Multiple Microgrids

A Review of Architectures and Operation and Control Strategies

Saha, Diptish; Bazmohammadi, Najmeh; Vasquez, Juan C.; Guerrero, Josep M.

Published in:
Energies

DOI (link to publication from Publisher):
10.3390/en16020600

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

energies

Review

Multiple Microgrids: A Review of Architectures and Operation and Control Strategies

Diptish Saha *, Najmeh Bazmohammadi, Juan C. Vasquez and Josep M. Guerrero *

Center for Research on Microgrids (CROM), AAU Energy, Aalborg University, 9220 Aalborg, Denmark
* Correspondence: dsa@energy.aau.dk (D.S.); joz@energy.aau.dk (J.M.G.)

Abstract: Several issues of individual microgrids (MGs) such as voltage and frequency fluctuations mainly due to the intermittent nature of renewable energy sources' (RESs) power production can be mitigated by interconnecting multiple MGs and forming a multi-microgrid (MMG) system. MMG systems improve the reliability and resiliency of power systems, increase RESs' utilization, and provide cost-efficient power to the consumers. This paper provides a comprehensive review of the conducted studies in the MMG area summarizing different operational goals and constraints proposed in the literature for efficient operation of MMGs. Besides, different MMG architectures in which the MGs can be interconnected to form an MMG system and their characteristics are discussed. This paper also provides a state-of-the-art review on different control strategies and operation management methodologies for the operation and control of MMGs in centralized, decentralized, distributed, and hierarchical structures. A classification of different sources of uncertainties in an MMG system and proposed uncertainty handling strategies are also presented. Finally, the paper is complemented with a discussion of the main open issues and future research directions of MMG systems.

Keywords: microgrid cluster; energy management system; multi-microgrid architectures; interconnected microgrids; multi-microgrid operation and control

Citation: Saha, D.; Bazmohammadi, N.; Vasquez, J.C.; Guerrero, J.M. Multiple Microgrids: A Review of Architectures and Operation and Control Strategies. *Energies* **2023**, *16*, 600. https://doi.org/10.3390/en16020600

Academic Editor: Antonio Cano-Ortega

Received: 7 December 2022
Revised: 25 December 2022
Accepted: 29 December 2022
Published: 4 January 2023

1. Introduction

The energy sector significantly contributes to global CO_2 emissions, accounting for around 14 Gigatons (Gt) of CO_2 [1] in 2019. Fossil fuels were the primary source of energy in the past century, and the ever-increasing energy demand was responsible for 38 Gt of CO_2 emissions in 2018 [1]. It is evident that, as we move towards a more electric society, our energy needs will increase, and more sustainable alternatives to produce energy will be required.

In this regard, renewable energy sources (RESs) have attracted a great deal of attention during the recent decade. Recently published reports show that 27% of the global energy demand was fulfilled by RESs in 2019. Moreover, RESs contributed to around 34% of the world's installed energy generation capacity in 2019 [2]. There are various types of renewable sources of energy such as solar and wind power, biogas, bioliquids, geothermal, hydropower, solid biomass, tidal, wave, and ocean energy. However, in the renewable electricity sector, growth is mainly driven by solar and wind power. Among the RESs, solar power system technologies are the fastest-growing renewable source, accounting for approximately 55% of all the newly established renewable energy technologies in 2019, while the wind power contribution was around 33% of the remaining renewable energy installed capacity [2].

In recent years, the electricity grids have undergone a big transformation due to integrating a large number of distributed energy resources (DERs). Since the power from renewable-based DERs is highly dependent on environmental factors such as solar irradiance, ambient temperature, and wind velocity, energy storage systems (ESSs) such as batteries are commonly deployed to smooth out power fluctuations [3,4]. According to the

U.S. Department of Energy, a microgrid (MG) is defined as 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 and disconnect from the grid to enable it to operate in both grid-connected or islanded mode [5]. Standalone MGs can provide power to rural areas, off-grid systems, where it is either difficult, expensive, or impossible to establish a connection with the main power system, electric ships [6–8], more electric aircraft [9–12], and space MGs and satellite systems [13].

The conventional grid is a central power dispatch system where large power generation systems supply the loads through long power transmission and distribution lines. The central power generation makes the dispatch system unreliable as any disturbance or fault might result in the disconnection of many critical loads. Upon the introduction of the MG concept, the conventional power system will be transformed into a distributed and more flexible power system, where MGs can be automatically isolated from the main grid to prevent from propagating the disturbance or affecting the normal operation of other parts of the system. However, these self-governing distributed systems demand the development of an advanced control system. The control of MGs consists of the control of power converters, power-sharing among the distributed generator (DG) units, controlling the voltage and frequency (at the point of common coupling (PCC)) for grid-connected MGs, and charging and discharging of ESSs, among others. Furthermore, the MG controller has to be intelligent enough to make decisions about the switch over from (to) islanded to (from) grid-connected modes of operation. A significant amount of work has been performed by researchers to establish the required control infrastructure for the operation of MGs. The control of different types of power converters for coordinating the smooth operation of an MG is discussed in [14]. The optimal operation of an MG is achieved in [15] by optimizing the usage of DG units and power exchange with the main grid. In [16], load balance among three phases of a four-wire MG is maintained using single-phase converters connected among the phases. In grid-connected mode, the voltage and frequency of the MG are dictated by the main grid and maintained within the permissible range [17]. On the other hand, islanded MGs become vulnerable to blackouts due to the fluctuations in power from RESs and loads, thereby voltage and frequency disturbances [17]. Droop-based coordinated control of the RESs and ESSs is discussed in [18,19]. Other aspects of MG control are addressed in [20–24].

The reduced number of synchronous generators and the massive incorporation of inverter-based RESs resulted in the reduced inertia of power systems [25] and the instability and vulnerability of MGs. To resolve these issues, instead of always connecting an MG to the main grid, the interconnection of MGs as a multi-microgrid (MMG) network is suggested as a promising solution to enhance the stability and power quality of the power system [4,25,26]. In addition, the interconnection of MGs to form an MMG system facilitates more-efficient energy utilization, especially renewable energy, through sharing of resources among MGs [4]. As a result, the reliability of individual MGs and the entire power system will be increased. The connections among MGs can be also altered to further improve the reliability and stability of MGs [25,27]. However, there are practical challenges that need to be appropriately dealt with. The MMG concept also enhances the resiliency of MGs. In the case of low-probability, high-impact extreme events such as natural disasters, an MMG system is capable of supporting the operation of the main grid, as well as its MGs to maintain their main functionalities. If the power source of an MG is lost, other MGs can supply the critical loads of the damaged MG for a period of time or until the damaged MG is restored to normal operation [4,25]. Furthermore, from a top-down point of view, in case the electricity system is undergoing a faulty operation, the functional sections of the grid can be sectionalized to restore electricity supply. The sectionalized system can act as an MMG through synchronizing different sections for coordinated operation [25]. In an MMG system, the interconnection of closely located MGs can reduce the power transmission distances and, thereby, the power losses. The reduced transmission losses and more-efficient utilization of power resources through power sharing can help to provide more cost-efficient power to consumers. MGs in an MMG system might be of various types such as residential, commercial, or industrial MGs with different load profiles. The complementary nature of the generation and load profiles of MGs in an MMG system can support their efficient collaboration and power sharing, thereby enhancing the RESs utilization [4]. Along with the many benefits provided by MMGs, various challenges and complexities are involved, which can be classified into economic, control, and operation management, protection, and communication issues. Furthermore, as there might be multiple stakeholders and mixed ownership in an MMG system, data privacy and financial issues might impose new challenges. In addition, the interoperability of multi-vendor controllers and standardization process difficulties need to be addressed [4,25].

This paper presents an overview of different MMGs' architectures and power transmission technologies. Besides, various control and energy management techniques of MMGs reported in the literature in different centralized, decentralized, distributed, and hierarchical structures are explored, and their advantages and disadvantages are discussed. An MMG system can have several operating goals at the MMG and MG levels due to the different attitudes of MGs owners. Besides, the operation of the MMG system is subject to several technical and operational limits, which are included as constraints while designing the operating algorithm of the MMG systems. This paper provides an overview of the MMGs operational objectives reported in the literature and discusses several technical and operational constraints considered in recent publications. Further, this paper provides a thorough discussion of different uncertainty sources in an MMG system and the proposed uncertainty handling techniques.

The rest of the paper is organized as follows. Different architectures of MMG systems are discussed in Section 2, and Section 3 discusses the MMG architectures according to the line and interconnection technologies, while the operational goals and constraints of MMGs are explored in Sections 4.1 and 4.2, respectively. Different control structures, the energy management system (EMS) of MMGs, and different techniques to handle the uncertainties in an MMG system are presented in Sections 5 and 6, respectively. The challenges involved in further developing MMGs are discussed in Section 7. Finally, concluding remarks are given Section 8.

2. Multi-Microgrid Architectures

There are different ways in which MGs can be connected to form an MMG system. While in a single MG, RESs, ESSs, and loads are connected to a single PCC, MMGs have multiple PCC and PCC locations. Different names are also used for MMGs including nested MGs [25], networked MGs [4], interconnected MGs [28], and coupled MGs [26]. However, all of them convey the same concept of interconnecting single MGs with each other.

The most-common way of forming an MMG system is directly connecting the MGs to the main grid. In this architecture, different MGs are directly connected to the main grid, and there is no direct power line among MGs. This architecture is in the form of a star and is known as a radial topology [28] and parallel-connected MGs with an external grid [3], as shown in Figure 1a. In the grid-connected mode, the EMS is comparatively simple to implement as there is only one single power line connecting the MGs to the main grid. An MG with energy surplus/shortage can sell/buy its energy to/from the main grid [28]. In case of any disturbance in the upstream network, MGs can disconnect from the main grid and switch to the islanded mode. However, there will also be no connection to other MGs [3]. Expanding and connecting new MGs to this architecture is relatively straightforward, if the MMG control and communication system can support new MGs. As there are no direct power lines among the MGs, the energy exchange takes place through the main grid power line. Hence, the main grid power line should have the required capacity to support the power flow to an MG and also in between the MGs. Sharing of energy among the MGs in this architecture may create power congestion and thermal stress in the power line of the main grid. The operator has to ensure the safe operation and maintain the reliability of the network buses and the main grid [28].

To have a direct power exchange capability between the MGs, along with their connection to the main grid, the adjacent MGs are directly connected to each other in a daisy-chain topology [28], as shown in Figure 1b. This topology enables an MG to exchange power with the adjacent MGs (in the case it is allowed by the system regulators), in addition to the main grid, which increases the reliability of the MMG system. However, the technical challenges of coordinating different MGs need to be addressed. A similar topology named parallel MGs on a single distribution feeder is discussed in [4], where two adjacent MGs are connected by an exclusive power line and are also connected to the main grid. Among several serially connected MGs, if only one of them is connected to the main grid, the architecture is called a serial MGs on single distribution feeder [4], as shown in Figure 1c. Moreover, in an interconnected MGs on multiple distribution feeders architecture, serially interconnected MGs are separately connected to different distribution feeders, as shown in Figure 1d [4]. The implementation of EMS is comparatively complex in these architectures as the power can be transferred from both the main grid and the neighboring MGs [28]. These MMG architectures have various operating switches, so the configuration of the MMG and MMG clusters can change dynamically [4]. Therefore, the EMS may have to consider several architectures while scheduling the energy exchange for the stability of the MMG and the grid [4]. The MGs' operations in these MMGs are strongly coupled, and their energy schedules are more connected [28]. These MMG architectures are more reliable than the radial topology as the MGs will have several alternatives for power exchange in case of faults or natural calamities.

