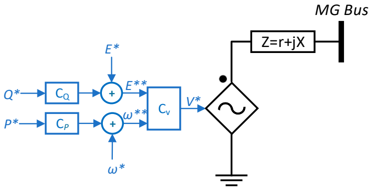
2.5. Power Converters in MGs

Today, PEL-based technologies are used as an interface between an MG and its different devices, such as DERs and ESSs [55–57]. Since the stability of the rotating electric machines (directly coupled ones) imposes strict voltage and frequency boundaries, PEL technologies used in interconnected DERs enable us to relax the mentioned boundaries [9]. Besides its advantages, the dominant presence of PEL-based devices in MGs causes serious challenges such as [9]:

- Increased control complexities, such as increased difficulties in controlling voltage and frequency caused by the short lines and low inertia of MGs
- Strong coupling between reactive and active powers with crucial control and market implications, particularly for voltage characteristics, caused by MGs' particular characteristics such as relatively large R/X ratios
- Increased safety and protection challenges caused by the low contribution of PEL-based DERs in system faults and errors
- Lacking computation and communication facilities of typical power systems in MGs
- Need for low-cost and efficient solutions

According to the operation of power converters in an ACMG, they can be categorized into three classes: grid-supporting, grid-forming, and grid-feeding structures, whose main characteristics and simplified diagrams are presented in Table 7 [13,58,59].

Table 7. Main characteristics of different types of power converters used in ACMGs with their simplified circuit diagrams.

Converter Type	Characteristics and Features	Simplified Diagram
Grid-forming	• Can be shown as an ideal AC voltage source with a low-output impedance [13]. • Using a proper control loop to set the voltage amplitude (E*) and frequency (ω*) of the local grid. • Used to form a reference AC voltage in MGs, especially in islanded mode [60]. • Note: In the main grid, reference AC voltage is formed by synchronous generators [60].	
Grid-feeding	• Employed for delivering power (energy) to an energized network [13]. • Can be modeled as an ideal current source paralleled with a high impedance and connected to the grid. • At the connection point, it should be synchronized with AC voltage to achieve an accurate power exchange with the grid [13]. • Generally, a converter/generator, forming the grid voltage, is required to enable this converter to operate. • Hence, it cannot operate independently in islanded mode [13].	
Grid-supporting	• Can be represented in two models [13]: 1. An ideal AC-controlled current source paralleled with a shunt impedance. 2. An ideal AC voltage source in series with a link impedance. • Contributing to keeping the voltage amplitude and frequency of the grid close to rating values by regulating its output voltage/current (delivering proper active and reactive powers) [13]. • While controlling it as a voltage source, the internal control loop usually emulates the link impedance effect. • Partially similar to both grid-feeding and grid-forming converters: ➢ In the case of controlling it as a current source, at least one grid-forming converter is needed to enable it to operate [13]. ➢ In the case of controlling it as a voltage source, it can operate in both grid-tied and islanded modes [13].	 Current source-based model  Voltage source-based model

2.6. Control Strategies of MGs

For controlling conventional power networks, multi-layer solutions/methods are commonly employed due to equipment diversity and complicated relations among multiple subsystems [9]. A hierarchical structure can be characterized by three sets of common properties [9,61]: the vertical arrangement of subsystems, the action priority of higher-level subsystems over lower-level ones, and higher-level subsystems' dependence upon lower levels' actual performance.

Despite orienting the actions' priority in a top-down command manner, decision modules/units should possess a given freedom of action to lead to the effective utilization of the multi-layer control structure [9], meaning that regardless of considering the action priority, each level must be as independent as possible. Generally, the concept of layers is defined as decomposing a decision problem vertically into sub-problems. For classifying control architectures developed for subsystems, two factors can be used [9]: the model complexity (used for the dynamic control of the grid) and the communication degree (between different units' controllers or hierarchical levels). Based on these factors, control structures can be classified and briefly explained as follows [9]:

- Centralized: There is only a single central controller managing, communicating, and controlling the whole MG/system.
- Distributed: There are several individual controllers, and some information about their behavior is shared among them.
- Decentralized: Several individual controllers exist; however, no information is shared among them.

Table 8 lists and compares the major characteristics of the above-mentioned structures.

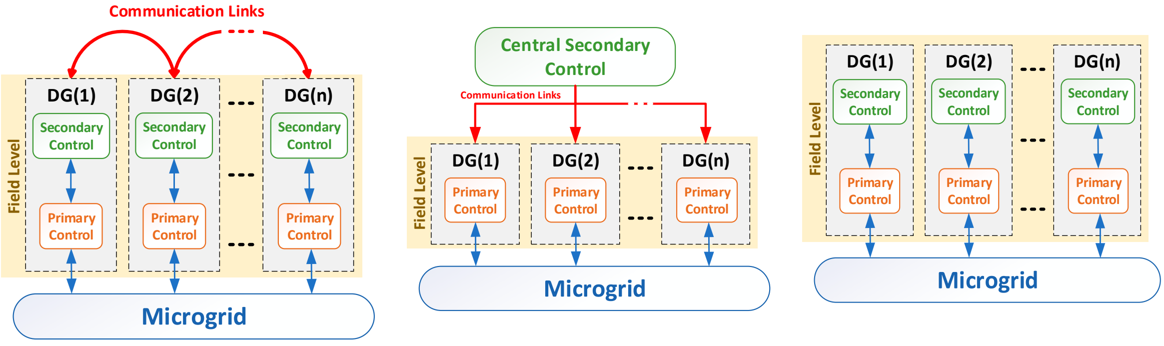
Table 8. Comparing the characteristics of different control strategies.

Characteristic	**Control Strategy**		
	Centralized	**Distributed**	**Decentralized**
Solution	Global optimal	Sub-optimal	Non-optimal
Reliability	Low	Moderate	High
Computational burden and complexity	High	Moderate	Low
Scalability	Low	Moderate	High
Communication degree	High	Moderate	No
Model complexity	High	Moderate	Low
Stability affected by communication	High	Moderate	No

By following the architecture of traditional power systems, three levels are defined for the hierarchical control of MGs: primary, secondary, and tertiary levels. As a controversial issue, up to now, no agreement has been reached on the definitions of their boundaries [9]. However, different control layers can be separated based on their two factors: control functionalities and time intervals. Accordingly, in the following, the major levels of the hierarchical control of an MG are briefly explained [8,9]:

- Primary (local/field level): It operates at the fastest time scale compared to other levels and is responsible for maintaining voltage and frequency stability and also ensuring proper power sharing among DERs.
- Secondary (management/MG level): In comparison to the primary level, this level has a slower time scale; its main responsibilities are mitigating the voltage and frequency deviations caused by primary control, facilitating synchronization with the upstream network, and performing optimal economic management. Note that its computed control outputs are used as input data for primary control. In Figure 5, simple diagrams of centralized, distributed, and decentralized secondary controllers are shown [8].
- Tertiary (highest/grid level): As the highest control level of an MG with the longest time scale, it determines the interactions of the MG with other MGs and also the upstream grid. Moreover, it is responsible for coordinating the MG with the distribution system to solve the energy management problem. It provides the input data for the secondary level by setting optimal operating points and producing optimal profiles as

references. For a better understanding, a schematic of a hierarchical control system of an MG is shown in Figure 6 [8].



(**a**) (**b**) (**c**)

Figure 5. Various secondary control architectures: (**a**) distributed; (**b**) centralized; (**c**) decentralized.

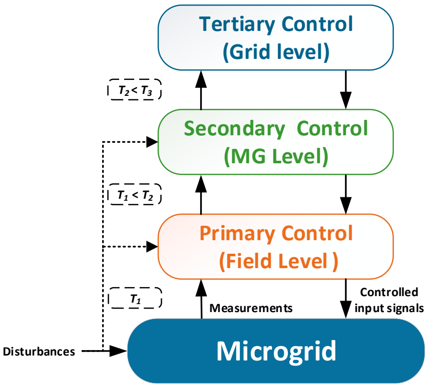


Figure 6. General schematic of the hierarchical control system of MGs.

3. Communication Requirements and Standards

In this section, communication standards and requirements are discussed. For the proper operation of an MG, a cost-effective, robust, and reliable communication system with suitable coverage, security, and latency must be established. Several standards have been presented for this aim, and some of the most important ones are listed in Table 9. In addition, some papers present the communication requirements and standards [62–65].

Table 9. Standards related to the communication systems of MGs.

Standard	Title
IEC 61850-7-420 [66]	Communication networks and systems for power utility automation—Part 7-420: Basic communication structure—Distributed energy resources logical nodes
IEC 61850-8-2 [67]	Communication networks and systems for power utility automation—Part 8-2: Specific communication service mapping (SCSM)—Mapping to Extensible Messaging Presence Protocol (XMPP)
IEC 61850-90-12 [68]	Communication networks and systems for power utility automation—Part 90-12: Wide area network engineering guidelines
IEC 61400-25-2 [69]	Wind turbines—Part 25-2: Communications for monitoring and control of wind power plants—Information models
IEEE 1547 [70]	IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems
IEEE 2030 [71]	2030–2011—IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads

Based on the corresponding function and location, architectures of the communication system of a smart power system, such as a smart MG, can be generally classified into three levels: HAN, FAN, and WAN [63,72]. Compared to other layers in an MG, the HAN layer needs the least bandwidth covering the load level, including EVs, smart appliances, etc. On the other hand, the FAN layer is employed for coordinating among operators, ESSs, DERs, and energy marketing entities, leading to it having higher bandwidth links compared to the HAN layer. Moreover, WAN is the highest communication layer responsible for exchanging the information between the MG and the upstream network (main utility grid), while the MG operates in grid-tied mode. Table 10 lists the characteristics of these levels and their applications [63,65,72–75].

Table 10. Characteristics of HAN, FAN, and WAN and their applications in smart power systems.

Communication Level	Characteristics	Applications	Technologies
HAN	• Short coverage ranges (up to hundreds of meters) • LB (up to hundreds of kbps)	• Smart-MG/-grid applications at the consumer level • Communication between MG assets • Home automation applications • In MGs, home energy management systems (9.6–56 kbs bandwidth with 0.2–2 s latency) • In MGs, EV charging (9.6–56 kbs bandwidth with 2 s–5 min latency)	• WiFi [76] • Zigbee [76] • Bluetooth [76] • HSPA M2M
FAN	• Coverage ranges up to kilometers • Communication bandwidth up to tens of Mbps • Portal to transmit information between the HAN and WAN layers	• Suitable for MG communities' applications • Long-distance communication needed for real-time energy management and monitoring • Demand response • In MGs, DER, and ESS (9.6–56 kbs bandwidth with 20 ms–15 s latency)	• PLC • RF-mesh • WiMax • WiFi • Cellular (LTE)
WAN	• Wide coverage ranges • The HBcom system processing the whole aggregated data • Sending/receiving command signals to and from other layers	• Power transmission/generation scales • Adaptive islanding	• Cellular • Fiber optics • PON • SDH

In communication networks, several limitations such as the coverage range, vulnerability to noises, bandwidth and data transfer ratio, transmission delays, and ZOH delays exist that should be considered in the control system design. As one of the main limitations, delay can be caused by communication links congestion due to a high traffic volume, distance and obstacles (such as buildings and trees) between transceivers, propagation, interferences and noises generated by other devices/networks, malicious activity, network flooding, and service complete denial [77,78]. In a PEL-intensive smart MG, cyber-attacks can impose adverse impacts on system operation and stability due to the low inertia of MG, especially in islanded mode [79]. Cyber-attacks can be classified into three main categories: data availability, integrity, and confidentiality attacks. In a secure cyber layer (communication network), system data are timely and accessible, accurate and trustworthy, and viewed and employed only by authorized operators. Among cyber-attacks, FDIA is one of the most critical problems of a smart MG targeting data integrity. It gets more challenging if FDIA is crafted intelligently, which cannot be detected by conventional methods [80]. Several studies and standards have been published on cyber-security topics [79,81,82].

Generally, MGs should be equipped with a reliable and secure communication network providing two-way communication between the components and other MGs. For this aim, several well-known and widely used communication protocols/standards, such as MQTT, CIM, Modbus, and OPC-UA, have been introduced. Since the main focus of this article is not to cover these protocols, some recent publications, such as [83–86], can be referred to for more information.

4. Low-Bandwidth Communication Technologies

Here, LBcom technologies, classified into wired and WL technologies, are discussed. Wired technologies need more implementation costs compared to WL ones. This gets worse in MGs, which are usually placed in remote areas. Moreover, the wiring will reduce the communication system's modularity. However, unlike WL technologies, wired ones do not need any battery. In addition, they show more robustness against interference over WL technologies.

4.1. LB Wired Technologies

For different communication layers of MGs, several wired technologies, such as PLC and Ethernet in the HAN layer, PLC, Ethernet, coaxial cable, and DSL (digital subscriber line) in the FAN layer, and fiber-optic in the WAN layer, can be employed based on requirements and conditions. However, among them, only CAN, UNBPLC, and NBPLC can be classified as LBcom technologies, whose essential characteristics are listed in Table 11 [65]. So far, PLC has been a widely used technology in power systems for communicating information through the power lines, making it a technology with a lower implementation cost compared to other wired technologies whose most challenging issue is their high implementation costs.

Table 11. Characteristics of LB wired technologies for the MGs communication system.

Technology	Standard/Protocol	Characteristics	Advantages	Disadvantages
PLC	UNBPLC	• Data rate: 100 bpc • Coverage: 150 km	• Simple, convenient, and cost-effective • No need for separate infrastructure other than the power grid	• Vulnerable to the interference of MG noises or weather conditions
	NBPLC	• Data rate: 10–500 kbps • Coverage: 150 km		
CAN	-	• Data rate: up to 1 Mbps	• Priority-based access • Low cost • Error detection capabilities • Robust, fault-tolerant, multi-host serial communication	• Low data transfer rate • Latency

4.2. LB WL Technologies

These days, WL technologies have been increasingly used in MGs, resulting in a decreased complexity and cost in the communication system of MGs. Since the focus of this paper is on LB technologies, the important characteristics of different LB WL technologies are presented in Table 12 [65,76,87–90].

Table 12. Characteristics of LB WL technologies for the MGs communication system.

Technology	Standard/ Protocol	Characteristics and Applications	Advantages	Disadvantages
WPAN	Z-Wave	• Data rate: 40 kbps • Coverage: 30 m • Application: smart appliances and HEMS	• Mesh connectivity • Free bandwidth • No interference	• High power consumption • Low data rate
	WirelessHART	• Data rate: 115 kbps • Coverage: 200 m • Application: smart meters and HEMS	• Scalable • Backward-compatible	• Short coverage range • Low data rate • Interference
	ZigBee	• Data rate: 250 kbps • Coverage: 100 m • Application: Widely used in HAN, smart homes, smart meters, monitoring, and EVs	• Low cost • Low power consumption • Low complexity • Provides tree, star, and mesh networks by Direct Sequence Spread Spectrum modulation • Point-to-multipoint connection • Flexible for expansion • Encryption code	• Short coverage range • Low data rate • Interference
	ZigBee pro (Inter-WPAN)	• Data rate: 250 kbps • Coverage: 1.6 km • Application: V2G (Vehicle-to-grid)	• Mesh connectivity	• Low data rate • Interference
	Bluetooth	• Data rate: 1–2 Mbps • Coverage: 15–30 m • Application: smart appliances and HEMS	• Higher data rate • Free bandwidth • Low power consumption • Low complexity • Flexible for expansion	• Not safe • Too short of a coverage range • Vulnerable to noise • No encryption code
Cellular Network Communication	2G (GSM)	• Data rate: 14.4 kbps • Coverage: 1–10 km • Application: DMS, EMS, AMI, DR	• Existing infrastructures and service model • Ubiquitous coverage • Good coverage range	• Low data rate
	2.5G (GPRS)	• Data rate: 144 kbps • Coverage: 1–10 km • Application: DMS, EMS, AMI, DR	• Ubiquitous coverage • Good coverage range	• Low data rate
	3G	• Data rate: 2 Mbps • Coverage: 1–10 km • Application: DMS, EMS, AMI, DR	• Ubiquitous coverage • Higher data rate • Good coverage range • Low latency	• Monthly recurring costs • High-cost licensed spectrum • Uncertainty of stable connectivity in severe weather conditions
LPWAN	LoRa	• Data rate: (LoRa modulation: 0.3–37.5 kbps; LoRaWAN: 50 kbps) • Coverage: (Urban area: 2–5 km; Rural area: 10–15 km) • Application: DMS, AMI	• Good coverage range • Low power consumption compared to Cellular Network	• Low data rate

Table 12. *Cont.*

Technology	Standard/ Protocol	Characteristics and Applications	Advantages	Disadvantages
Satellite Network	LEO	• Data rate: (Iridium: 2.4–28 kbps) • Coverage: 100–6000 km • Application: DMS, AMI, a solution for MG communication in remote places, a redundant path for creating backup communication	• Wide-area coverage • High reliability	• High cost • High latency
	MEO	• Data rate: (Inmarsat-B: 9.6–128 kbps) • Coverage: 100–6000 km • Application: DMS, AMI, a solution for MG communication in remote places, a redundant path for creating backup communication	• Wide-area coverage • High reliability	• High cost • High latency
	GEO	• Data rate: (BGAN: 1 Mbps) • Coverage: 100–6000 km • Application: DMS, AMI, a solution for MG communication in remote places with no access to other WL technologies, a redundant path for creating backup communication	• Wide-area coverage • High reliability	• High cost • High latency

5. LBcom-Based Control Methods

As explained, each control infrastructure, i.e., decentralized, distributed, and centralized, has its advantages and drawbacks compared to others. Generally, to have an optimal solution, a communication system should be employed in the control system, which in turn results in increased complexity, decreased reliability, and increased cost. To overcome these drawbacks while achieving a sub- or global-optimal solution, several LBcom-based control methods have been developed, which are reviewed in Sections 5.1–5.4.

As mentioned, recent LBcom tools such as Zigbee, PLC, and Bluetooth are low-cost, with flexible operation and distributed intelligence, and they require no extra wired connection [91]. Moreover, built-in checking rules are employed in these digital modules, making them reliable even in a highly electromagnetic EMI environment. Several diverse signals, such as phase, amplitude, or control commands, can be transmitted through them by multiplexing a single digital communication channel. However, these tools can provide low data transmission rates, causing challenges such as communication delays and ZOH periods for their applications, especially in high-level coordination [91]. In designing LBcom-based controllers and stability analyses of MGs, these limitations should be considered properly. For instance, while most studies only consider pure transmission delay (Δt_1) [91–95], ZOH (Δt_2) can be larger than it, as shown in Figure 7.

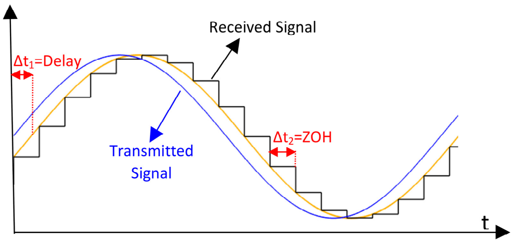


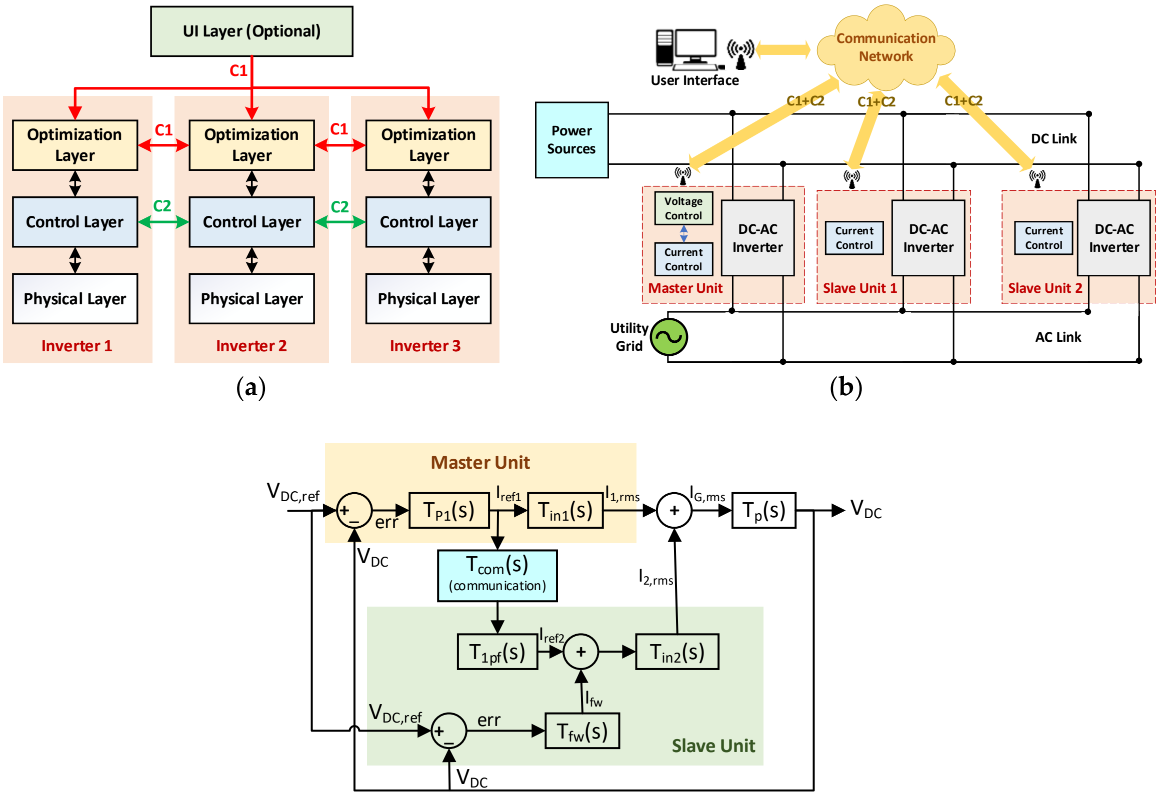
Figure 7. Simple waveforms of a transmitted signal and the corresponding received signal with its transmission delay (Δt_1) and ZOH (Δt_2) in an LB digital communication network [91].

5.1. Primary Control

In a hierarchical strategy, primary control is the first control layer with the fastest time scale. This control level works on the variables of MG, such as frequency and voltage, to guarantee their proper set-point tracking [8]. Maintaining system stability and reliability, system performance improvement, and appropriate power sharing between DERs are the major responsibilities of this level [96]. The most well-known communication-based primary controllers can be classified into concentrated, master–slave, distributed, and current-sharing methods that generally include central processing and data distribution units. The central processing unit performs the needed computations. Shared information between PEL converters is distributed through the data distribution unit. Despite providing a fast dynamic response and semi-optimal/optimal solutions (such as desirable current-sharing ability), a relatively HBcom link is usually required by these controllers, causing an increased complexity and implementation cost for them. These controllers can be negatively impacted by communication limitations such as delays, causing grave challenges for MGs, such as overall stability problems [91–93].