To further increase the energy exchange capability among MGs in an MMG system, all MGs in a radial topology are connected by direct power lines, as can be seen in Figure 1e, which is called a mesh topology [28]. A similar topology named grid series interconnected MGs [3] (Figure 1f) is also introduced in which "*n*" MGs can be interconnected. This MMG system must maintain the required voltage and frequency, as it is not connected to an external grid. In this topology, the faulty section of the MMG system can be disconnected, and external support to the sub-clusters in the MMG system is not completely lost. Therefore, this topology can have better performance during the off-grid operation mode. Instead of connecting all the MGs, the MGs can also be connected to form a ring, as shown in Figure 1g, which is called the ring formation [3]. In this architecture, the power exchange between two MGs may take place through inter-mediator MGs, and the power line connecting the MGs must be capable of transferring the required energy. In [3], a topology named mixed parallel-series connection (Figure 1h) is presented, which is a combination of parallel MGs on a single distribution feeder and serial MGs on a single distribution feeder [4]. In this topology, there is the possibility of power exchange among the connected MGs if the MMG is not connected to the main grid. The MMGs that can operate in both grid-connected and islanded modes can form a cluster of MGs, which are called MG clusters [3], as shown in Figure 1h. These MG clusters have at least one connection to the main grid [3] and can connect to the main grid at the time of need. In the mesh topology [28], and grid series-interconnected MGs [3], the reliability of the MMG system increases due to the ability of direct power exchange between the MGs, but at the expense of the increased establishment cost of power lines and control complexity. However, there is the risk of fault propagation among MGs. Thus, a trade-off can be made among reliability, establishment cost, and control complexity. In the mesh architecture, the MMG system can disconnect faulty MGs to restrict the voltage–frequency-related disturbances to the faulty MG and ensure the reliable operation of the rest of the MG cluster.

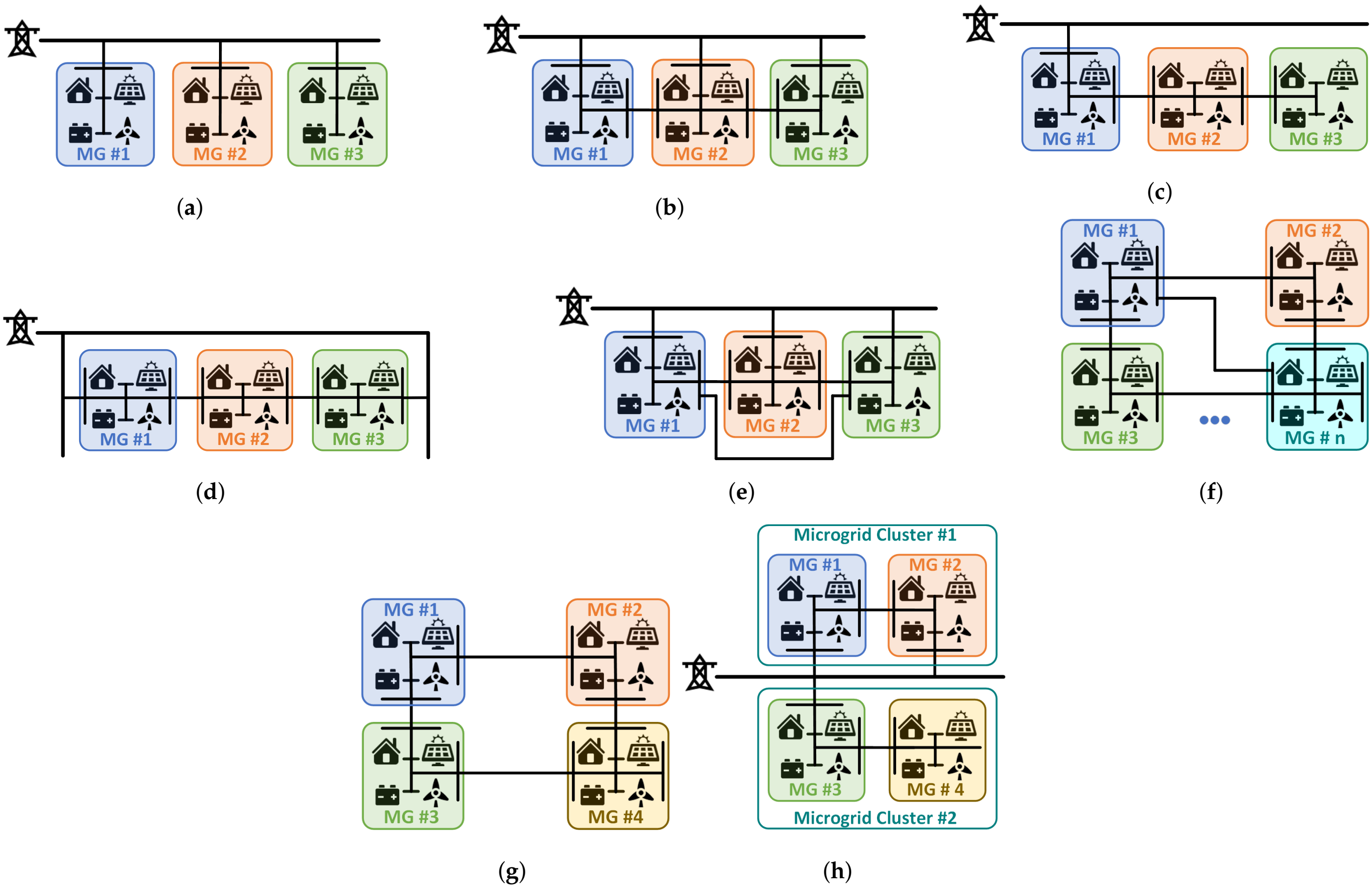

Figure 1. Different architectures of MMGs. (**a**) Radial topology [28], parallel-connected MGs with an external grid [3]. (**b**) Daisy-chain topology [28]. (**c**) Serial MGs on a single distribution feeder [4]. (**d**) Interconnected MGs on multiple distribution feeders [4] (**e**) Mesh topology [28]. (**f**) Grid series-interconnected MGs [3]. (**g**) Ring formation [3]. (**h**) Mixed parallel-series connection [3].

It is worth mentioning that the MMG system does not always maintain the same architecture, but rather, the MMG architecture encounters frequent changes due to the connection and disconnection of MGs from the MMG system or the MG cluster from the main grid. These connections and disconnections are due to disturbances or support the MGs' needs in an MMG system. In this sense, advanced robust control techniques are required to establish energy management, power sharing, disturbance and fault handling, and uncertainty mitigation in MMGs. A comprehensive review of the recent advances in the control and operation management of MMGs will be presented in the following sections. Table 1 presents a review of the commonly used MMG architectures.

Table 1. Review of MMG architectures reported in the literature.

MMG Architecture	Ref.
Radial	[29–83]
Daisy-chain	[84,85]
Mesh	[86–89]
Ring	[80,90–96]
Serial	[97,98]
Mixed parallel-series connection	[99–102]
Serial MGs on a single distribution feeder	[103,104]
Parallel MGs on a single distribution feeder	[105]
Interconnected MGs on multiple distribution feeders	[106]

3. AC, DC, and Hybrid AC–DC Interconnection Technologies

There are different MMG architectures depending on the line and interconnection technologies [3]. The line technology of an MMG system can be AC, DC, or AC–DC [3]. The AC transmission and distribution system is a very mature technology and is widely used in residential, commercial, and industrial areas. Over the years, AC three-phase systems have shown a higher efficiency and lower cost compared to single-phase systems [3]. Load sharing among MGs in an AC MMG system is discussed in [43,91]. On the other hand, DC MGs eliminate the synchronization problems, the usage of bulky transformers, and harmonic and power quality issues while facilitating the parallel operation of DERs. In the case of offshore renewable energy technology such as offshore wind farms, high voltage DC (HVDC) transmission is widely used [3]. DC MGs are interconnected to form DC MG clusters in [107], and their stability is analyzed considering the effect of constant power loads and interconnecting line impedance. Load sharing with voltage improvement of two interconnected DC MGs is discussed in [108]. Energy exchange in a DC energy network connecting multiple houses is investigated in [109] using a peer-to-peer architecture. A fast fault detection–protection scheme with simultaneous control of interconnected DC MGs is designed in [110]. To exploit the benefits of both AC and DC technologies, various hybrid AC–DC MGs are also investigated by researchers. The EMS and optimal scheduling strategy of a hybrid AC–DC MMG system are discussed in [93,111], respectively.

Regarding the interconnection technology, the authors of [3] classify the MMG architectures based on the interconnection of MMGs using either conventional power transformers or power converters. A conventional power transformer can be used to interconnect two AC MGs, while a power converter must be used in the case of interconnecting a hybrid MG. Power transformers are more reliable and less expensive than power converters and provide electrical isolation. However, power transformers are less controllable for the energy and power sharing requirements of an MMG system [3]. In this case, the power exchange among the MGs or an MG and the main grid cannot be directly controlled. Power exchange takes place depending on the generated power of the MGs or the main grid at the PCC [43]. Furthermore, the voltage and frequency of one MG may be dictated by the main grid or other MGs [43]. Hence, the MG becomes vulnerable to disturbances at the main grid or other MGs. On the other hand, power electronic converters are more expensive, but provide a higher control flexibility for the power management of MMGs [3]. The MG's controller can send control signals to the local interconnecting power converters for appropriate power exchange, thereby providing the capability to regulate power generation and power exchange independently in an MG [43]. Solid-state transformers or isolated converters can provide the required electrical isolation while using power converters for interconnecting MGs.

4. Multi-Microgrid Operation and Control

An MMG system is formed by grouping of the individual MGs. Similar to a single MG comprising generation and consumption units, an MMG system consists of MGs, which act as loads, while they cannot supply their own power demand and are dependent on external power sources, which might be due to the deviation of the power generation of RESs from expected values, a fault in the MG, or operational purposes such as economic/environmental goals. The MGs that share their surplus energy with load MGs can be considered as power-generating units. This similarity in the operation of an MG and an MMG system represents the applicability and expandability of the MGs' control to MMG structures. According to the hierarchical control structure of MGs, the control of MGs can be organized into three layers, namely primary, secondary, and tertiary [112]. The primary layer is responsible for maintaining the reference voltage and frequency by controlling the DER units. The active and reactive power sharing between various DG units, power converters' control, and their parallel operation are also managed by the primary-level controllers. The voltage and frequency deviations resulting from the load and generation changes in the MG are adjusted by the secondary-level controllers. Furthermore, while connecting the MG to the external grid, the secondary-level controllers are responsible for the phase, voltage, and frequency synchronization [4,112]. The tertiary-level controllers control the flow of power and energy between the external grid and the MGs in the grid-connected mode [112], and are responsible for energy management, economic dispatch, and the optimal power flow of the MGs [4]. The primary layer has a time scale in the order of microseconds or milliseconds, while the secondary and tertiary controllers' time scales are in the order of seconds and minutes/hours, respectively. Therefore, the controller time scale increases from the lower-level controllers to the upper-level controllers. Similarly, in the case of an MMG, the operational time scale of the controllers at the MMG level may be higher than those at the MG level. Reliable communication links are required to be established among multiple controllers to communicate control commands and information.