To solve these problems, several LBcom-based primary control methods have been presented for MG applications. By establishing an LBcom system, master–slave methods can be used in a wide range with no wire implementation and a low cost, achieving proper load/current sharing and plug-n-play features for DERs. In [92], an analog RF WLcom-based master–slave control approach with robustness against delays is presented for the load sharing of a parallel buck converter system as an islanded DCMG. In [97], a model for the dq frame-based master–slave controller is presented, where the system is modeled as a time-delay system with parallel inverters to achieve accurate load sharing in an ACMG. In [91], a master–slave LBcom-based current-sharing control method, immune to delays, high EMI noises, and ZOH, is presented for parallel interfacing inverters as an ACMG. Unlike the steady state, the oscillation and instability are avoided by decoupling the inverters at transients in this method. Unlike the papers focused on the delay-bound calculation, the system's tolerability to communication delays is increased. Figure 8a–c, respectively, show a typical configuration of a system with two separate communication systems, the LB WLcom system, and control diagrams of the method of [91].

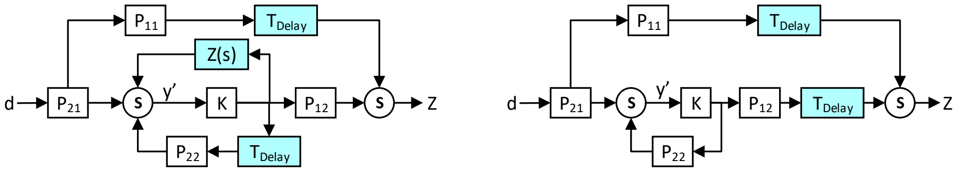
Some methods/studies are non-master–slave-based. In [98], two communication-based and -free droop control methods are developed for load sharing in LV isolated ACMGs. In [99], the effect of the time-varying delay of a WLcom on load sharing among DERs in islanded smart ACMGs is studied, and an optimal control method is developed, whose block diagrams are shown in Figure 9. In [100], the impact of the latency of WLcom technologies including ZigBee within HAN on the power converters and the bus voltage during islanding in a centrally controlled DCMG has been studied. In [101], a robust and stable PLC-based ACMG architecture considering the noise and delays of the LBcom system is presented for achieving an automatic and proper load sharing among DGs without using the droop method. This MG can adapt to changes and also minimize the battery support amount simultaneously.



(**a**) (**b**)

(**c**)

Figure 8. (**a**) A typical configuration of a parallel inverter system with two separate communication systems C1 and C2; (**b**) The LB WLcom-based method of [91]; (**c**) Control diagram of the method of [91] considering the communication impact and having the voltage feed-forward loop in the slave unit.



(**a**) (**b**)

Figure 9. Block diagram of the load sharing control method presented in [99]: (**a**) with light-blue blocks to obtain a uniform delay time; (**b**) with a uniform delay time.

As mentioned, decentralized controllers, especially droop-based ones, suffer from limited stability, which is majorly caused by a lack of communication between DERs. To overcome this drawback, some droop-based control methods with an LBcom network have been developed for achieving proper power sharing in islanded ACMGs [102–106]. In [102], an application of WL sensor LB networks for power sharing and control in a droop-controlled ACMG with DGs is presented. In [103], the stability of the droop-based decentralized control is enhanced, where a power-sharing control method is developed based on a limited WLcom infrastructure, which is used for transferring all DGs' generation information. In [104], an online virtual impedance adjustment-based droop control approach with a one-way LBcom network is presented for proper power sharing at the steady state. The block diagram of this approach is shown in Figure 10. In [106], an LBcom-based adaptive voltage droop control is developed to improve reactive power sharing by compensating for the effect of voltage drops on the impedances of the feeder. The block diagram of this method is shown in Figure 11. Instead of direct control of the inverter's output voltage, the voltage droop slope is adjusted to compensate for the voltage drop mismatch across feeders by employing an LBcom system. The method's delay immunity comes from the fact that the tuning closed-loop control system includes no communication. In [105], an improved droop-based control method is presented for proper reactive power sharing among DGs. To achieve this aim, the voltage bias on the conventional droop control basis is changed, which is activated by employing a synchronization events sequence through an LBcom network with only communication delays. M. Eskandari et al. presented a servo control system for controlling power converters in ACMGs, by which droop-based VSIs are converted to servo-VSIs [107]. In addition to the mentioned droop-based controllers, in [38], an LBcom-based unified distributed control method is presented for achieving proper power sharing without frequency deviations in hybrid cascaded-parallel ACMGs under both resistive-inductive and -capacitive loads.

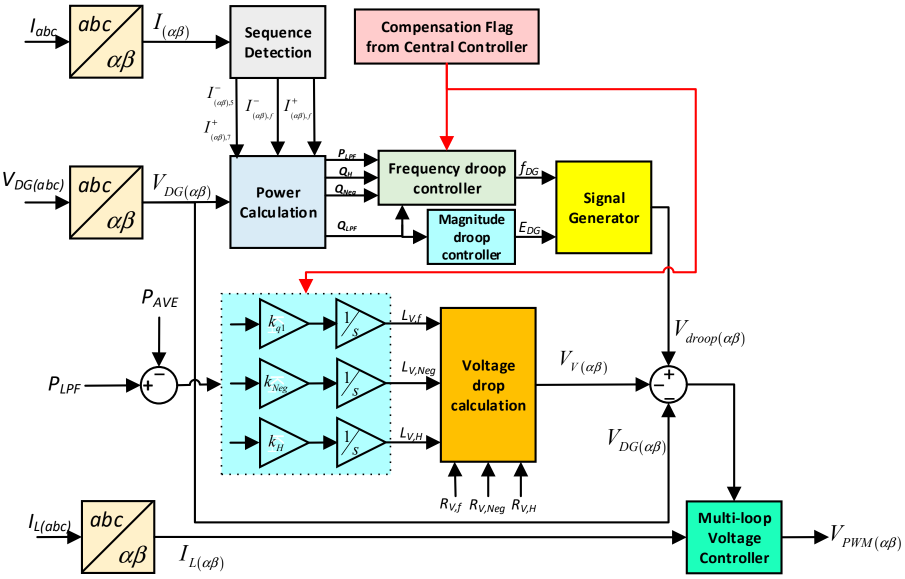


Figure 10. Block diagram of the control method of [104].

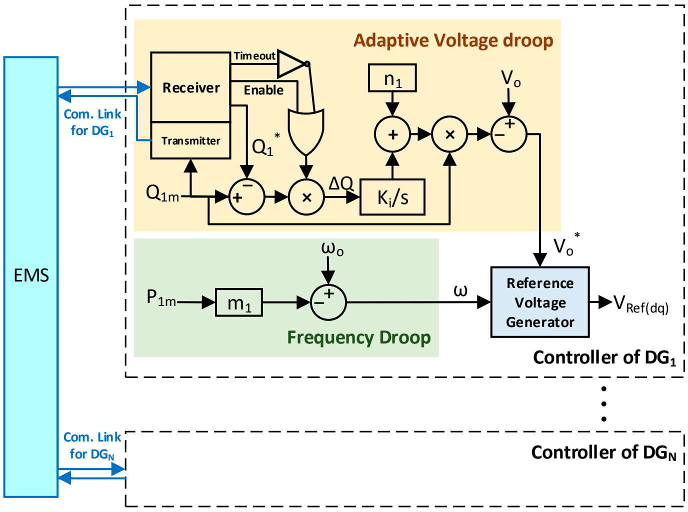


Figure 11. Block diagram of the controller of [106].

In DCMGs, load sharing and low-voltage regulation are the main objectives of control systems that cannot be achieved appropriately by conventional droop controllers simultaneously due to the error in nominal voltages and load distribution [108]. To address these problems, a distributed controller based on an LBcom system (CAN protocol with a 0.1 ms delay) is presented in [108], whose block diagram is shown in Figure 12.

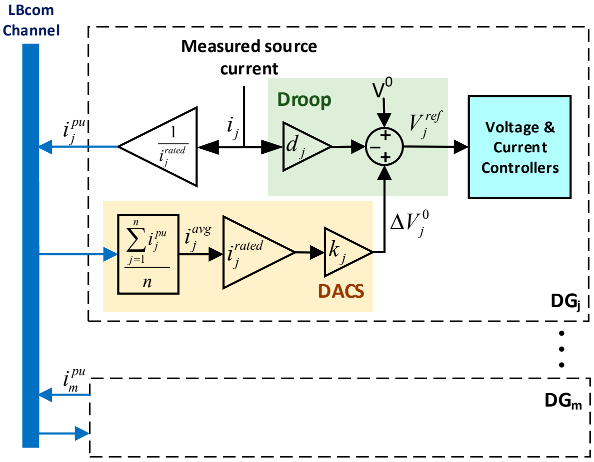


Figure 12. Block diagram of the control method introduced in [108].

Generally, ESSs are employed for absorbing the energy mismatches between the generation and the demand sides. Unlike previous works concentrating on energy management through communication systems, Oureilidis KO et al. introduced a WL control methodology for maintaining the frequency and voltage of an ACMG within permissible limits by employing an ESS [109]. Besides computing ESS capacity, proper reactive and active power sharing is achieved among parallel DERs by a droop controller.

In [110], the design, establishment, and requirements of the CAN protocol (with a speed up to 1 Mbps; robust against severe test conditions) as the communication link among high-frequency power converters are studied for controlling and coordinating the converters in a master–slave configuration.

In Table 13, the most important LBcom-based primary methods are summarized and categorized.

5.2. Secondary Control

In the hierarchical control strategy, the second control layer is called secondary control, whose main responsibility is to mitigate the deviations of the voltage and frequency introduced by the primary control. This control layer can be employed not only for synchronizing MG with the upstream power grid but also for realizing optimal economic management [9]. In comparison with the primary layer, secondary control is slower. It is noteworthy that the control outputs of this control level are delivered to the primary control as its input control signals. Typically, a conventional controller such as the centralized proportional-integral (PI) controller is utilized in the restoration of the voltage and frequency of an MG that can be designed to show a desirable performance in achieving optimal solutions for particular operating conditions [15]. However, this controller has several serious disadvantages, such as poor flexibility, limited scalability, and single-point failures. To solve the technical challenges of MGs, several LBcom-based secondary control methods have been introduced, which are presented in the following.

Table 13. Summarizing and categorizing important LBcom-based control methods in the primary control level.