The control objectives of an MMG system can be multifarious including power quality enhancement, economical operation of the MMG system, energy sharing among the MGs, and demand management, to name a few. These control objectives are fulfilled by the controllers at different control levels. Demand management is a critical control objective of the islanded MGs, as well as MMG systems to maintain the system stability.

In the following, the operational goals and constraints proposed in the literature for the efficient operation of MMGs are thoroughly reviewed and discussed.

4.1. Multi-Microgrid Operational Goals

MMG systems are comprised of multiple MGs following several goals at different MG and MMG levels. Hence, MGs' operation including decisions about power generation/consumption, energy storage, and power exchange with neighboring subsystems or the main grid are specified following their operating objectives. In what follows, common objective functions that have been used for the operation management of MMG systems are introduced:

- Voltage–frequency profile improvement: The power from RESs in MGs are fluctuating in nature due to the continuously changing weather conditions, while there are also abrupt changes in the consumers' demand. Frequent changes in power production and demand have a negative impact on maintaining the voltage and frequency stability of MGs. Furthermore, due to the vast integration of power electronic converters in MGs and reduced inertia, a major disturbance in the voltage–frequency of an MG can destabilize the MG, which can result in the MG's or even the MMG system's blackout [3,91]. Several control techniques are reported to use ESSs or sharing power among MGs or with the main grid to maintain the stability in case of voltage–frequency disturbances [43,44]. Voltage–frequency oscillations also occur due to faults in the power lines [92], the variation of the MMG architecture, and a change in the mode of operation (from grid-connected to islanded mode and vice versa) [90,104].
- Operation cost minimization: The operational cost of an MMG is mainly decreased by reducing the dependency of the MG on fossil-fuel-based power production and the main grid. RESs' power generation cost is relatively low, while they also impose a lower transmission cost due to less losses and relatively lower transmission distance. In general, the operational cost (the MG's revenue can be considered as a negative cost) of MMGs involves the power generation cost of dispatchable generators such as micro-turbines (MTs) [42,51,74], the operation and maintenance cost of RESs [30,32,35,36,113,114] and ESSs (batteries) [36,55,74,113–115], the cost of selling (purchasing) energy to (from) the main grid by the MMG system [42,47,55,70,74], the cost of selling (purchasing) energy to (from) the distributed system operator (DSO) by MGs [42,47,51,55,70,74], and the energy selling of MGs or the MMG to consumers [42,51]. The demand-management-related cost is also considered in the operational cost of MMGs by including the cost of load shedding [31,32,113] and the cost related to the increase or decrease in the power of controllable loads [56,115], which might be represented as the cost of consumer satisfaction or dissatisfaction in the case

of load shedding or load shifting [54,66,79,94]. Other costs such as the communication cost [31], the cost of RESs or DGs power curtailment [47,56,114,115], and the cost of exhaust gas emissions [36,114,116] are also considered in the operational costs.

- Maximization of RESs' utilization: To minimize the environmental impacts of electricity generation in an MMG system, the dependency of MGs on the conventional fuel-based energy resources must be reduced. To do so, the utilization of RESs needs to be maximized by either installing more RESs or sharing the surplus power generated from the RESs of an MG with other MGs in an MMG system [3,94]. In this sense, prioritizing the RES-based MGs [94,117], penalizing energy exchange with the main grid [53], coordinating the operation of RESs and electric vehicles (EVs) [84], and including the emission cost in the objective function [36,114,116] are among the proposed strategies. Different forms of incentives have been also proposed to encourage energy trading [54], prioritizing MGs that previously provided more reliable power to the neighboring MGs [118], and MGs having larger RESs and storage capacity for participation in the energy exchange [117].
- Transmission loss minimization: One of the objectives of MMG systems is to reduce power losses by supplying the loads using nearby resources [28,106]. Considering closely located MGs in an MMG system, power exchanges between MGs normally impose less power loss compared with power exchange with the main grid [28,66,93].
- Reliability improvement: The reliability of an MMG system is defined as the capability of providing continuous and steady electrical energy to consumers [4,25]. In an MMG system, the MGs have the possibility to exchange energy with other MGs and the main grid and sharing their loads, which increase the reliability of energy supply [65,81]. In emergency conditions, the MMG system can also allow sharing of ESSs to supply the critical loads of other MGs [25,68,117]. In the case of power deficit, the MG operator might need to implement outage management strategies that may lead to load curtailments to support critical loads. The authors of [34] discuss indices such as average energy not supplied (AENS) and system-average interruption duration index (SAIDI), which are dependent on the number of load nodes and customers. Similarly, in [96], loss of load (LOL) is considered as the reliability index. Furthermore, energy index reliability (EIR) is calculated using the expected power not served (EPNS) and load power. In [119], reliability cost is considered in the cost function while evaluating reliability in both grid-connected and islanded modes as connected mode energy not supplied (CENS) and islanded mode energy not supplied (IENS). The CENS depends on the loads affected during faults and fault duration, while the IENS depends on the loads interrupted in the islanded mode and the number of interrupted load points.
- Resiliency improvement: The resiliency of an MG is defined as the adequate preparation, adaptation, and resistance to a high-impact, low-probability event and recovering rapidly from the disruption [4,25]. Short-term aspects of resiliency include the readiness of the MG to face and withstand disruptions and to restore the MG after an interruption [68]. In extreme operating conditions, the MG's operator schedules the power supply following the priority of the critical loads and the available power resources [60,68,81,120]. In the long term, the MG operator can learn from previous events to adapt the operating strategy to deal with unprecedented situations [68]. Resiliency indices during an emergency event are proposed in [60,68,120] based on the expected curtailed load in a time duration and loads' priorities, respectively.
- Data privacy: For operation management, control, and power sharing in MMGs, the information of the energy production, consumption, and storage of MGs needs to be shared with the MMG operator. These data are vulnerable to theft and attacks, which raises privacy concerns for the MGs' operators and consumers. In this sense, one of the main operating goals of the MGs' operators is to minimize the information sharing. With this consideration, it is proposed that, instead of sharing the production and consumption profiles in their raw forms, MGs share their net energy profile, i.e., the energy demand subtracted from the energy production (positive/negative in the

case of power surplus/shortage). Hence, the complete generation and load profile of the MGs is not shared with the MMG's operator or other MGs, while the surplus and shortage of energy in MGs can be communicated [51].

4.2. Multi-Microgrid Technical and Operational Constraints

Along with several operational objectives, the control algorithms also need to consider the safe operating limits of the MGs and MMGs equipment and assets. The common constraints considered for the operation management of MMGs are presented in the following. It is worth noticing that all of these constraints are not specific to MMG systems. As the control and operation management of an MMG system include the interactions within and between MGs, some of the constraints apply to single MGs as well:

- RESs or DGs power capacity: DGs such as MTs and diesel generators have physical limitations on their output power [29,33,60,74] and the power ramp up/down rate [68,71,77,95] to comply with the safe operation requirements and prevent performance degradation. Moreover, the output power of RESs is dependent on the weather conditions, e.g., solar irradiance, ambient temperature, and wind speed. Besides, the committed amount of energy from RESs at a particular time must be considered [36].
- Power or energy balance: To maintain the stability of the MG and the MMG system, the generated power and demand must be balanced at all times; otherwise, voltage–frequency instability issues will arise. Hence, the stability of MGs must be considered while scheduling power exchange within the MMG system and between MGs and the main grid [61,94,116,121]. For the stable operation of MMGs, local MG controls are required to balance power generation and consumption considering power exchange with the main grid and adjacent MGs [42,47,68,101].
- ESS limits: To mitigate the power fluctuations of RESs, the integration of ESSs is of vital importance. In this regard, the surplus (deficit) power is stored in (supplied by) ESSs to maintain the voltage–frequency stability of the MG and the MMG system. All kinds of ESSs have technical limitations on their charging/discharging rates, their efficiencies, and their maximum/minimum storage capacity. Batteries are the most commonly used ESSs in MGs and as the shared storage facility among MGs in an MMG system. For safe battery operations, several constraints are put in place to prevent violating charging/discharging limits [29,33,74,77], avoid simultaneous charging and discharging [34,36,47,74,113], and avoid over-charging/discharging of batteries [54,74]. In [29,68,77,79], batteries are also not allowed to charge (discharge) to their maximum (minimum) power storage capacity so that they can be charged (discharged) in case of an emergency. Moreover, the charging and discharging efficiency of batteries are commonly considered [38,61,93,94]. Furthermore, terminal constraints might be included to ensure that the state of charge (SOC) of batteries is at the desired level at the end of the scheduling horizon [36,37].
- Interconnecting power line capacity: The power lines interconnecting MGs and connecting them with the main grid have physical limits on the maximum power that can be transmitted considering their thermal capacity. Depending on the type and diameter, different conductors have different power-handling capabilities. Moreover, the thermal limits of the conductors depend on the material of construction and the resistance of the material. For the exchange of power, the scheduling algorithms must restrict the amount of power that can be transferred through the interconnecting power lines for the safe operation of the MGs and MMG systems [68,77,79,122]. The thermal limits of the power line are also considered in [98]. In the case of a hybrid AC–DC MG, a fault or damage in the power line connecting the interconnecting power converters may affect the operation of the MMG, which is taken into account in [87] using uncertainty sets.
- PCC and MGs bus voltage: The interconnection and the power exchange between the main grid and MMG system or among MGs in an MMG system are established through the PCC of MGs. All the energy resources and loads of an MG are connected

to the PCC or to some extended line of the PCC. Hence, the PCC or the MGs bus voltage must be kept within the permissible limits to ensure the safe operation of the MMG system [42,120].

- Load shedding/Load management: Under emergency conditions, it might not be possible to supply all MGs' loads due to the stability issues of the MMG system. Thus, the MG operator is responsible for shifting or shedding a part of loads to maintain the stability of the system. The constraints limiting the amount of flexible loads that can be disconnected are considered in [47,56,81,115], while the constraints for shifting the loads to other time slots with sufficient power supply can be found in [47,76,123].
- Interconnecting converter or equipment power-handling capability: In an MMG system, several MGs are interconnected through isolating equipment, circuit breakers, power transformers, and power converters. These interconnecting equipment and converters have a specific power handling capability, which can affect the operation of MGs and the power exchange in the MMG system. In the case of AC–DC hybrid MMG systems, the constraints limit the amount of power that can be transferred from the AC bus to the DC bus through the bidirectional interconnecting power converters [93]. The power converters can act as reactive power generators limited by their size and capacity [32]. The power-handling capacity of transformers limits the maximum power exchange with the main grid at any time instant [113].
- Power exchange: The transmission of a large amount of power within a particular time slot might cause voltage–frequency-related instability in a perfectly stable grid [81,115,123]. Therefore, there are constraints that limit the total amount of power that is exchanged with other MGs or the main grid, which encourage self-dependency, bring equal opportunity of power exchange for all MGs, and reduce dependency on a single MG [30,46,47,64,67]. In some cases, the scheduled and actual power exchange between the MGs might differ due to several practical issues. Hence, there are limitations that restrict the deviation of actual power exchange from the scheduled value [81]. Furthermore, there are constraints that ensure only the surplus power from MGs is sold to other MGs or the main grid [86], and the energy bought from the main grid or other MGs should not be further traded [81,86], or it is not allowed to sell and buy energy at the same time [29,37,47].
- Energy trading prices: In an MMG system, there might be different MGs owners that support the MMG's operation by sharing and trading energy among each other or with the main grid. For energy trading, the MG owners might have different energy buying/selling prices. Constraints on the retail energy selling prices offered to the customers are taken into account in [113,124].

5. Multi-Microgrid Control Structure and Operation Management

A control system is the backbone of MMGs. Controlling the MMGs involves the control of the power converters, active/reactive power sharing among DERs, controlling the SOC and charging/discharging power of ESSs, synchronization of multiple MGs, voltage–frequency and generation–load balance in MGs, load management, economic, and optimal power scheduling, energy sharing among MGs, automatic grid restoration and resilient operation, and protection against unprecedented failure events, among others. Sharing of information among MGs in an MMG system helps the controllers find the optimal operating strategy for the stable and efficient operation of the system. Information sharing among MGs takes place through the designated communication system in the MMGs. For the control of MMGs, there are different control structures. These control structures are derived from the control structure of a single MG, which includes centralized, decentralized, distributed, and hierarchical, as described in the following sub-sections [3,28,125].

5.1. Centralized Control

For MMG operation and control, an MG shares the information of available power generation capacity (dispatchable and non-dispatchable), power demand, the SOC of

ESSs, the types of loads (controllable, uncontrollable, elastic, and inelastic), and the load priorities with a central entity that collects and stores this information in a central database through designated communication channels. In the centralized control structure (as shown in Figure 2), the central controller executes the operation management algorithms and the control commands are communicated to each MG. One of the main advantages of a centralized controller is that, since a single entity is responsible for the control decisions, it is straightforward to implement the coordination between different MGs. However, this might increase the risk of a single point of failure for the whole MMG system [28]. Moreover, these types of controllers generally require more communication and computational resources, which restricts their scalability [3,28].

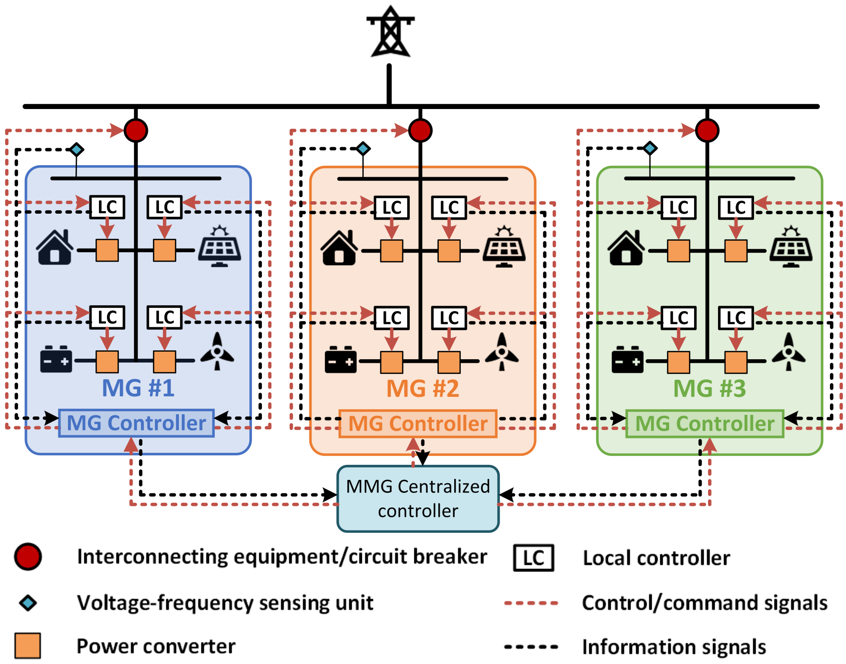

Figure 2. Centralized control architecture.

Minimizing the operational cost and maximizing the global benefits are the two main and primary objectives of a centralized EMS in MMGs. The authors of [29,31,33,35,36,38,39,84,106,117] mainly focus on the economic operation of a MMG system. A model predictive control (MPC)-based control was implemented in [29] to maximize the global benefits of the MMG system, taking into account the uncertainties in RESs' power generation and load demand. Their proposed algorithm schedules the power exchange between the MGs and distributed network operator (DNO). In [106], cooperation among two MGs is encouraged by reducing the energy drawn from the main grid as the controller has the information of the energy generation, storage, and load of both MGs and can schedule the sharing of available resources. The offline optimization Lagrange duality method is implemented considering the transmission losses and the distance between MGs. A similar study is presented in [31], where a three-stage multi-agent system (MAS)-based coalition game strategy is applied to form coalitions among MGs for cooperative and direct power exchange to achieve economical operation of MMGs. In [33], cooperative game theory is deployed to increase the energy efficiency of the MMGs while considering the interaction with distributed network (DN). In [117], the MGs with higher RES and ESS capacity are given higher priority and incentive for engaging in MMG energy exchange. A collaborative energy exchange scheduling scheme for residential MGs is discussed in [35] to minimize the operating cost of the MMG system using a method named column-and-constraint generation (C&CG) and to mitigate the disturbance caused by solar power uncertainty. The adaptive robust optimization (ARO) technique with a budget parameter is used in this study. Considering the intermittent nature of RESs, the EMS in [36] tries to minimize the operation cost by forming an MG coalition. In [36], a centralized macro station searches for the pair of MGs with lower power losses until demands of all MGs are met. To mitigate the uncertainty of RESs, reserve support among MGs is implemented in [38]. A real-time cooperative EMS is established in [39] namely "store-then-cooperate" and "cooperate-then-store", and it is shown that the performance is close to the optimal offline solution. In the store-then-cooperate strategy, the MGs charge the ESSs when there is a surplus generation and then transmit energy to other MGs and vice versa for the cooperate-then-store approach [39]. With increasing penetration of EVs, they are now considered as mobile ESSs. A cooperative operation of RESs and EVs is achieved in [84] to reduce the cost of operation of MMGs using the particle swarm optimization (PSO) algorithm. It is shown that the participation and cooperation of EVs in the operation of MMGs reduce the need for the installation of more RESs [84]. Finally, wild goats algorithm (WGA) is used in [41] for the optimal operation of an MMG system to maximize the profits of MG owners. Along with the economical operation of the MMG system, the main objective of [30] is the implementation of optimal power dispatch considering the probability distribution function (PDF) of the energy generation, consumption, power purchasing/selling of the MGs, operation and maintenance cost, and the cost of power transaction using the PSO algorithm. Similarly, the authors of [86] aim at minimizing load shedding when the MG cluster is operating in the islanded mode. A mixed integer linear programming (MILP)-based robust optimization (RO) technique is developed for the scheduling of MMG's operation considering the uncertainties in RESs power and load forecasts. In [85], to minimize the load curtailment, the optimal scheduling of energy resources is implemented in both grid-connected and islanded modes of operation. The resulting large-scale optimization problem is decomposed into multiple sub-problems using the alternating direction methods of multipliers (ADMM) decomposition method and solved by parallel computing techniques. Information is exchanged between the master and distributed computing nodes to find an optimal solution. In [32], an algorithm based on second-order cone programming (SOCP), point estimation method (PEM), and MPC is proposed to maximize the robustness of power exchange between MMGs and the DN taking into account the constraints and spinning reserve of the DN. A risk-constrained energy management strategy is proposed in [37] considering the variation of the MG's expected profit and the arising volatility in power exchange. Profit variation occurs due to the fluctuation in RESs power, resulting in energy exchange [37]. The voltage, frequency, and output power of MGs' converters will fluctuate in the case of the transition from grid-connected to islanded mode. MPC is used in [90] to regulate the MG's voltage, frequency, and power for safe islanding of the MG from the MMG system. A deep neural network (DNN) and model-free reinforcement learning (RL)-based technique are applied for intelligent MMG energy management in [40]. Given the retail price, the DNN estimates the aggregated MMG power exchange with the main distribution grid. The RL-based technique at the DSO-level then optimizes the retail pricing to maximize the profit of selling power and reduce the load peak-to-average (PAR) of the distribution system [40].

To increase the reliability of the MMG system, dynamic optimal planning is presented in [119]. The proposed optimal planning framework minimizes the operating costs and the energy not supplied in both grid-connected and islanded mode considering the optimal size, site, type, and uncertainties of RESs. The DNO applies the multi-objective PSO algorithm to minimize the cost functions, and the best solution is selected based on three different risk attitudes, namely risk averse, risk neutral, and risk seeker. The authors of [34] analyze the MMG reliability performance and outage management scheme by DSO. A reliability assessment framework is developed to divide the electricity grid into smaller MGs based on the location of protection devices. Different sections are evaluated using the reliability indices. A summary of the reviewed studies on centralized control and EMS of MMGs can be found in Table A2.

5.2. Decentralized Control

In the case of decentralized control (as shown in Figure 3), there is no communication between the controllers, and the power lines communicate based on changes in voltage and frequency [3,125]. The local controllers of MGs work independently without any information exchange with other entities, which enhances the MGs' autonomy and improves immunity against external disturbances and attacks. However, reaching the global optimum operating point of the system is difficult [33]. In [74], it is shown that a decentralized control system results in the degradation of MMG system performance due to the lack of cooperation among MGs.

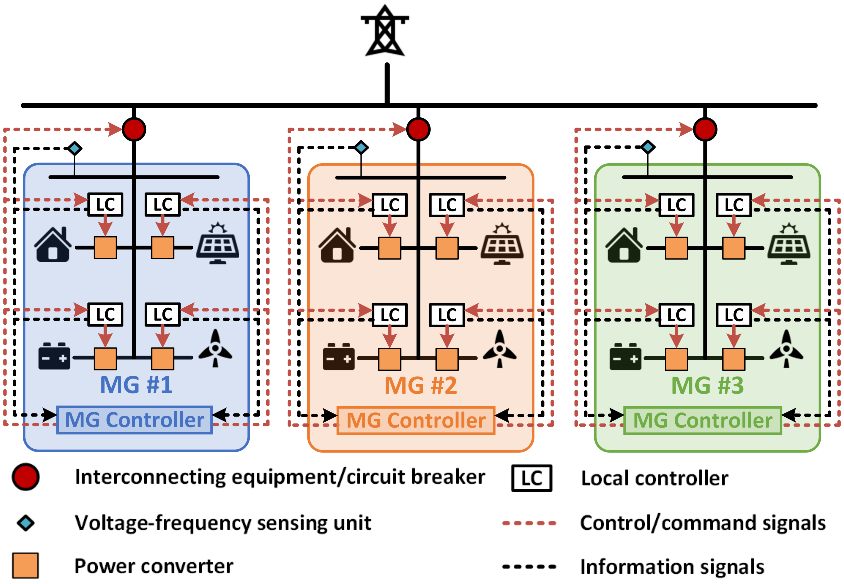

Figure 3. Decentralized control architecture.

In [43], in the event of communication failure, a decentralized droop-based control system tries to regulate voltage, frequency, and power in an MMG system. In [97], the connection of two MGs operating at different frequencies through a back-to-back (BTB) converter is discussed. A communication-less multi-frequency control method is proposed based on the droop control strategy.