Main Objectives	**Ref.**	**Characteristics/Results**	**Communication**	**Test System**	**Year**
Current/load sharing	[92]	• A master–slave-based controller • Proper current sharing among DERs • Desirable performance and stability in the presence of communication delays • Sending the reference current from master to slave units through WL LBcom	• LBcom • Analog WL RF	• DC network • Parallel DC-DC buck converters	2008
	[98]	• Introducing either communication-based or -free droop control methods for load sharing • By considering the close error margin difference and high cost of HBcom, LBcom is proved to be the best option • Considering communication delays	• LBcom &HBcom	• LV isolated ACMG	2010
	[99]	• A study on the effect of the time-varying delay on load sharing • Delay impact may be severe prior to the occurrence of latency	• HBcom & LBcom	• Islanded ACMG	2012
	[97]	• A dq frame-based master–slave control method • The reference current is sent from the master to slave units • Accurate load sharing • Maintaining MG stability by max. communication delay calculation	• WL network or CAN	• Two parallel inverters • Islanded ACMG	2017
	[100]	• A control method with a central controller • Impact of various WLcom technologies' latency, within HAN, on MG voltage and converters' switches • The design of an MG should be coordinated along with the selection of the communication technology	• Various WLcom technologies including LB	• DCMG • During islanding	2018
	[91]	• A master–slave control method • Robust against communication delays, high EMI noises, and ZOH • Proper current sharing • Good system stability	• LB WLcom • ZigBee	• ACMG • Input- & output-parallel inverters	2019
	[101]	• Automatic & proper load sharing without droop control in the primary control layer • Considering noise and delays in communication in the analysis	• LBcom • PLC technology	• Standalone ACMGs	2021

Table 13. *Cont.*

Main Objectives	Ref.	Characteristics/Results	Communication	Test System	Year
Active and/or reactive power sharing	[102]	• Application of WL sensor networks in ACMGs with DGs • Introducing a scheme for having reliable communication • Improving power sharing by DGs' reference signal correction	• LBcom	• Islanded ACMG	2012
	[103]	• A droop-based decentralized control method • Proper active and reactive power sharing while maintaining frequency and voltage • Enhanced system stability • Presenting two analytical models with and without considering delays	• LB WLcom • ZigBee, WiFi, and cellular	• Islanded ACMG with paralleled inverters	2013
	[104]	• An online virtual impedance-based droop control method • Proper power sharing based on online virtual impedance adjustment • Compensating for reactive, imbalance, and harmonic powers sharing errors • Good performance in the presence of a communication delay of a duration of a few milliseconds • Sending the compensation command from the central to the DGs local controller to obtain a synchronized compensation in DGs with no noise addition • Virtual impedance at fundamental positive & negative sequences and harmonic frequencies is determined based on transient real power variations	• One-way LBcom	• Islanded ACMG	2014
	[105]	• An improved droop control method • Proper reactive power sharing by sharing error reduction operation • Voltage regulation achieved by the voltage recovery operation • Achieving plug-and-play	• LBcom	• Islanded ACMG	2014
	[106]	• An adaptive voltage droop-based control method • Better reactive power sharing by compensating for the voltage drops' effect on feeder impedances • Immune to communication delays • Better response than that of a conventional droop under communication interruptions • Simple implementation • No need for feeder parameters and any estimation algorithm	• LBcom	• MV Islanded ACMG	2015
	[107]	• Introducing a fast-response strategy for accurate reactive power sharing • Determining reactive power references based on V/Q droop coefficients • Introducing a servo-VSI to a fast-track reactive power reference • Developing an optimization-based method to determine optimal servo-VSI parameters • Robustness against communication delay and interruption	• LBcom	• Islanded ACMG	2017
	[38]	• A unified distributed control method • Proper power sharing without frequency deviations • Automatic match load feature by introducing a sign function • Supporting power management & plug-and-play • Slightly affected by communication delays and failures in steady state	• LBcom	• Hybrid cascaded–parallel ACMG	2019

Table 13. *Cont.*

Main Objectives	Ref.	Characteristics/Results	Communication	Test System	Year
Voltage regulation and proper load sharing	[108]	• A distributed control method • High reliability • Good low-voltage regulation • Proper load sharing	• LBcom • CAN with a small delay	• Islanded DCMG • Parallel DC-DC converters	2012
Voltage and frequency regulation and energy management	[109]	• A WL energy management method based on using ESS • Maintaining the voltage and frequency of MG within permissible limits • Relatively proper power sharing is achieved • Non-linear loads are not considered to prove the method's performance • Supplying the load by a high-quality voltage in both grid-tied and islanded modes under several load scenarios	• LBcom	• Islanded and grid-tied ACMG	2012
Voltage control	[110]	• Design, establishment, and requirements of the CAN protocol as a communication link of a master–slave method • Simple voltage control • Providing priority access to the CAN bus • In the case of failure in the master unit, the slaves' communication is not affected.	• LBcom CAN	• Two paralleled DC-DC converters supplying a common load	2012

In conventional DC droop controllers commonly used for sharing load current among DERs in DCMGs, the more the output current increases, the more the output voltage of the DC bus decreases linearly [93]. The output voltages of converters are not equal to each other due to their line resistances, causing a degraded accuracy for the output current sharing. In addition, the droop action causes increased voltage deviation of the DC bus as the load changes. So far, in DC islanded MGs, several LBcom-based secondary control methods have been presented to address these challenges. In [93], an improved LBcom-based decentralized droop controller was developed for DC bus voltage restoration and accurate current sharing in DCMGs. In [111], P. Ghalebani and M. Niasati presented a non-centralized droop-based control method with an LBcom system for achieving a more accurate power sharing and also a decreased voltage deviation in isolated DCMGs. In [112], an LBcom-based average voltage regulation strategy with an algorithm-based solution for an equal voltage correction factor is developed. In [113], an LBcom-based distributed secondary control method is developed for droop-controlled DCMGs. It is not only able to obtain proper power sharing but also can restore the DC bus voltage deviation by using the voltage-shifting strategy. In [114], an improved droop-based method is presented for achieving proper power sharing and bus voltage restoration in isolated DCMGs.

In [115], a distributed secondary frequency and voltage control method for islanded ACMGs is presented based on the LBcom network, which is also able to achieve active and reactive power sharing. For similar aims, a distributed secondary frequency and voltage approach based on an uncertain LBcom system without a central control unit is presented in [116]. Moreover, the authors of [117] studied HMGs, where inaccurate load sharing among some DERs and large voltage/frequency deviations in AC and DC buses can be caused by poor power management in sub-grids and bidirectional interlinking converters. To solve these problems simultaneously, a coordination factors-based distributed power management technique with an LBcom system is developed in [117].

Besides the mentioned secondary controllers, some papers studied only frequency control based on LBcom networks for islanded ACMGs [118,119]. In [118], the communication delays' impact on the secondary frequency control with the LBcom system is studied, where the adverse impact of communication delays is reduced by the introduced gain scheduling approach. Since, in the real world, weak/unreliable communication conditions such as LBcom infrastructures and communication failures can impose negative impacts on the performance of a typical consensus-based controller and MG stability, in [119], a distributed consensus-based secondary frequency control method is presented for islanded ACMGs, where the impact of weak communication is mitigated in two parts.

For achieving only power sharing among DERs in islanded ACMGs, a distributed secondary cooperative strategy based on networked multiagent systems is developed in [120], consisting of two distributed secondary controllers.

In [121], a distributed iterative event-triggered secondary control method for multiple DERs' voltage synchronization and optimal load sharing with economical operation is presented for a master–slave-based islanded DCMG. In this method, the controller sampling frequency is reduced in comparison to continuous-time feedback control.

Even though using the VSGs can increase the inertia of inverter-based MGs, severe oscillations may also be caused by using multiple paralleled VSGs. In [122], an LBcom-based secondary frequency control method is presented for frequency damping and restoration in islanded ACMGs with distributed VSGs. In this study, active power sharing is accomplished by the event-triggered communication mechanism.

As one of the secondary control level's responsibilities, GS has been studied in some papers [123,124]. In [123], a fast CAN communication-based GS strategy is presented for an ACMG, providing a smooth transfer from the islanded to grid-connected mode. Through the CAN network, the phase angle derived from the grid voltages is transmitted to all MSs. In [124], a simple GS method based on the CAN protocol is presented to achieve a less transient and faster synchronization of RESs.

In Table 14, the essential LBcom-based secondary control methods are summarized and categorized.

5.3. Tertiary Control

In the tertiary control layer, an MG's interactions with both the upstream/main grid and other neighbor MGs are determined by considering it as a part of the system's global operation. This control level coordinates the MG with the distribution system in order to optimally solve energy management problems with the consideration of the MG's dynamical behavior (such as weather forecast information and electric energy prices) and external criteria, such as technological, economic, and environmental ones. Generally, this control level generates optimal profiles as the references and sets optimal operating points for the secondary control level as its input signals [125], resulting in achieving improved operation stability in the whole system [13]. In ancillary services or the local energy market, the amount of the energy flow demanded from the secondary controller for achieving a cost-effective operation will be determined by the tertiary level in an MG. Power flow distribution [25] and DERs' power dispatch will be further optimized by this level, which has the longest time intervals among all control levels in a hierarchical control structure [126]. So far, researchers have not paid sufficient attention to the impact and utilization of the LBcom system on the tertiary control level.

5.4. More Than One Control Layer

Some studies on more than one control layer have been published, where an LBcom network is used. In [127,128], a consensus-based P-f/Q-V droop control method and a fuzzy-based consensus control method with an LBcom network for proper power sharing are respectively introduced for ACMGs. In [129], the authors presented a WLcom system based on ZigBee technology for data transfer between primary and secondary control layers. So far, several papers have studied ZigBee and its different applications in MGs, such as the data monitoring of DCMGs and real-time measurement and data transfer [130,131]. On the other hand, there are several papers attempting to solve ZigBee's limitations, such as its low data transfer rate and caused data transfer delay, by presenting data traffic scheduling and management schemes [132–135]. Generally, in MGs' communication systems, data transmission delay must be within an acceptable limit. To this end, it is crucial to use an efficient data coding method and a suitable data code length. By considering these points, an efficient data payload code and an appropriate data management scheme for a ZigBee-based control layer are presented in [129].

Table 14. Summarizing and categorizing important LBcom-based control methods in the secondary control level.

Main Objectives	Ref.	Characteristics/Results	Communication	Test System	Year
Current/load/power sharing and voltage restoration	[93]	• An LBcom-based improved decentralized droop controller • Desirable DC bus voltage restoration and accurate current sharing • Only transferring DC current and voltage values through LBcom • Considering the communication delay in the analysis	• LBcom	• Two-node islanded DCMG	2014
	[111]	• A non-centralized droop-based control method • Accurate power sharing and decreased voltage deviation • Robust against the system's physical characteristics (line resistances, DG capacities, and local loads' presence) • Transmitting only current information through LBcom lines • Considering only pure communication delays on controller performance	• LBcom	• Isolated DCMG	2018
	[112]	• An average voltage regulation strategy with an algorithm-based solution for the equal voltage correction factor • Providing proper load sharing through a droop controller with a high droop gain • Providing good voltage regulation through an LB CAN communication • Possessing merits such as fault tolerance, plug-n-play, and expandability • Through LB links, each converter only needs to share local DC bus voltage information • Communication delays are considered in stability analysis.	• LBcom • CAN	• Droop controlled DCMG	2019
	[113]	• An improved voltage-shifting strategy • Proper power sharing and desirable DC bus voltage restoration • Transmitting only one variable per converter (λ) through an LBcom link • Communication delay is considered in the analysis	• LBcom • CAN 2.0 with 125 kbps	• Islanded DCMGs	2020
	[114]	• An improved droop-based control method • Proper power sharing achieved by the power compensation strategy • Reduction in bus voltage deviation achieved by adding a voltage compensation term • Transferring only information of the DGs' output powers through LBcom links • No delays and noises are considered for LBcom networks.	• LBcom	• Isolated DCMG	2020