5.3. Distributed Control

An intermediate of centralized and decentralized control is distributed control (as shown in Figure 4), where there is communication between multiple controllers, which cooperate to achieve a common goal [126]. These types of controllers feature a high degree of flexibility to support the integration of new MGs, which facilitates plug-and-play operation [4,126]. In [91], a distributed control scheme is proposed to regulate the power exchange and the average voltage among MGs. The controllers are interconnected through low-bandwidth communication links, controlling the current of DERs. In [92], a robust distributed control scheme is implemented to mitigate the poorly damped oscillations through proper regulation of ESSs and DGs among interconnected MGs. In [100], active power sharing among interconnected MGs is studied while accounting for communication delay and communication loss in the interlinking converters. The converter control agents request information from neighboring controllers, and using an event-based control scheme and consensus protocol among multiple agents, the active power load of individual MGs is adjusted. Furthermore, a distributed algorithm is designed in [48] for energy exchange with neighboring MGs to minimize the transmission power losses.

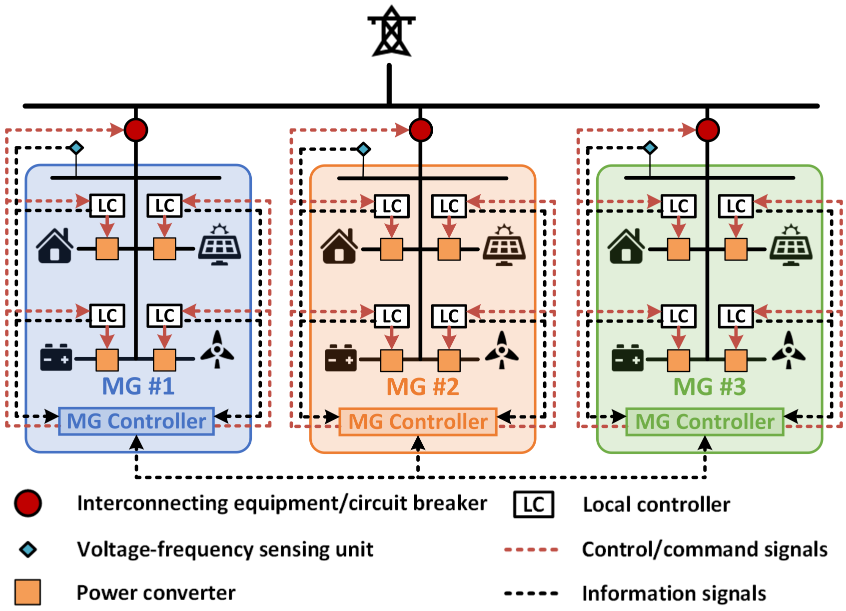

Figure 4. Distributed control architecture.

In [51], the operation cost of DNO and MGs is minimized using a bi-level stochastic optimization algorithm. The algorithm uses a deterministic decomposition methodology, and the bi-level problem is solved using progressive hedging. ADMM is a widely used method for distributed operation management and control. In [55], ADMM is used by the EMS to minimize the overall cost of the MMG system. The proposed algorithm reduces the communication overhead since only direct neighbors communicate with each other. In [93], the optimization of operational cost is performed using ADMM in an AC–DC hybrid MMG system, where a DC network interconnects the MGs. Similarly, the authors of [56] consider distribution system (DS) and MGs as distinct entities with the objective of minimizing operating costs. Power exchange among the DS and MGs is determined using ADMM considering the uncertainties in RESs production and load. In [61], DNO performs economic energy management using the coordinated distributed MPC (DMPC) technique and provides references to the MGs. An algorithm derived from ADMM named distributed adjustable robust optimal scheduling algorithm (DAROSA) is proposed in [105] to optimize the MGs operating cost by trading energy among MGs and the main grid. The ARO deals with the uncertainties of RESs production, MGs' load, and the buying/selling electricity prices of the main grid. In [64], considering the existence of multiple MMG stakeholders, an analytical target cascading (ATC)-based optimization framework is developed to improve the operational performance of the MMG system and benefits of all stakeholders. The diagonal quadratic approximation (DQA) technique is employed for implementing the parallel operation. Using ATC and DQA, energy trading and energy dispatch are implemented considering the uncertainty in RESs and loads. Cooperative energy trading among MGs is discussed in [47] using the ATC algorithm, which shows performance improvement compared to the independent operation. In [46], the performance of integrated ATC and C&CG is compared with the C&CG performance for economic dispatch and coordinated operation of MMGs. In [45], ATC is used to decouple the DN and MGs power dispatch so that the MGs and DNs can use their resources independently to achieve economical operation, which is called dynamic economic dispatch (DED). According to [52], optimal scheduling of MMG systems using ADMM reduces the coalition operation cost of the MMG system while sharing only the information of the expected power to be exchanged, which preserves the MGs' privacy.

In addition to the operating cost of MGs, energy exchange with the DS is reduced in [53] to encourage a higher contribution of RESs. MPC and MILP are employed for energy management of the MMG system. The MPC technique accounts for the future behavior of the system in a receding horizon manner, making the solution strategy more robust against uncertainty [53]. In [94], DMPC is used to optimize RES utilization and coordinate renewable energy sharing among MGs. The EMS improves the RES utilization while reducing the deep discharge of the battery and the customer dissatisfaction. The authors of [62] develop an optimal strategy for internal resource scheduling and energy trading of MGs using DMPC and a dimensionally distributed algorithm based on PSO. To benefit from the diversity that exists in the RESs production and load patterns of different MGs in an MMG system, a bargaining-based incentive mechanism is developed in [54] for energy scheduling and trading among multiple MGs. Considering the presence of multiple MG owners and stakeholders with different attitudes in an MMG system, distributing the economical benefits of cooperative operation in a fair manner is a challenging issue. In this regard, Nash bargain theory is used in [54] to encourage energy trading and having a fair benefit sharing among MGs. An online ADMM-based energy management strategy for the DNO is proposed in [57] to schedule the power exchange of interconnected MGs. The objective is to minimize the power production cost of MGs, and the prediction of the uncertain RESs production and power demand is not required. In [87], a decentralized–distributed adaptive RO (DD-ARO) methodology is proposed to address the distributed scheduling of AC–DC hybrid MMGs in case of accidental communication or source–load power line failures. Active and reactive power sharing among MGs in MMGs are discussed in [100] considering the impact of communication delay and the loss of the controllers using MAS and event-based distributed consensus control. The proposed DD-ARO method consists of two optimization problems, which include a MILP-based minimization problem and a tri-level min–max–min problem solved using C&CG and the Benders decomposition algorithms. Besides, the privacy concerns of multiple stakeholders are taken into consideration for economic operation and uncertainty management.

Several studies design the voltage and frequency control of MMGs using distributed control. In [49], voltage and frequency control and restoration techniques are designed using droop control for active power sharing. The voltage is restored to the desired value for all DGs regardless of frequency using finite-time voltage control, and a distributed consensus-based control restores the frequency to the desired value. In [50], a proportional–integral droop control with distributed averaging algorithms, called the distributed-averaging proportional–integral (DAPI) method, is designed for voltage–frequency regulation. The neighboring DGs communicate with each other and share information for voltage–frequency regulation and active–reactive power sharing. The authors of [58] propose an adaptive voltage and frequency control for DGs using distributed cooperative control and an adaptive neural network. The proposed control technique simplifies multiple layers of control and achieves good active–reactive power sharing with reduced dependency on system dynamics. In [59], in case the voltage of one MG moves outside the limits, the MG controller tackles the voltage problem by instantly communicating with the neighboring MGs in the MMG system. MPC is employed for coordination and distributed sharing of resources considering the different load profiles of industrial, commercial, and residential MGs. Similarly, the authors of [127] focus on frequency regulation while maintaining the voltage in all buses of the MMG system using DMPC. Using a consensus-based ADMM, the neighboring MGs operate in a limited communication framework to ensure privacy and scalability.

Along with voltage control, the authors of [91] discuss the load sharing and power management of MMGs. A droop-based control scheme along with a combination of global positioning system (GPS) timing technology and non-linear voltage–current characteristics for fast dynamic response of load sharing is designed. The voltage and frequency control is performed using a distributed averaging technique according to the average voltage of the network, for regulating the tie-line current and improving the voltage profile. In [101], a real-time control method for power sharing among MGs consisting of multiple DERs and loads is proposed using a novel distributed optimal tie-line power flow (DOTLPF) control technique. In [65], a unified small-signal dynamic model of the MMG system facilitates load sharing among MGs and the plug-and-play operation. Droop control is implemented for the output power regulation of the MGs, and distributed control is used for the power sharing of DGs in each MG. In [92], a robust distributed control scheme is proposed to mitigate the power oscillations caused by dynamic interactions among MGs in an MMG system. In [99], a distributed real-time optimal power flow (RTOPF) is proposed, where the MGs are modeled and controlled using the MASs approach. In [103], an MAS-based distributed secondary control is implemented for active–reactive power and droop control of DGs in MMG clusters. In the event of switching to the islanded mode, the voltage and frequency change due to the change in the power control references [104]. In [104], this problem is addressed by implementing differential game theory (DGT) for solving the multi-agent non-cooperative distributed coordination problem.

Control strategies can also ensure the resilience-oriented operation of MMGs. The authors of [60] define a resilience index based on the ability of MGs to supply critical loads at the time of power interruption. A consensus algorithm in a distributed framework establishes the optimal load shedding of MGs. The proposed fault-tolerant control of MGs in [63] maintains the power balance within and between the MGs to increase the reliability of the MMG system. The control system maintains the voltage and frequency of MGs within the permissible range in the case of the generation and load fluctuations. A summary of the reviewed studies on distributed control and EMS of MMGs is presented in Table A3.

5.4. Hierarchical Control

The hierarchical control (as shown in Figure 5) allows organizing the MMG control at several control levels. Communication is established among the controllers of different levels to share the control signals or information. The controllers may have different time scales in the order of minutes or hours. Generally, in hierarchical control, each control level is associated with the objective(s) of the MMG system. Furthermore, each control level can be divided into several sub-layers, where upper-level controllers can schedule references for the lower-level controllers. For instance, the EMS in an MMG system might have two levels. The upper-level controller could be responsible for optimizing the energy exchange of the entire MMG system, demand management, market prices, and so on, while the lower-level controllers might be responsible for controlling the power production and demand at the MG level, maintaining power balance, minimizing the MG operational cost, etc., following the references provided by the upper-level controllers. In [66], the power scheduling and power trading are split into two levels, where the first tier accounts for the user utility function and grid load variance and the second tier controls the power generation and energy storage in the MGs.