Table 14. *Cont.*

Main Objectives	Ref.	Characteristics/Results	Communication	Test System	Year
Voltage and frequency restoration and proper power sharing	[115]	• Developing distributed controllers using localized information and nearest-neighbor communication • Introducing a frequency controller for the rapid regulation of the MG's frequency while maintaining active power sharing among DGs • By tuning the voltage controller, a simple trade-off between voltage regulation and reactive power sharing is achieved • Not requiring any knowledge of the MG's topology, impedances, or loads. • No central controller	• LBcom	• Islanded ACMG	2015
	[116]	• A distributed frequency and voltage control approach based on an uncertain LBcom system • No central controller • Developing two discrete-time secondary controllers based on an iterative learning mechanism • Providing proper voltage and frequency restoration and active power sharing for all DGs • Each DG only needs to have the intermittent information of its neighbors through an LBcom link • Acceptable system stability and robust against uncertainties and noises • Not considering LBcom delays	• Uncertain LBcom	• Isolated ACMG	2018
	[117]	• A power management method • Providing accurate active power sharing among all AC/DC DERs • Proving reactive power sharing among AC DERs • Providing AC voltage/frequency and DC voltage restorations • Robust against communication latency or failure	• LBcom	• Islanded HMG	2021
Frequency restoration/control	[118]	• A study on the impact of communication delays on secondary frequency control with a central control unit • Exchanging information between central and local controllers through LBcom • Introducing a small-signal method for obtaining delay margins in order to maintain MG stability	• LBcom	• Islanded ACMG	2014
	[119]	• Distributed consensus-based frequency control for MGs under weak communications • The impact of weak communication is mitigated by: • Introducing an event-triggered decentralized technique and a time-varying control gain • Presenting a distributed secondary frequency control with finite-time convergence performance	• Weak communication • LBcom	• Islanded ACMG	2020
Active and reactive power sharing	[120]	• A distributed secondary cooperative method based on networked multiagent systems • Developing two distributed secondary controllers based on time-varying, local, and LBcom systems to achieve proper power sharing among DERs • Communication delays are considered • Sharing only the current and active/reactive load information of each DER in an intermittent and distributed way with its neighboring units	• LBcom • Intermittent communication	• Islanded ACMG including 4 DERs with local loads	2016

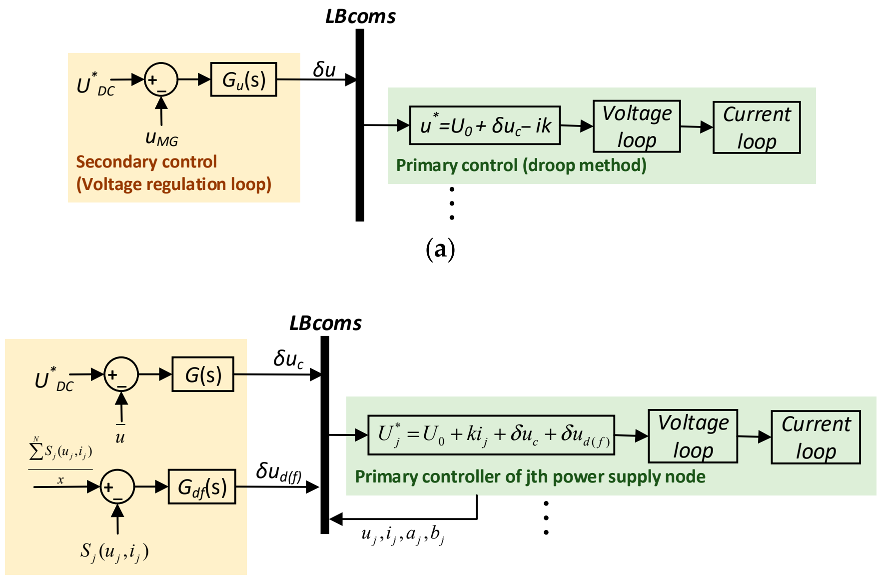
Table 14. *Cont.*

Main Objectives	Ref.	Characteristics/Results	Communication	Test System	Year
DERs' voltage synchronization and optimal load sharing	[121]	• A distributed iterative event-triggered secondary control method • Achieving voltage synchronization of multiple DERs and optimal load sharing • Sharing the local voltage and current of the DG with some nearest neighbors at a specified event-triggered time • Communication limitations are not considered	• LBcom	• Master–slave-based islanded DCMG	2018
Frequency restoration and oscillation damping with active power sharing	[122]	• A secondary frequency control method for distributed VSGs • Proper frequency damping and restoration without affecting the virtual inertia bestowed by VSGs • Achieving the active power sharing through the event-triggered communication mechanism • Demonstrating stability and Zeno-free behavior by ultimately uniformly bounded theory • Robust against both measurement noises and communication delays	• LBcom	• Islanded ACMG	2020
Grid Synchronization (GS)	[123]	• A fast CAN communication-based grid synchronization (GS) strategy • Providing a smooth transfer from the islanded mode to the grid-connected mode. • The communication delay is considered to be small but known and definite	• LBcom • CAN	• ACMG	2015
	[124]	• A CAN-based GS technique for RESs • Sharing information between controllers through CAN • A simple study without considering real-world limitations and problems	• LBcom • CAN	• Islanded & grid-tied RESs • ACMG	2017

In 2016, J. Ma et al. introduced a hierarchical power flow sharing and voltage regulation control method for transmission loss minimization in islanded DCMGs with merits such as improved expandability and reduced cost, resulting from its independence from information such as grid conductance and load distribution matrices [136]. The LBcom network is used for sharing needed information between primary and secondary control layers. Figure 13a,b, respectively, show the block diagram of the conventional method and the presented methods in [136]. In 2019, M. Eskandari et al. presented a fuzzy consensus protocol for improving the power-sharing performance of droop controllers in IN-ACMGs [137]. In addition, a consensus protocol, coordinated with reactive power sharing, is developed for average voltage profile restoration, resulting in an enhanced power quality [137]. In [138], a control method is introduced for the fast and simultaneous realization of reactive power sharing and voltage regulation in an IN-ACMG.

To achieve the desired frequency and voltage regulation for all DGs of all MGs and also proper active and reactive power sharing among MGs in a cluster of autonomous MGs with diverse numbers of heterogeneous DERs, a distributed cooperative hierarchical control approach based on intermittent communication is presented in [139]. In another study [140], active power sharing and frequency restoration in an IN-ACMG are aimed at developing a phase-angle feedback-based control along with a controller for feedback gains' adaptive tuning.

In Table 15, the characteristics of LBcom-network-based methods with more than one control layer are summarized and categorized.



(**a**)

(**b**)

Figure 13. Block diagrams of: (**a**) the conventional hierarchical method; and (**b**) the hierarchical control-based OPF realization method of [136] for DCMGs.

Table 15. Summarizing and categorizing LBcom-network-based control methods with more than one control layer.

Main Objectives	Ref.	Characteristics/Results	Communication	Test System	Year
Active and/or reactive power sharing	[127]	• Introducing a consensus-based droop control with a sparse communication network for proper active and reactive power sharing • Suitable for ACMGs with either uniform-ratio or pure-resistive lossy line impedances • No communication limitations are considered	• LBcom	• LV Islanded ACMG	2014
	[128]	• Developing a fuzzy-based consensus control protocol • Inserting consensus signals into the droop controller to achieve accurate power sharing • Adjacent buses are connected by LBcom links • LBcom limitations are not considered.	• LBcom	• Multi-bus ACMG	2018
Realizing an efficient ZigBee-based controller	[129]	• Introducing an efficient data payload code and an appropriate data management scheme for a ZigBee-based control layer • Communication delay impact on MG dynamic performance is studied • Focusing on communication between primary and secondary control	• LBcom • ZigBee	• DCMG	2015

Table 15. *Cont.*

Main Objectives	Ref.	Characteristics/Results	Communication	Test System	Year
Power sharing and voltage regulation/restoration	[136]	• A hierarchical power flow sharing and voltage regulation control method for transmission loss minimization • Primary control improves grid stability and reliability by setting a voltage droop characteristic for each power converter • Secondary control is responsible for realizing optimal power flow • The LB network's limitations, such as delays and noises, are not considered in proving the performance	• LBcom	• Islanded DCMGs • IEEE 14-bus modified for a 400 V DCMG	2016
	[137]	• Developing a small-signal model to evaluate the stability and performance of droop control • Providing accurate active and reactive power sharing by introducing a fuzzy-based consensus protocol • Introducing a consensus algorithm to restore the voltage profile while maintaining accurate reactive power sharing • Adjacent buses are linked by LBcom links • LBcom network limitations are not considered	• LBcom	• IN-ACMG	2019
	[138]	• Developing a power flow method for droop-based isolated MGs • Introducing a supplementary control loop for a V-Q droop-control loop for accurate reactive power sharing and voltage regulation • Achieving voltage regulation without an independent secondary controller • Determining the supplementary loop gain by developing a new state-space model • Sending information (a DC voltage) to DG controllers • LBcom network limitations are not considered	• LBcom	• IN-ACMG	2019
Frequency and voltage regulation among DGs and proper power sharing among MGs	[139]	• A distributed cooperative hierarchical control approach for a cluster of autonomous MGs • Achieving desirable frequency and voltage regulation for all DGs of all MGs • Providing proper active and reactive power sharing among MGs • An approach including droop-based secondary and tertiary control layers based on an iterative learning mechanism • Only sharing information of each DG with its neighbors through LBcom links • Using a two-layer sparse communication network model where one or some DERs are pinned from each MG's lower network to create an upper network • Allowing different numbers of heterogeneous DGs in each MG • Testing the method performance in the presence of delays, data dropout, and link failure	• LBcom • Intermittent communication	• Islanded ACMG Clusters	2017
Frequency restoration and active power sharing	[140]	• Developing a phase-angle feedback-based control method for frequency restoration • Developing a controller for the adaptive tuning of feedback gains to achieve proper active power sharing • Transferring information through one-way LBcom links • Robustness against communication delays and failures	• LBcom	• IN-ACMG	2019

6. Conclusions

This paper presents a comprehensive review paper on the different aspects of an MG, including its concept, challenges, advantages, components, and communication and control systems. As mentioned, communication-based control methods can provide a global-/sub-optimal solution that cannot be achieved by communication-free control methods (decentralized methods). However, employing communication infrastructure in an MG can cause some serious challenges, such as a high establishment cost, low reliability, high complexity, etc. As a solution, instead of using high-cost and complex HB technologies with a high power consumption, LBcom-based control methods have been introduced, which are developed based on LBcom technologies such as PLC, ZigBee, Bluetooth, CAN, and so forth. However, there is always a trade-off. Besides their advantages, LBcom systems suffer from drawbacks such as limited (low) bandwidth (low data transfer rate) and vulnerability to noise and communication delays, which can lead to severe problems in MGs, such as affecting their stability. Hence, several LBcom-based control methods with consideration of these problems have been presented for MG applications so far. As one of the main objectives of this paper, an overview is given about the most important wired and WL LBcom-based control methods for MG applications. There is still a long way to go to reach a desirable research point in this field. There are several challenges and open problems in using LBcom in control methods of MGs that should be investigated and solved by introducing efficient control algorithms, especially in the tertiary control layer and also the entire hierarchical control structure. Moreover, future methods should be robust against the LBcom link's inherent limitations, such as variable and fixed communication delays.

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Abbreviations

ACMG	AC microgrid
ADM	Active demand management
AMI	Advanced metering interface
CAN	Controller area network
CIM	Common Information Model
CSI	Current source inverter
DCMG	DC microgrid
DER	Distributed energy resource
DG	Distributed generation
DMS	Distribution management system
DR	Demand response
EMI	High electromagnetic interference
EMS	Energy management system
EV	Electric vehicles
ESS	Electrical energy storage
FACTS	Flexible AC transmission systems
FAN	Field area network
FC	Fuel cells
FDIA	False data injection attack
GEO	Geostationary earth orbits
GS	Grid synchronization
HAN	Home area network
HB	High bandwidth
HBcom	High bandwidth communication
HEMS	Home energy management systems
HSPA M2M	High-speed packet access machine-to-machine
HV	High voltage
HMG	Hybrid AC/DC microgrid
IN-ACMG	Islanded networked AC microgrid
LB	Low bandwidth

LEO	Low earth orbits
LoRa	Long range
LPWAN	Low-power wide-area network
LTE	Long-term evolution
LV	Low voltage
MEO	Medium earth orbit
MG	Microgrid
MQTT	Message Queue Telemetry Transport
MV	Medium voltage
MS	Micro source
NBPLC	Narrow band power line communication
OPC-UA	Open platform communication-unified architecture
PEL	Power electronics
PLC	Power line communication
PON	Passive optical network
PV	Photovoltaic
RES	Renewable energy source
RF	Radio frequency
SDH	Synchronous digital hierarchy
SG	Smart grid
UNBPLC	Ultra-narrow band power line communication
VSGs	Virtual synchronous generators
VSI	Voltage source inverter
ZOH	Zero-order-hold
WAN	Wide area network
WL	Wireless
WLcom	Wireless communication
WPAN	Wireless personal area network

References

1. Choudhury, S. A comprehensive review on issues, investigations, control and protection trends, technical challenges and future directions for Microgrid technology. *Int. Trans. Electr. Energy Syst.* **2020**, *30*, e12446. [CrossRef]
2. Shalchi, A.; Abbasi, M.; Abbasi, E.; Tousi, B.; Gharehpetian, G.B. New DTR line selection method in a power system comprising DTR, ESS, and RES for increasing RES integration and minimising load shedding. *IET Gener. Transm. Distrib.* **2020**, *14*, 6319–6329. [CrossRef]
3. Palizban, O.; Kauhaniemi, K. Microgrid control principles in island mode operation. In Proceedings of the 2013 IEEE Grenoble Conference, Grenoble, France, 16–20 June 2013.
4. Abbasi, M.; Miyab, M.S.; Tousi, B.; Gharehpetian, G.B. Using dynamic thermal rating and energy storage systems technologies simultaneously for optimal integration and utilization of renewable energy sources. *Int. J. Eng.* **2020**, *33*, 92–104.
5. Abbasi, M.; Abbasi, E.; Mohammadi-Ivatloo, B. Single and multi-objective optimal power flow using a new differential-based harmony search algorithm. *J. Ambient. Intell. Humaniz. Comput.* **2021**, *12*, 851–871. [CrossRef]
6. Gholami, K.; Abbasi, M.; Azizivahed, A.; Li, L. *An Efficient Bi-Objective Approach for Dynamic Economic Emission Dispatch of Renewable-Integrated Microgrids*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 1–20.
7. Al-Saedi, W.; Lachowicz, S.W.; Habibi, D.; Bass, O. Power flow control in grid-connected microgrid operation using Particle Swarm Optimization under variable load conditions. *Int. J. Electr. Power Energy Syst.* **2013**, *49*, 76–85. [CrossRef]
8. Mohammed, A.; Refaat, S.S.; Bayhan, S.; Abu-Rub, H. Ac microgrid control and management strategies: Evaluation and review. *IEEE Power Electron. Mag.* **2019**, *6*, 18–31. [CrossRef]
9. Vasilakis, A.; Zafeiratou, I.; Lagos, D.T.; Hatziargyriou, N.D. The Evolution of Research in Microgrids Control. *IEEE Open Access J. Power Energy* **2020**, *7*, 331–343. [CrossRef]
10. Zafari, P.; Zangeneh, A.; Moradzadeh, M.; Ghafouri, A.; Parazdeh, M.A. *Various Droop Control Strategies in Microgrids, in Microgrid Architectures, Control and Protection Methods*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 527–554.
11. Rokrok, E.; Shafie-Khah, M.; Catalão, J. Review of primary voltage and frequency control methods for inverter-based islanded microgrids with distributed generation. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3225–3235. [CrossRef]
12. Sen, S.; Kumar, V. Microgrid control: A comprehensive survey. *Annu. Rev. Control* **2018**, *45*, 118–151. [CrossRef]
13. Rocabert, J.; Luna, A.; Blaabjerg, F.; Rodríguez, P. Control of power converters in AC microgrids. *IEEE Trans. Power Electron.* **2012**, *27*, 4734–4749. [CrossRef]

14. Vandoorn, T.; De Kooning, J.D.M.; Meersman, B.; Vandevelde, L. Review of primary control strategies for islanded microgrids with power-electronic interfaces. *Renew. Sustain. Energy Rev.* **2013**, *19*, 613–628. [CrossRef]
15. Guerrero, J.M.; Vasquez, J.C.; Matas, J.; De Vicuña, L.G.; Castilla, M. Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization. *IEEE Trans. Ind. Electron.* **2010**, *58*, 158–172. [CrossRef]
16. Han, Y.; Li, H.; Shen, P.; Coelho, E.A.A.; Guerrero, J.M. Review of active and reactive power sharing strategies in hierarchical controlled microgrids. *IEEE Trans. Power Electron.* **2016**, *32*, 2427–2451. [CrossRef]
17. Basak, P.; Saha, A.K.; Chowdhury, S.; Chowdhury, S.P. Microgrid: Control techniques and modeling. In Proceedings of the 2009 44th International Universities Power Engineering Conference (UPEC), Glasgow, UK, 1–4 September 2009.
18. Ishaq, S.; Khan, I.; Rahman, S.; Hussain, T.; Iqbal, A.; Elavarasan, R.M. A review on recent developments in control and optimization of micro grids. *Energy Rep.* **2022**, *8*, 4085–4103. [CrossRef]
19. Shahgholian, G. A brief review on microgrids: Operation, applications, modeling, and control. *Int. Trans. Electr. Energy Syst.* **2021**, *31*, e12885. [CrossRef]
20. *IEEE Standard for the Specification of Microgrid Controllers*; IEEE: Piscataway, NJ, USA, 2017.
21. Ton, D.T.; Smith, M. The US department of energy's microgrid initiative. *Electr. J.* **2012**, *25*, 84–94. [CrossRef]
22. Marnay, C.; Abbey, C.; Joos, G.; Ash, K.; Bando, S.; Braun, M.; Chatzivasileiadis, S.; Driesen, J.; Hatziargyriou, N.; Iravani, R.; et al. Microgrids 1 Engineering, Economics, & Experience–Capabilities, Benefits, Business Opportunities. and Examples. *Relatório Técnico* **2015**, *635*, 3.
23. Yoldaş, Y.; Önen, A.; Muyeen, S.M.; Vasilakos, A.V.; Alan, İ. Enhancing smart grid with microgrids: Challenges and opportunities. *Renew. Sustain. Energy Rev.* **2017**, *72*, 205–214. [CrossRef]
24. Zhu, X.; Han, X.-Q.; Qin, W.-P.; Wang, P. Past, today and future development of micro-grids in China. *Renew. Sustain. Energy Rev.* **2015**, *42*, 1453–1463. [CrossRef]
25. Justo, J.J.; Mwasilu, F.; Lee, J.; Jung, J.-W. AC-microgrids versus DC-microgrids with distributed energy resources: A review. *Renew. Sustain. Energy Rev.* **2013**, *24*, 387–405. [CrossRef]
26. Patrao, I.; Figueres, E.; Garcerá, G.; González-Medina, R. Microgrid architectures for low voltage distributed generation. *Renew. Sustain. Energy Rev.* **2015**, *43*, 415–424. [CrossRef]
27. Che, L.; Shahidehpour, M. DC microgrids: Economic operation and enhancement of resilience by hierarchical control. *IEEE Trans. Smart Grid* **2014**, *5*, 2517–2526.
28. Planas, E.; Andreu, J.; Gárate, J.I.; de Alegría, I.M.; Ibarra, E. AC and DC technology in microgrids: A review. *Renew. Sustain. Energy Rev.* **2015**, *43*, 726–749. [CrossRef]
29. Tavakkoli, M.A.; Radan, A.; Hassibi, H. Simulation and analysis of a compact electronic infrastructure for DC micro-grid: Necessity and challenges. *Smart Grid Renew. Energy* **2012**, *3*, 73. [CrossRef]
30. Kakigano, H.; Miura, Y.; Ise, T. Low-voltage bipolar-type DC microgrid for super high quality distribution. *IEEE Trans. Power Electron.* **2010**, *25*, 3066–3075. [CrossRef]
31. Ding, G.; Gao, F.; Zhang, S.; Loh, P.C.; Blaabjerg, F. Control of hybrid AC/DC microgrid under islanding operational conditions. *J. Mod. Power Syst. Clean Energy* **2014**, *2*, 223–232. [CrossRef]
32. Ambia, M.N.; Hasanien, H.M.; Al-Durra, A.; Muyeen, S.M. Harmony search algorithm-based controller parameters optimization for a distributed-generation system. *IEEE Trans. Power Deliv.* **2014**, *30*, 246–255. [CrossRef]
33. Unamuno, E.; Barrena, J. Hybrid ac/dc microgrids—Part I: Review and classification of topologies. *Renew. Sustain. Energy Rev.* **2015**, *52*, 1251–1259. [CrossRef]
34. Wang, Y.; Chen, Z.; Wang, X.; Tian, Y.; Tan, Y.; Yang, C. An estimator-based distributed voltage-predictive control strategy for AC islanded microgrids. *IEEE Trans. Power Electron.* **2014**, *30*, 3934–3951. [CrossRef]
35. Hou, X.; Sun, Y.; Zhang, X.; Zhang, G.; Lu, J.; Blaabjerg, F. A self-synchronized decentralized control for series-connected H-bridge rectifiers. *IEEE Trans. Power Electron.* **2019**, *34*, 7136–7142. [CrossRef]
36. He, J.; Li, Y.W.; Wang, C.; Pan, Y.; Zhang, C.; Xing, X. Hybrid microgrid with parallel-and series-connected microconverters. *IEEE Trans. Power Electron.* **2017**, *33*, 4817–4831. [CrossRef]
37. Ge, X.; Han, H.; Yuan, W.; Sun, Y.; Su, M.; Zhang, X.; Hai, K.L. An integrated series-parallel microgrid structure and its unified distributed control. In Proceedings of the 2018 IEEE 4th Southern Power Electronics Conference (SPEC), Singapore, 10–13 December 2018.
38. Yuan, W.; Wang, Y.; Ge, X.; Hou, X.; Han, H. A unified distributed control strategy for hybrid cascaded-parallel microgrid. *IEEE Trans. Energy Convers.* **2019**, *34*, 2029–2040. [CrossRef]
39. Moran, B. Microgrid load management and control strategies. In Proceedings of the 2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D), Dallas, TX, USA, 3–5 May 2016.
40. Penkey, P.K. *Critical Load Serving Capability by Microgrid Operation*; University of Idaho: Moscow, ID, USA, 2016.
41. Baker, K.; Hug, G.; Li, X. Optimal integration of intermittent energy sources using distributed multi-step optimization. In Proceedings of the 2012 IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 22–26 July 2012.
42. Guerrero, J.M.; Chandorkar, M.; Lee, T.-L.; Loh, P.C. Advanced control architectures for intelligent microgrids—Part I: Decentralized and hierarchical control. *IEEE Trans. Ind. Electron.* **2012**, *60*, 1254–1262. [CrossRef]