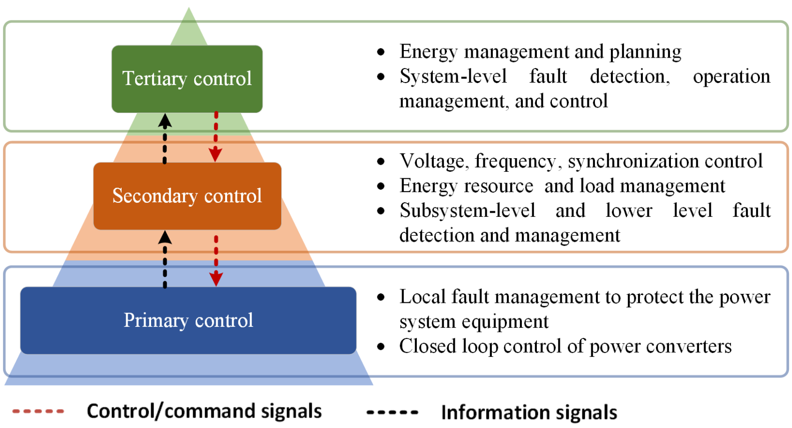

Figure 5. Hierarchical control architecture.

In [128], the hierarchical approach is adopted in an AC–DC hybrid MMG system for power exchange among MGs, maintaining the normal operation of the MMG system. A hierarchical EMS is implemented in [95] to achieve power balance within each MG at the

MG level and power exchange coordination between the DN and MGs at the MMG level using RO and MILP. The authors of [69] design a two-level EMS to minimize the operating cost of the MMG system using MILP. A central autonomous controller executes the control signals from the DSO for MGs operation management and control, while the MG central controller (MGCC) controls the micro-sources, controllable loads, and ESSs of individual MGs. Similarly, distributed economic MPC (EMPC) is implemented in [74] for economical operation of the whole DS. At the upper layer, the DNO maintains the supply–demand balance in the MMG system, schedules power exchanges, and provides references to the lower-level MGs controllers. At the lower layer, MG controllers maintain the power balance and minimize the operation cost of the MG, while tracking the references provided by DNO using DMPC and EMPC. A stochastic EMS in the chance constrained MPC (CCMPC) framework is designed in [88] for the operation management of MMGs. After coordinating the operation of MGs and scheduling power exchange among MGs and between the MGs and the main grid at the upper level, the decisions are communicated to the lower-level EMSs. Taking into account the several sources of uncertainties, CCMPC ensures the satisfactory operation of each MG at the lower level. In [76], to minimize the operation cost of the MMG system, the EMS is also informed about the MGs adjustable power in addition to their power shortage and surplus information. In [70], a bi-level optimization based on multi-period imperialist competition algorithm (ICA) is implemented for economic and optimal operation, demand-side management, and scheduling the interactions among MGs in an MMG system. In [42], the economic operation of an MMG system is discussed considering the DNO and MGs as distinct entities. The problem is modeled as a stochastic bi-level problem, where the upper level is related to DNO and deals with operational constraints such as power flows and voltage levels. The MGs controllers at the lower level minimize the operating costs of the individual systems. In [73], EVs are considered as ESSs to reduce the peak energy exchange with the main grid and the operational cost of the MMG system. At the first level, the total power exchange between the MMG system and the main grid is kept within the permissible limits, and the total electricity cost of the MMG system is minimized. At the second level, the charging and discharging power are allocated to each EV by optimizing the transitions between charging and discharging modes to increase the lifetime of the EV batteries. Similarly, the authors of [78] design an EV coordination mechanism to minimize the system cost. Using the gradient projection method, the EV charging/discharging coordination is accomplished based on the time of use (TOU) pricing and the power exchange capability between MGs in the MMG system to minimize the load PAR ratio.

To optimize both the performance of the MG and user satisfaction, the authors of [66] design a two-tier power control problem, which is solved using an online algorithm. The first tier maximizes the user satisfaction while minimizing the transmission cost between the main grid and the MMG system and the grid load variance. The second tier control is responsible for minimizing the power generation and transmission cost for each MG and ESS utilization. In [67], a bi-level optimization problem is discussed to maximize the DSO's profit at the upper level and minimize the cost of MGs in the lower level. Bi-level optimization is also implemented in [114] to reduce the power loss and improve the voltage profile at the upper level. The optimal operation of DGs is determined at the lower level using the self-adaptive genetic algorithm and non-linear programming. A day-ahead optimal power scheduling approach is discussed in [75], where a two-level interactive model is developed using the Stackelberg game. The DNO acts as a leader, which facilitates the trading of power and announces the trading prices of each MG operator (MGO). The MGO schedules the energy exchange with the DNO considering the day-ahead trading prices. The authors of [77] develop an agent-based cooperative power management using Nash bargain solution (NBS) for resource management of MGs in an MMG system. The upper-level controller maintains the power balance at all PCCs of the MMG system, and the lower-level controller coordinates the operation of the micro-sources (MSs)' control agents using internal bargaining.

Along with the optimal operation and minimization of operational costs, the authors of [72] design a bi-level multi-objective cooperative dynamic EMS in grid-connected MMGs. The DNO minimizes the power fluctuations, voltage deviations, and power loss at the MMG level, while the MGs controllers minimize the power loss and operational costs at the MG level. The interaction between MGs and DN is modeled as a bi-level optimization problem and solved using a hybrid algorithm of hierarchical genetic algorithm (HGA)–non-dominated sorting genetic Algorithm II (NSGA-II)–rough set theory (RST). The interaction between MGs is modeled using an interactive energy game matrix (IEGM). In [122], a bi-level interactive energy management is implemented for enhancing power balance in an MMG system and handling uncertainties. At the upper level, the energy exchange among MGs is optimized considering the operational costs, user priorities, and power consumption behavior of each MG. At the lower level, the MG operation is optimized using the MPC technique to minimize the deviation from the planned strategies generated at the upper level. In [44], a voltage regulation mechanism is proposed for an MMG system based on MAS. A bi-level game model is developed where the Stackelberg-game-based incentive mechanism and static-game-based voltage control strategies are implemented at the DNO level and MG level, respectively. In [102], a hierarchical DMPC algorithm is designed to optimize the operation of MMGs taking into account the MGs' privacy while exchanging information and the flexibility to adapt to changes in the MMG network. The optimization problem is solved in a distributed way using ADMM, and an MPC-based scheme is utilized at each time step by individual MGs. To coordinate different EMS of MGs in an MMG system, the authors of [62] propose an MAS-based stochastic programming approach taking into account the complicated interactions of MGs, restrictions, and uncertainties. In [79], a two-time-scale control scheme based on MPC is deployed in an MMG system when the demand exceeds the power generated by RESs and batteries. The control strategy is divided into three levels, where energy trading between the DNO and MGs is scheduled at the top level, the load balance of each MG and battery ESSs operation optimization are dealt with at the middle level, and load shedding decisions are made at the lowest level. In some scenarios, the power management optimization can become a challenging task for cooperative agents due to the limited or incomplete knowledge of the internal behavior of MGs beyond the PCC [80]. A bi-level model-free RL-based algorithm is designed in [80] to handle the relation between the power exchange among MGs and the retail price of power. At the upper level, a central agent maximizes the power exchange profit of MGs by predicting the behavior of their unknown internal entities. At the lower level, the MGCC optimizes the power-flow-constrained power management of the MG considering the pricing signal obtained from the cooperative agent.

To enhance the resiliency of MMGs, the authors of [120] design an exhaustive framework for the optimal operation and self-healing of DGs. During normal operation, a two-stage stochastic optimization is implemented to optimize the operation of MGs considering the predicted outputs of non-dispatchable DGs and load consumption at the first level. At the second level, power generation is adjusted based on the variations of non-dispatchable DGs output power. During the normal operation, the goal is to minimize the operational costs and maximize the MGs' profit. In faulty conditions, corrective measures are taken to restore the system by sectionalizing the faulty section into multiple self-sufficient MGs. In [68], the DSO is the coordinator of the MMG system at the upper level, which minimizes load shedding in the whole system. In case of a disturbance, the system is managed by automatic power scheduling mechanisms to share available resources among MGs. At the lower level, the MGCC is responsible for the individual MGs operation management. A novel resiliency index is also defined in [68] to evaluate the effectiveness of the designed structure in terms of the expected energy curtailment during emergency conditions. In [71], a self-healing mechanism is designed for MMGs. In case of a fault in an MG, the resources of other MGs are shared to compensate for the generation deficiency in the faulty MG and support the critical functionalities of the MMG system. At the lower level, the local EMS of the self-adequate MGs controls the DGs, ESSs, and loads while communicating with the neighboring MGs. In case of an emergency, the damaged MG broadcasts its power support request, and using an average consensus algorithm, a solution strategy is devised. At the upper level, after receiving the operating schedules of local EMSs, the operation of the DGs, ESSs, and loads is optimized. In [96], the MMG system's reliability is maximized while considering the minimization of the operation cost. The reliability of the MMG system is evaluated considering uncertainties in MGs components in both grid-connected and islanded modes of operation. ICA is used in the proposed hierarchical EMS. Preserving the privacy of MGs customers, the authors of [129] develop an EMS for day-ahead scheduling of an MMG system with the objectives of operation cost minimization in the grid-connected mode and maximizing resiliency and reliability in the islanded mode using MILP. At the lower level, the MG's EMS optimizes the local resources operation and informs the upper-level controller, which optimizes the operation cost of the MMG network. In the islanded mode, the resiliency of the MMG system is increased by sub-grouping of MGs. In [129], the resiliency index of an MG is defined as the ratio of the amount of load restored during a particular event to the total amount of the MG's load. In [81], the resiliency of an MMG system is enhanced by maximizing the energy sharing among MGs in case of an emergency, neglecting the financial benefits and without compromising the MGs' privacy. In an emergency situation, if the MG operates in the islanded mode, the total operational cost is minimized, while in the case of being connected to the MMG system, power exchange is maximized to minimize load shedding. At the first level, the MG's EMS schedules its resources and calculates the amount of import/export power from/to the MMG system. At the second level, the MG's EMS communicates with its neighbors to share the scheduled power. A summary of the reviewed studies on hierarchical control and EMS of MMGs is presented in Table A4.

The advantages and disadvantages of centralized, decentralized, distributed, and hierarchical control structures are listed in Table A1.

6. Uncertainty Handling Techniques

RESs are a significant source of uncertainty for MG operation and control. The power generated from RESs fluctuates due to the frequently changing weather conditions. Fluctuation in the generated power creates power imbalance in MGs, which can lead to voltage–frequency-related instability and faults. Moreover, the continuously changing power demand in MGs further aggravates the voltage–frequency-related fluctuations. Several methods have been proposed including robust optimization [93], stochastic optimization [60,74], and modeling uncertainties using probability distribution functions [42,51] to reduce the effect of uncertainties on the operation of MMGs. An overview of the recent studies on uncertainty management of MMGs including the proposed uncertainty handling technique and studied uncertainty resources is provided in Table A5.

7. Future Trends in Multi-Microgrids Control

The development of MMG systems provides substantial benefits to the operation of MG- and RES-based energy production. During the last few years, a big effort has been made to support MMGs' development, and several control and communication techniques have been proposed to enhance their operation. However, more studies are required to address the following issues to further enhance the safety and reliability of MMGs:

- Artificial intelligence (AI)-based uncertainty management: Identifying different sources of uncertainty, designing advanced dynamic modeling and prediction methods of uncertain parameters using AI and machine learning methodologies, and developing efficient uncertainty management techniques are among the main requirements of the next-generation MGs and MMG systems.
- Multi-layer control and communication systems: The operation of MMGs is dependent on the performance of multiple controllers and communication systems. The complexity of communication and control increases with the increase of the architecture complexity of the MMG systems [25]. Moreover, several controllers in an MMG

system interact through the designated communication channels adopting different communication protocols, which might hinder the information exchange. Furthermore, the stability of the MMG system needs to be maintained in the presence of delay or the loss of communication.