43. Abbasi, M.; Tousi, B. Novel controllers based on instantaneous pq power theory for transformerless SSSC and STATCOM. In Proceedings of the 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Milan, Italy, 6–9 June 2017.
44. Abbasi, M.; Tousi, B. A novel controller based on single-phase instantaneous pq power theory for a cascaded PWM transformerless statcom for voltage regulation. *J. Oper. Autom. Power Eng.* **2018**, *6*, 80–88.
45. Abbasi, M.; Shayestehkhah, H.; Tousi, B. Application of an additive self-tuning controller for static synchronous series compensator for damping of sub-synchronous resonance oscillations. *Int. J. Eng.* **2018**, *31*, 564–573.
46. Li, Y.W.; Vilathgamuwa, D.M.; Loh, P.C. A grid-interfacing power quality compensator for three-phase three-wire microgrid applications. *IEEE Trans. Power Electron.* **2006**, *21*, 1021–1031. [CrossRef]
47. Leggate, D.; Kerkman, R.J. Adaptive Harmonic Elimination Compensation for Voltage Distortion Elements. U.S. Patent 10,250,161, 2 April 2019.
48. Gopakumar, P.; Reddy, M.J.B.; Mohanta, D.K. Letter to the editor: Stability concerns in smart grid with emerging renewable energy technologies. *Electr. Power Compon. Syst.* **2014**, *42*, 418–425. [CrossRef]
49. Gaur, P.; Singh, S. Investigations on issues in microgrids. *J. Clean Energy Technol.* **2017**, *5*, 47–51. [CrossRef]
50. Guo, Y.; Zhao, Z.; Huang, L. SoC estimation of lithium battery based on AEKF algorithm. *Energy Procedia* **2017**, *105*, 4146–4152. [CrossRef]
51. Pham, D.H.; Hunter, G.; Li, L.; Zhu, J. Microgrid topology for different applications in Vietnam. In Proceedings of the 2012 22nd Australasian Universities Power Engineering Conference (AUPEC), Bali, Indonesia, 26–29 September 2012.
52. Cai, S.; Wang, S.; Wang, C.; Jia, G. Economic perspective of smart grid. *Autom. Electr. Power Syst.* **2009**, *20*, 13–87.
53. Asano, H.; Bando, S. Economic evaluation of microgrids. In Proceedings of the 2008 IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, PA, USA, 20–24 July 2008.
54. Kriett, P.O.; Salani, M. Optimal control of a residential microgrid. *Energy* **2012**, *42*, 321–330. [CrossRef]
55. Abbasi, M.; Abbasi, E.; Li, L.; Tousi, B. Design and Analysis of a High-Gain Step-Up/Down Modular DC–DC Converter with Continuous Input Current and Decreased Voltage Stress on Power Switches and Switched-Capacitors. *Sustainability* **2021**, *13*, 5243. [CrossRef]
56. Abbasi, M.; Nazari, Y.; Abbasi, E.; Li, L. A new transformer-less step-up DC–DC converter with high voltage gain and reduced voltage stress on switched-capacitors and power switches for renewable energy source applications. *IET Power Electron.* **2021**, *14*, 1347–1359. [CrossRef]
57. Abbasi, M.; Abbasi, E.; Li, L. New transformer-less DC–DC converter topologies with reduced voltage stress on capacitors and increased voltage conversion ratio. *IET Power Electron.* **2021**, *14*, 1173–1192. [CrossRef]
58. Engler, A. Control of inverters in isolated and in grid tied operation with regard to expandability in tutorial: Power Electronics for Regenerative Energy. In Proceedings of the 2004 IEEE 35th Annual Power Electronics Specialists Conference, Aachen, Germany, 20–25 June 2004.
59. De Brabandere, K.; Bolsens, B.; Van den Keybus, J.; Woyte, A.; Driesen, J.; Belmans, R. A voltage and frequency droop control method for parallel inverters. *IEEE Trans. Power Electron.* **2007**, *22*, 1107–1115. [CrossRef]
60. Green, T.C.; Prodanović, M. Control of inverter-based micro-grids. *Electr. Power Syst. Res.* **2007**, *77*, 1204–1213. [CrossRef]
61. Mesarovic, M.D. Multilevel systems and concepts in process control. *Proc. IEEE* **1970**, *58*, 111–125. [CrossRef]
62. Serban, I.; Cespedes, S.; Marinescu, C.; Azurdia-Meza, C.A.; Gomez, J.S.; Hueichapan, D.S. Communication requirements in microgrids: A practical survey. *IEEE Access* **2020**, *8*, 47694–47712. [CrossRef]
63. Saleh, M.; Esa, Y.; El Hariri, M.; Mohamed, A. Impact of information and communication technology limitations on microgrid operation. *Energies* **2019**, *12*, 2926. [CrossRef]
64. Kumar, S.; Islam, S.; Jolfaei, A. Microgrid communications—Protocols and standards. *Var. Scalability Stab. Microgrids* **2019**, *139*, 291.
65. Tightiz, L.; Yang, H.; Piran, M.J. A survey on enhanced smart micro-grid management system with modern wireless technology contribution. *Energies* **2020**, *13*, 2258. [CrossRef]
66. *Basic Communication Structure–Distributed Energy Resources Logical Nodes: IEC 61850-7-420*; IEC: Geneva, Switzerland, 2009.
67. *Specific Communication Service Mapping (SCSM)—Mapping to Extensible Messaging Presence Protocol (XMPP): IEC 61850-8-2*; IEC: Geneva, Switzerland, 2018.
68. *Wide Area Network Engineering Guidelines*; IEC: Geneva, Switzerland, 2015.
69. *Communications for Monitoring and Control of Wind Power Plants—Information Models*; IEC: Geneva, Switzerland, 2015.
70. Photovoltaics, D.G.; Storage, E. *IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems*; IEEE: Piscataway, NJ, USA, 2007.
71. Photovoltaics, D.G.; Storage, E. *IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads*; IEEE: Piscataway, NJ, USA, 2011.
72. Kuzlu, M.; Pipattanasomporn, M.; Rahman, S. Communication network requirements for major smart grid applications in HAN, NAN and WAN. *Comput. Netw.* **2014**, *67*, 74–88. [CrossRef]
73. Webster, R.; Munasinghe, K.; Jamalipour, A. Optimal resource allocation for smart grid applications in high traffic wireless networks. In Proceedings of the 2014 IEEE International Conference on Smart Grid Communications (SmartGridComm), Venice, Italy, 3–6 November 2014.

74. Emmanuel, M.; Seah, W.K.; Rayudu, R. Communication architecture for smart grid applications. In Proceedings of the 2018 IEEE Symposium on Computers and Communications (ISCC), Natal, Brazil, 25–28 June 2018.
75. Sörries, B. Communication Technologies and Networks for Smart Grid and Smart Metering by CDG 450 Connectivity Special Interest Group (450 SIG). 2013. Available online: http://www.cdg.org/resources/files/white_papers/CDG450SIG_Communication%20_Technologies_Networks_Smart_Grid_Smart_Metering_SEPT2013.pdf (accessed on 3 December 2022).
76. Safdar, S.; Hamdaoui, B.; Cotilla-Sanchez, E.; Guizani, M. A survey on communication infrastructure for micro-grids. In Proceedings of the 2013 9th International Wireless Communications and Mobile Computing Conference (IWCMC), Sardinia, Italy, 1–5 July 2013.
77. Zhang, B.; Ng, T.E.; Nandi, A.; Riedi, R.; Druschel, P.; Wang, G. Measurement based analysis, modeling, and synthesis of the internet delay space. In Proceedings of the 6th ACM SIGCOMM Conference on Internet Measurement, New York, NY, USA, 25–27 October 2006.
78. Rubin, I. Path delays in communication networks. *Appl. Math. Optim.* **1975**, *1*, 193–221. [CrossRef]
79. Nejabatkhah, F.; Li, Y.W.; Liang, H.; Ahrabi, R.R. Cyber-security of smart microgrids: A survey. *Energies* **2021**, *14*, 27. [CrossRef]
80. James, J.; Hou, Y.; Li, V.O. Online false data injection attack detection with wavelet transform and deep neural networks. *IEEE Trans. Ind. Inform.* **2018**, *14*, 3271–3280.
81. Shi, X.; Li, Y.; Cao, Y.; Tan, Y. Cyber-physical electrical energy systems: Challenges and issues. *CSEE J. Power Energy Syst.* **2015**, *1*, 36–42. [CrossRef]
82. Liang, G.; Zhao, J.; Luo, F.; Weller, S.R.; Dong, Z.Y. A review of false data injection attacks against modern power systems. *IEEE Trans. Smart Grid* **2016**, *8*, 1630–1638. [CrossRef]
83. Reddy, G.P.; Kumar, Y.V.P.; Chakravarthi, M.K. Communication Technologies for Interoperable Smart Microgrids in Urban Energy Community: A Broad Review of the State of the Art, Challenges, and Research Perspectives. *Sensors* **2022**, *22*, 5881. [CrossRef]
84. González, I.; Calderón, A.J.; Portalo, J.M. Innovative Multi-Layered Architecture for Heterogeneous Automation and Monitoring Systems: Application Case of a Photovoltaic Smart Microgrid. *Sustainability* **2021**, *13*, 2234. [CrossRef]
85. Marzal, S.; Salas, R.; González-Medina, R.; Garcerá, G.; Figueres, E. Current challenges and future trends in the field of communication architectures for microgrids. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3610–3622. [CrossRef]
86. Kim, J.-S.; So, S.M.; Kim, J.T.; Cho, J.W.; Park, H.J.; Jufri, F.H.; Jung, J. Microgrids platform: A design and implementation of common platform for seamless microgrids operation. *Electr. Power Syst. Res.* **2019**, *167*, 21–38. [CrossRef]
87. Arbab-Zavar, B.; Palacios-Garcia, E.; Vasquez, J.; Guerrero, J. Smart inverters for microgrid applications: A review. *Energies* **2019**, *12*, 840. [CrossRef]
88. Raza, N.; Akbar, M.Q.; Soofi, A.A.; Akbar, S. Study of smart grid communication network architectures and technologies. *J. Comput. Commun.* **2019**, *7*, 19. [CrossRef]
89. Ghorbanian, M.; Dolatabadi, S.H.; Masjedi, M.; Siano, P. Communication in smart grids: A comprehensive review on the existing and future communication and information infrastructures. *IEEE Syst. J.* **2019**, *13*, 4001–4014. [CrossRef]
90. Gungor, V.C.; Sahin, D.; Kocak, T.; Ergut, S.; Buccella, C.; Cecati, C.; Hancke, G.P. Smart grid technologies: Communication technologies and standards. *IEEE Trans. Ind. Inform.* **2011**, *7*, 529–539. [CrossRef]
91. Li, D.; Ho, C.N.M. A delay-tolerable master–slave current-sharing control scheme for parallel-operated interfacing inverters with low-bandwidth communication. *IEEE Trans. Ind. Appl.* **2019**, *56*, 1575–1586. [CrossRef]
92. Mazumder, S.K.; Tahir, M.; Acharya, K. Master–slave current-sharing control of a parallel DC–DC converter system over an RF communication interface. *IEEE Trans. Ind. Electron.* **2008**, *55*, 59–66. [CrossRef]
93. Lu, X.; Guerrero, J.M.; Sun, K.; Vasquez, J.C. An improved droop control method for dc microgrids based on low bandwidth communication with dc bus voltage restoration and enhanced current sharing accuracy. *IEEE Trans. Power Electron.* **2013**, *29*, 1800–1812. [CrossRef]
94. Lai, J.; Zhou, H.; Lu, X.; Yu, X.; Hu, W. Droop-based distributed cooperative control for microgrids with time-varying delays. *IEEE Trans. Smart Grid* **2016**, *7*, 1775–1789. [CrossRef]
95. Setiawan, M.A.; Abu-Siada, A.; Shahnia, F. A new technique for simultaneous load current sharing and voltage regulation in DC microgrids. *IEEE Trans. Ind. Inform.* **2017**, *14*, 1403–1414. [CrossRef]
96. Gavriluta, C.; Candela, I.; Luna, A.; Rocabert, J.; Rodríguez, P. Adaptive droop for primary control in MTDC networks with energy storage. In Proceedings of the 2013 15th European Conference on Power Electronics and Applications (EPE), Lille, France, 2–6 September 2013.
97. Alfergani, A.; Khalil, A. Modeling and control of master-slave microgrid with communication delay. In Proceedings of the 2017 8th International Renewable Energy Congress (IREC), Amman, Jordan, 21–23 March 2017.
98. Majumder, R.; Ledwich, G.; Ghosh, A.; Chakrabarti, S.; Zare, F. Droop control of converter-interfaced microsources in rural distributed generation. *IEEE Trans. Power Deliv.* **2010**, *25*, 2768–2778. [CrossRef]
99. Ci, S.; Qian, J.; Wu, D.; Keyhani, A. Impact of wireless communication delay on load sharing among distributed generation systems through smart microgrids. *IEEE Wirel. Commun.* **2012**, *19*, 24–29.
100. Saleh, M.; Esa, Y.; Mohamed, A. Effect of wireless communication delay on DC microgrids performance. In Proceedings of the 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, USA, 23–27 September 2018.
101. Miller, D.; Mirzaeva, G.; Townsend, C.D.; Goodwin, G.C. The Use of Power Line Communication in Standalone Microgrids. *IEEE Trans. Ind. Appl.* **2021**, *57*, 3029–3037. [CrossRef]

102. Majumder, R.; Bag, G.; Kim, K.-H. Power sharing and control in distributed generation with wireless sensor networks. *IEEE Trans. Smart Grid* **2012**, *3*, 618–634. [CrossRef]
103. Liang, H.; Choi, B.J.; Zhuang, W.; Shen, X. Stability enhancement of decentralized inverter control through wireless communications in microgrids. *IEEE Trans. Smart Grid* **2013**, *4*, 321–331. [CrossRef]
104. He, J.; Li, Y.W.; Blaabjerg, F. An enhanced islanding microgrid reactive power, imbalance power, and harmonic power sharing scheme. *IEEE Trans. Power Electron.* **2014**, *30*, 3389–3401. [CrossRef]
105. Han, H.; Liu, Y.; Sun, Y.; Su, M.; Guerrero, J.M. An improved droop control strategy for reactive power sharing in islanded microgrid. *IEEE Trans. Power Electron.* **2014**, *30*, 3133–3141. [CrossRef]
106. Mahmood, H.; Michaelson, D.; Jiang, J. Reactive power sharing in islanded microgrids using adaptive voltage droop control. *IEEE Trans. Smart Grid* **2015**, *6*, 3052–3060. [CrossRef]
107. Eskandari, M.; Li, L.; Moradi, M.H. Decentralized optimal servo control system for implementing instantaneous reactive power sharing in microgrids. *IEEE Trans. Sustain. Energy* **2017**, *9*, 525–537. [CrossRef]
108. Anand, S.; Fernandes, B.G.; Guerrero, J. Distributed control to ensure proportional load sharing and improve voltage regulation in low-voltage DC microgrids. *IEEE Trans. Power Electron.* **2012**, *28*, 1900–1913. [CrossRef]
109. Oureilidis, K.O.; Demoulias, C.S. Microgrid wireless energy management with energy storage system. In Proceedings of the 2012 47th International Universities Power Engineering Conference (UPEC), Uxbridge, UK, 4–7 September 2012.
110. Thale, S.; Agarwal, V.; Unni, K. CAN based control of DC-DC converters in distributed generation units operating in master slave configuration. In Proceedings of the 2012 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Bengaluru, India, 16–19 December 2012.
111. Ghalebani, P.; Niasati, M. A distributed control strategy based on droop control and low-bandwidth communication in DC microgrids with increased accuracy of load sharing. *Sustain. Cities Soc.* **2018**, *40*, 155–164. [CrossRef]
112. Prabhakaran, P.; Goyal, Y.; Agarwal, V. A novel communication-based average voltage regulation scheme for a droop controlled DC microgrid. *IEEE Trans. Smart Grid* **2017**, *10*, 1250–1258. [CrossRef]
113. Silva, W.W.A.; Oliveira, T.R.; Donoso-Garcia, P.F. An improved voltage-shifting strategy to attain concomitant accurate power sharing and voltage restoration in droop-controlled DC microgrids. *IEEE Trans. Power Electron.* **2020**, *36*, 2396–2406. [CrossRef]
114. Zhao, X.; Yang, L. An Improved Droop Control Method to Improve Bus Voltage and Ensure Accurate Proportional Load Power Sharing in Isolated DC Microgrids. In Proceedings of the 2020 12th IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Nanjing, China, 20–23 September 2020.
115. Simpson-Porco, J.W.; Shafiee, Q.; Dorfler, F.; Vasquez, J.C.; Guerrero, J.M.; Bullo, F. Secondary frequency and voltage control of islanded microgrids via distributed averaging. *IEEE Trans. Ind. Electron.* **2015**, *62*, 7025–7038. [CrossRef]
116. Lu, X.; Yu, X.; Lai, J.; Guerrero, J.M.; Zhou, H. Distributed secondary voltage and frequency control for islanded microgrids with uncertain communication links. *IEEE Trans. Ind. Inform.* **2016**, *13*, 448–460. [CrossRef]
117. Shen, X.; Shuai, Z.; Huang, W.; Chen, Y.; Shen, J. Power Management for Islanded Hybrid AC/DC Microgrid with Low-bandwidth Communication. *IEEE Trans. Energy Convers.* **2021**, *36*, 2646–2658. [CrossRef]
118. Liu, S.; Wang, X.; Liu, P.X. Impact of communication delays on secondary frequency control in an islanded microgrid. *IEEE Trans. Ind. Electron.* **2014**, *62*, 2021–2031. [CrossRef]
119. Deng, S.; Chen, L.; Zheng, T.; Guo, Y.; Mei, S. Distributed Secondary Frequency Control for Microgrids Under Weak Communication Conditions. In Proceedings of the 2020 IEEE Power & Energy Society General Meeting (PESGM), Montreal, QC, Canada, 2–6 August 2020.
120. Lai, J.; Zhou, H.; Lu, X.; Liu, Z. Distributed power control for DERs based on networked multiagent systems with communication delays. *Neurocomputing* **2016**, *179*, 135–143. [CrossRef]
121. Lai, J.; Lu, X.; Yu, X.; Yao, W.; Wen, J.; Cheng, S. Distributed multi-DER cooperative control for master-slave-organized microgrid networks with limited communication bandwidth. *IEEE Trans. Ind. Inform.* **2018**, *15*, 3443–3456. [CrossRef]
122. Shi, M.; Chen, X.; Zhou, J.; Chen, Y.; Wen, J.; He, H. Frequency Restoration and Oscillation Damping of Distributed VSGs in Microgrid With Low Bandwidth Communication. *IEEE Trans. Smart Grid* **2020**, *12*, 1011–1021. [CrossRef]
123. Thale, S.S.; Agarwal, V. Controller area network assisted grid synchronization of a microgrid with renewable energy sources and storage. *IEEE Trans. Smart Grid* **2015**, *7*, 1442–1452. [CrossRef]
124. Haripriya, M.; Vasanthanayaki, C. CAN based grid synchronisation technique of a micro grid with Renewable source. In Proceedings of the 2017 International Conference on Innovations in Green Energy and Healthcare Technologies (IGEHT), Coimbatore, India, 16–18 March 2017.
125. Dörfler, F.; Simpson-Porco, J.W.; Bullo, F. Breaking the hierarchy: Distributed control and economic optimality in microgrids. *IEEE Trans. Control. Netw. Syst.* **2015**, *3*, 241–253. [CrossRef]
126. Vandoorn, T.L.; Vasquez, J.C.; De Kooning, J.; Guerrero, J.M.; Vandevelde, L. Microgrids: Hierarchical control and an overview of the control and reserve management strategies. *IEEE Ind. Electron. Mag.* **2013**, *7*, 42–55. [CrossRef]
127. Lu, L.-Y.; Chu, C.-C. Consensus-based droop control synthesis for multiple DICs in isolated micro-grids. *IEEE Trans. Power Syst.* **2014**, *30*, 2243–2256. [CrossRef]
128. Eskandari, M.; Li, L.; Moradi, M.H. Improving power sharing in islanded networked microgrids using fuzzy-based consensus control. *Sustain. Energy Grids Netw.* **2018**, *16*, 259–269. [CrossRef]

129. Setiawan, M.A.; Shahnia, F.; Rajakaruna, S.; Ghosh, A. ZigBee-based communication system for data transfer within future microgrids. *IEEE Trans. Smart Grid* **2015**, *6*, 2343–2355. [CrossRef]
130. Chen, Y.-K.; Wu, Y.-C.; Song, C.-C.; Chen, Y.-S. Design and implementation of energy management system with fuzzy control for DC microgrid systems. *IEEE Trans. Power Electron.* **2012**, *28*, 1563–1570. [CrossRef]
131. Norman, C.; Chan, J.Y.; Lau, W.H.; Poon, J.T.; Lai, L.L. Real-time power-quality monitoring with hybrid sinusoidal and lifting wavelet compression algorithm. *IEEE Trans. Power Deliv.* **2012**, *27*, 1718–1726.
132. Huang, J.; Wang, H.; Qian, Y.; Wang, C. Priority-based traffic scheduling and utility optimization for cognitive radio communication infrastructure-based smart grid. *IEEE Trans. Smart Grid* **2013**, *4*, 78–86. [CrossRef]
133. Huang, Y.-K.; Pang, A.-C.; Hsiu, P.-C.; Zhuang, W.; Liu, P. Distributed throughput optimization for zigbee cluster-tree networks. *IEEE Trans. Parallel Distrib. Syst.* **2011**, *23*, 513–520. [CrossRef]
134. Tung, H.Y.; Tsang, K.F.; Chui, K.T.; Chi, H.R.; Hancke, G.P.; Man, K.F. The generic design of a high-traffic advanced metering infrastructure using ZigBee. *IEEE Trans. Ind. Inform.* **2013**, *10*, 836–844. [CrossRef]
135. Tseng, C.H. Coordinator traffic diffusion for data-intensive Zigbee transmission in real-time electrocardiography monitoring. *IEEE Trans. Biomed. Eng.* **2013**, *60*, 3340–3346. [CrossRef]
136. Ma, J.; Yuan, L.; Zhao, Z.; He, F. Transmission loss optimization-based optimal power flow strategy by hierarchical control for DC microgrids. *IEEE Trans. Power Electron.* **2016**, *32*, 1952–1963. [CrossRef]
137. Eskandari, M.; Li, L.; Moradi, M.H.; Wang, F.; Blaabjerg, F. A control system for stable operation of autonomous networked microgrids. *IEEE Trans. Power Deliv.* **2019**, *35*, 1633–1647. [CrossRef]
138. Eskandari, M.; Li, L.; Moradi, M.H.; Siano, P.; Blaabjerg, F. Simultaneous reactive power sharing141 and voltage regulation in an autonomous networked microgrid. *IET Gener. Transm. Distrib.* **2019**, *14*, 1366–1377. [CrossRef]
139. Lu, X.; Lai, J.; Yu, X.; Wang, Y.; Guerrero, J.M. Distributed coordination of islanded microgrid clusters using a two-layer intermittent communication network. *IEEE Trans. Ind. Inform.* **2017**, *14*, 3956–3969. [CrossRef]
140. Eskandari, M.; Li, L.; Moradi, M.H.; Siano, P.; Blaabjerg, F. Active power sharing and frequency restoration in an autonomous networked microgrid. *IEEE Trans. Power Syst.* **2019**, *34*, 4706–4717. [CrossRef]

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