- *Interaction between multiple owners and multi-vendor controllers:* In an MMG system, there are various MG owners with different attitudes for the MG's operation. The presence of mixed ownership and multiple stakeholders in MMGs results in a complex operation management problem. Besides, the operation of MMG systems involves different controllers and control loops. Different control loops may operate at different frequencies ranging from a few hundreds of Hertz (Hz) to a few KHz. The different control loops frequencies may create harmonic interactions between different converters or components connected to the system [25]. These interactions are addressed by outer or inner control loops. In the case of multi-vendor controllers, different manufacturers have different control strategies and allow different variables to be controlled, which makes the system integration very complex [25]. Hence, standardization is an important issue in the development of interconnected structures.
- *Exposure to cyber-attacks:* The communication links are vulnerable to cyber-attacks and false data injection, which might endanger the stability of the MMG system [25]. In this regard, central communication systems are secure for the MMGs' operation as all information is processed centrally, which makes the system more alert to malicious information injection [4]. On the other hand, a distributed system can have access to partial data of the neighboring controllers, which makes the system more prone to cyber-attacks, as it is very challenging to detect corrupt information [4].
- *MG protection issues:* MMG systems' operation may involve frequent changes in the MMG architecture and mode of operation, which can cause severe problems in the coordination and adjusting the sensitivity limits of the protection relays. In this sense, adaptive techniques [4] and learning-based strategies to adjust operational settings might be among the promising solutions.

8. Conclusions

MMG systems enhance power systems' operation by improving voltage–frequency stability, system reliability, and resiliency and providing ample opportunities for uncertainty management and economical operation. The operation management of MMG systems involves coordinating various power generation, conversion, transmission, and storage technologies with different technical constraints and operating requirements. Besides, the flexibilities on the demand side should be identified and deployed to maximize the system's efficiency. The operational goals of MMGs can be fulfilled using different centralized, decentralized, distributed, and hierarchical control structures taking into account their specific characteristics and system requirements.

This paper presented an overview of recent advances in the control and operation management of MMGs and their different system architectures. Various operational goals of MMG systems, as well as their technical and operational constraints were summarized. The advantages and disadvantages of various MMG architectures were discussed, and existing challenges for the safe and reliable operation and control of MMGs were explored. Finally, several issues to enhance the operational reliability of MMGs were identified, and the future trends of MMG systems were discussed.

According to the study conducted in this paper, there are potential research areas that can be explored to facilitate the adoption of MMG concepts in power systems. In this regard, recent advances in AI techniques can be deployed to manage uncertainty in an MMG system effectively. In the case of communication between several controllers in an MMG system, different controllers might adopt different communication protocols, thereby hindering smooth information exchange, which might cause stability problems. Hence, efficient control techniques to maintain the smooth operation of the MMG system are required. The stability of the MMG system should also be ensured in case of communication loss or delay. To guarantee the cyber security of MMG systems and ensure their stable operation, advanced attack detection and mitigation techniques are required. A detailed study on the state-of-the-art of detection and mitigation of cyber-attacks for MMG systems is still missing and is considered as a future work by the authors. Regarding protection systems of MMG systems, the automatic adaptation of protection relays' settings is critical as the system architecture may change frequently. Finally, standardization is needed for a smooth integration of the multi-vendor controllers that might be used in an MMG system.

Author Contributions: Conceptualization, D.S., N.B., J.C.V. and J.M.G.; methodology, D.S. and N.B.; resources, J.C.V. and J.M.G.; writing—original draft preparation, D.S.; writing—review and editing, N.B., J.C.V. and J.M.G. visualization, D.S. and N.B.; supervision, N.B., J.C.V. and J.M.G.; project administration, J.C.V. and J.M.G.; funding acquisition, J.M.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by VILLUM FONDEN under the VILLUM Investigator Grant (No. 25920): Center for Research on Microgrids (CROM).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Summary of different control structures.

Control Structure	Advantages	Disadvantages	Suggested Applications
Centralized	• A single entity is responsible for all the control decisions • The global optimum operating point is attainable due to access to all the required information • Implementation is straightforward	• High risk of a single point of failure • High computational and communication burden • Limitation on expandability and scalability • Preserving the data privacy is an issue	• Small-scale systems • Systems with fixed architectures and less probability of expansion • When sufficient computational resources are available
Decentralized	• Controllers work independently and no communication infrastructure is needed to exchange information among controllers • Local controllers communicate based on locally available information, such as the system's voltage and frequency changes • Enhances MGs' autonomy and their immunity to external disturbances and attacks	• Reaching the global optimum operating point of the MMG system is difficult • Lack of cooperation among MGs • There is a risk of instability due to the lack of information	• When attaining the global optimum point is not necessary • In case preserving the privacy of MGs and their autonomy are sought
Distributed	• Benefits from the advantages of both centralized and decentralized architectures • Communication among multiple controllers is required to achieve a common goal • Reduces the need for powerful computational resources by including several local controllers • Allows easy expansion of the system and facilitates the plug-and-play operation and integration of new MGs	• Complex implementation • Communication delays might introduce new challenges • Preserving the privacy of individual MGs might be challenging	• When there is a possibility for system expansion and the plug-and-play operation is required • When sharing private data of MGs is not critical

Table A1. *Cont.*

Control Structure	Advantages	Disadvantages	Suggested Applications
Hierarchical	• Controllers are organized at different levels and coordinate with each other by setting references and constraints boundaries • Allows dividing a large problem into several sub-problems handled by several controllers • Allows controllers to be in different time scales	• Complex implementation • Communication delays and loss of communication introduce new challenges • Managing the time frame to preserve stability and robustness is complex	• Large-scale systems • In case of the existence of hierarchy among different controllers • In systems with a variety of control tasks and different time scales

Table A2. Summary of the recently published articles on the centralized control of MMGs.

Ref.	Area	Objective	Control Technique	Remarks
Control level: Tertiary				
[29]	Energy management	Maximizing the global benefits	MPC	Rolling time horizon technique is used to capture system dynamics and cope with uncertainties
[106]	Energy management	Minimizing system cost and energy drawn from the main grid	Lagrange duality method	The distance between MGs and transmission losses are considered in energy exchange
[30]	Power management	Economical operation of MMG and optimal power dispatch	PSO	The distance between MGs and transmission losses are considered in energy exchange
[31]	Power management	Economic power transaction	MAS	Power loss, transmission and communication cost per unit distance between MGs are considered in energy exchange
[86]	Energy management	Economical operation of MMG and minimizing load shedding	MILP	-
[32]	Power management	Economical operation of MMG and power interchange robustness	SOCP	Low computation burden in PEM; It is shown that SOCP provides better operating points than SQP
[119]	Reliability	Optimal dynamic planning	Multi-Objective PSO	-
[33]	Energy management	Economical operation of MMG and maximizing energy efficiency	Cooperative game theory	Network power loss is considered
[117]	Energy management	Optimal coordinated dispatch of ESSs	Lexicographic programming	-
[34]	Reliability	Reliability enhancement and outage management of MMGs	MPC	Flexible and optimal load shedding in emergency conditions
[35]	Energy management	Economical operation of MMG	Adaptive RO	EVs considered as ESS in each residential MG
[36]	Energy management	Economical operation of MMG	Proposed algorithm	-
[37]	Energy management	EMS considering expected profit and mitigating volatility of MGs' power exchange	PSO	-
[38]	Energy management	Optimal operation of MMG and cooperative energy scheduling	Game theory; RO	Electricity prices are forecasted

Table A2. *Cont.*

Ref.	Area	Objective	Control Technique	Remarks
[39]	Energy management	Cooperative EMS to minimize energy cost	Lagrange duality method	Cooperation between MGs and ESSs yields lowest energy cost
[84]	Energy management	Economical operation of MMG considering EVs	Improved PSO	-
[40]	Energy management	Smoothing power exchange between MGs	DNN; RL	Degradation cost of ESSs is considered; The proposed Data-driven DNN has high computational efficiency
[41]	Energy management	Optimal operation of MMG	WGA	The proposed EMS improves reliability, profit allocation fairness, and customer satisfaction
[85]	Energy management	Optimal scheduling; demand response	ADMM	Power loss due to power exchange between the main grid and MGs is considered

Table A3. Summary of the recently published articles on the distributed control of MMGs.

Ref.	Area	Objective	Control Technique	Remarks
Control level: Tertiary				
[48]	Power management	Minimizing power losses of the MMG	Proposed distributed algorithm	Transmission and conversion losses are considered
[51]	Energy management	Economic operation of MMG	Bi-level stochastic optimization	Information exchange between DNO and MGs is only about power exchange at the PCC
[52]	Energy management	Privacy-preserving optimal scheduling	ADMM	Forecasting errors show limited influence on the cost of MMG
[53]	Energy management	Economical operation of each MG in MMG	MPC	-
[100]	Power Management	Power sharing among MGs	MAS; Droop control	Communication burden reduced by event-based control
[54]	Energy management	Energy trading and scheduling	ADMM; Nash bargain solution	Diverse supply/load profiles of MGs are considered
[55]	Energy management	Economic Operation of the MMG	ADMM; MPC	Different DC energy exchange architectures compared
[56]	Energy management	Economical operation of the MMG	ADMM	ADMM with improved convergence speed is proposed
[57]	Energy management	Online energy management	ADMM	-
[60]	Resiliency	Survivability of critical loads during emergency period islanding	Consensus algorithm	AC and DC side interlinking converter losses is considered
[93]	Energy management	Economic operation of the MMG	ADMM	-
[61]	Energy management	Economic operation of the MMG	DMPC	-
[94]	Energy management	Optimizing utilization of RESs	DMPC	-

Table A3. *Cont.*

Ref.	Area	Objective	Control Technique	Remarks
[105]	Energy management	Economical operation of the MMG	ADMM; ARO	Uncertainty on energy prices influence the energy scheduling result; Degradation cost of batteries (ESS) is considered
[62]	Energy management	Developing an Efficient strategy for internal device scheduling and energy trading	MPC; PSO	-
[64]	Energy Management	Coordinating the operation of MMG and maximizing the benefits of multiple stakeholders	ATC; ARO	Reducing the computational time by using parallel algorithms about 26.1% compared to non-parallel algorithms
[87]	Power Management	Scheduling of MMG with various entities considering accidental communication failures	Modified ATC	It is shown that DD-ARO have 15% higher robustness rate against multiple uncertainties compared to stochastic optimization
[45]	Power management	Autonomous optimized dynamic economic dispatch model	ATC	ATC provides an advantage in terms of computational efficiency
[46]	Power management	Comparing integrating ATC and CCG with independent CCG	ATC; CCG	ATC and CCG provided better privacy and lower communication burden; Independent CCG shows fast convergence speed
[47]	Energy management	Energy trading among MGs and economical Operation of each MG	ATC	-
Control level: Secondary				
[49]	Operation optimization	Voltage and frequency control	Droop control	-
[50]	Operation optimization	Voltage and frequency control	DAPI controllers	Controllers do not need information about MG architecture, line impedance or load demand
[92]	Operation optimization	Reducing grid power oscillations due to faults	PI control	-
[99]	Operation optimization	Optimal power flow control	MAS	-
[103]	Operation optimization	Distributed cooperative control for islanded MGs	MAS	-
[91]	Operation optimization	Load sharing and voltage—power profile regulation	Distributed averaging; Droop control	Reduced dynamic response delay by directly incorporating output current in the control loop
[58]	Operation optimization	Voltage and frequency control	Adaptive neural network	-
[104]	Operation optimization	Non-cooperative coordination control for energy trading	Differential game theory	Implementation of many ADS control functions and self-healing is simplified
[59]	Operation optimization	Voltage control	MPC	Load profiles of three MGs considered are of industrial, commercial, and residential types

Table A3. *Cont.*

Ref.	Area	Objective	Control Technique	Remarks
[101]	Operation optimization	Power sharing, maintaining schedule tie-line power flows, prevent disturbance propagation	Distributed control agent (CA); DOTLPF	DOTLPF can be configured randomly which makes it suitable for plug-and-play operation of DERs
[127]	Operation optimization	Frequency regulation for different system topologies and operating modes	MPC; ADMM	-
[63]	Reliability	Power balance; fault tolerant	MAS	-

Table A4. Summary of the recently published articles on the hierarchical control of MMGs.

Ref.	Area	Objective	Control Technique	Remarks
Control level: Tertiary				
[120]	Resiliency	Self healing and sectionalization in fault condition	Stochastic optimization	-
[66]	Energy management	Improving MGs performance and user satisfaction	Dual decomposition	-
[67]	Optimization	Economical operation of MMG	MILP	RESs utilization increased compared to centralized model
[68]	Resiliency	Outage Management of MMG	MPC; MILP	-
[69]	Energy management	Economical operation of MMG	MILP	The proposed method improves decision-making efficiency
[70]	Energy management	Economical operation of each MG and demand response	Multi-period ICA	The proposed algorithm is simple, accurate, and fast converging
[71]	Resiliency	Optimal operation and self-healing	Average consensus algorithm	The proposed algorithm preserves privacy; low computation and communication complexity
[96]	Reliability	Reliable and optimal operation of the system	ICA	-
[72]	Energy management	Minimizing energy waste and operating cost	Game matrix; Genetic algorithm	Optimal operation includes improved power quality, energy utilization, adaptability, and autonomy
[73]	Energy management	Economic energy exchange scheduling using EVs as ESSs	Dual decision variables; Scenario tree	The algorithm results in less frequent charging/discharging cycles of EV batteries
[114]	Energy management	Optimizing power dispatch and operating strategy	Self-adaptive genetic algorithm; Non-linear programming	-
[74]	Energy management	Economic operation of MMG	MPC	Better trade-off between performance and computational burden has been achieved
[95]	Energy management	Maximizing the use of MMG resources	CCG	Detailed operating information of participating MGs is not required

Table A4. *Cont.*

Ref.	Area	Objective	Control Technique	Remarks
[129]	Energy management	Economical operation of MMG in grid connected mode and resiliency enhancement in islanded mode	MILP	Resiliency is enhanced through cluster formation
[75]	Energy management	Power scheduling optimization	Stackelberg game; CCG; MILP	Influence of price signals on the scheduling strategy of ESS in each MG is considered
[76]	Energy management	Economical operation of MMG with the information of adjustable power	MILP; MAS	Self-discharge rate and converter losses are considered in BESS modeling
[102]	Operation optimization	Hierarchical distributed operation optimization of MMG	MPC; ADMM	-
[77]	Power management	Cooperative resource allocation in MMG	Cooperative game theory; NBS	NBS obtains a fair, unique, and Pareto-optimal solution
[122]	Energy management	Economical operation and minimizing deviation from planned strategies	MPC; Game model	Enhancement of the system resilience under emergency situation is discussed
[62]	Energy management	EMS using heterogeneous agent optimization problem	Stochastic programming	Penalty for under-utilizing the power already purchased is considered
[78]	Energy management	Economical operation of the MMG and optimal EV coordination	Gradient projection method	Bounded random variable is added to uncertainties as they are usually finite and have no specific statistical rules
[88]	Energy management	Stochastic energy management	Stochastic MPC	-
[79]	Energy management	EMS and demand response for the whole MMG	MPC	-
[80]	Power management	Decision-making under incomplete information	MINP; RL	Proposed RL solver is faster compared to conventional solvers; considering forgetting factor makes the model adaptive to system parameter changes
[42]	Energy management	Economic operation of MMG	MPCC	-
[81]	Resiliency	Maximizing power export to other MGs for enhancing resilience operation	Proposed algorithm	-
[82]	Reliability	Restoring power by controlling the DGs, RESs and ESSs and considering power demand	MPC; MILP	-
[89]	Energy management	Energy trading among MGs considering safety and security limits of distribution network	Stackelberg game; SOCP	-
[83]	Energy management	Economic rescheduling of the MMG to restrict losses due to failure	MPC	-

Table A5. Uncertainty handling techniques and uncertainty resources.

Uncertainty Handling Technique	Ref.	Uncertainty Source	Forecasting/Modeling Technique
Robust optimization	[86]	RESs, Load	-
	[34]	RESs, Load	-
	[38]	PV, wind, load, electricity prices	RESs: Forecast percentage error considered Load: Forecast percentage error considered
	[60]	RESs, load	-
Adjustable robust optimization	[93]	PV, load	-
	[105]	RESs, load, electricity prices	-
Adaptive robust optimization	[35]	PV	-
	[87]	PV, wind, load, line fault	-
Two-stage robust optimization	[75]	PV, wind, load	-
	[95]	PV, Wind	-
	[56]	PV, wind, load	-
Two-stage adaptive robust optimization	[64]	RESs, load	-
Stochastic optimization	[120]	PV, wind, load	RESs: Beta function Load: Normal distribution
	[74]	Wind, load	RESs: Non-Gaussian probabilistic forecasting model Load: Gaussian processes regression
	[73]	Wind, EV charging/discharging	Wind: Normal distribution
	[41]	PV, wind, load	PV: Beta distribution function Wind: Weibull distribution function Load: Normal distribution function
Stochastic scenario based modeling	[119]	PV, wind, load	PV: Beta distribution function Wind: Weibull distribution function Load: Normal distribution function
Probabilistic modeling	[30]	PV, wind, load, power exchange	PV: Normal distribution Wind: Weibull distribution function Load: Normal distribution
Point Estimation Method (PEM)	[32]	PV, wind, load	-
Conditional probability distribution	[61]	PV; wind, load	RESs: Least-square support vector machines Load: Least-square support vector machines
Scenario based	[37]	PV, wind, load	-
	[62]	PV, wind, load	-
	[40]	Wind, load	-
	[96]	PV, wind, load	PV: Beta distribution function Wind: Weibull distribution function Load: Normal distribution
Taguchi's orthogonal array testing	[70]	PV, wind, load	-

References

1. Crippa, M.; Guizzardi, D.; Muntean, M.; Schaaf, E.; Solazzo, E.; Monforti-Ferrario, F.; Olivier, J.; Vignati, E. *Fossil CO_2 Emissions of All World Countries—2020 Report, EUR 30358 EN*; Publications Office of the European Union: Luxembourg, 2020.
2. Almuni, M.; Moorkens, I.; Saarikivi, R.J.; Tomescu, M. *ETC/CME Report 7/2020: Renewable Energy in Europe 2020—Recent Growth and Knock-On Effects*; Climate Change Mitigation and Energy (ETC/CME): Flanders, Belgium, 2020; 113p.
3. Bullich-Massagué, E.; Díaz-González, F.; Aragüés-Peñalba, M.; Girbau-Llistuella, F.; Olivella-Rosell, P.; Sumper, A. Microgrid clustering architectures. *Appl. Energy* **2018**, *212*, 340–361. [CrossRef]
4. Alam, M.N.; Chakrabarti, S.; Ghosh, A. Networked Microgrids: State-of-the-Art and Future Perspectives. *IEEE Trans. Ind. Inform.* **2019**, *15*, 1238–1250. [CrossRef]
5. Ton, D.T.; Smith, M.A. The US department of energy's microgrid initiative. *Electr. J.* **2012**, *25*, 84–94. [CrossRef]
6. Xie, P.; Guerrero, J.M.; Tan, S.; Bazmohammadi, N.; Vasquez, J.C.; Mehrzadi, M.; Al-Turki, Y. Optimization-Based Power and Energy Management System in Shipboard Microgrid: A Review. *IEEE Syst. J.* **2021**, *16*, 578–590. [CrossRef]
7. Jin, Z.; Savaghebi, M.; Vasquez, J.C.; Meng, L.; Guerrero, J.M. Maritime DC microgrids-a combination of microgrid technologies and maritime onboard power system for future ships. In Proceedings of the 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), Hefei, China, 22–26 May 2016; pp. 179–184.
8. Jin, Z.; Sulligoi, G.; Cuzner, R.; Meng, L.; Vasquez, J.C.; Guerrero, J.M. Next-generation shipboard dc power system: Introduction smart grid and dc microgrid technologies into maritime electrical netowrks. *IEEE Electrif. Mag.* **2016**, *4*, 45–57. [CrossRef]
9. Buticchi, G.; Costa, L.; Liserre, M. Improving system efficiency for the more electric aircraft: A look at dc\/dc converters for the avionic onboard dc microgrid. *IEEE Ind. Electron. Mag.* **2017**, *11*, 26–36. [CrossRef]
10. Buticchi, G.; Bozhko, S.; Liserre, M.; Wheeler, P.; Al-Haddad, K. On-board microgrids for the more electric aircraft—Technology review. *IEEE Trans. Ind. Electron.* **2018**, *66*, 5588–5599. [CrossRef]
11. Ghanbari, N.; Bhattacharya, S. Constant Power Load Analysis in Droop Controlled Microgrids for More Electric Aircraft Application. In Proceedings of the 2020 IEEE Transportation Electrification Conference & Expo (ITEC), Chicago, IL, USA, 23–26 June 2020; pp. 814–819.
12. Tarisciotti, L.; Costabeber, A.; Chen, L.; Walker, A.; Galea, M. Current-fed isolated DC/DC converter for future aerospace microgrids. *IEEE Trans. Ind. Appl.* **2018**, *55*, 2823–2832. [CrossRef]
13. Lashab, A.; Yaqoob, M.; Terriche, Y.; Vasquez, J.C.; Guerrero, J.M. Space Microgrids: New Concepts on Electric Power Systems for Satellites. *IEEE Electrif. Mag.* **2020**, *8*, 8–19. [CrossRef]
14. Rocabert, J.; Luna, A.; Blaabjerg, F.; Rodríguez, P. Control of power converters in AC microgrids. *IEEE Trans. Power Electron.* **2012**, *27*, 4734–4749. [CrossRef]
15. Tsikalakis, A.G.; Hatziargyriou, N.D. Centralized control for optimizing microgrids operation. In Proceedings of the 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–28 July 2011; pp. 1–8.
16. Brandao, D.I.; Caldognetto, T.; Marafão, F.P.; Simões, M.G.; Pomilio, J.A.; Tenti, P. Centralized Control of Distributed Single-Phase Inverters Arbitrarily Connected to Three-Phase Four-Wire Microgrids. *IEEE Trans. Smart Grid* **2017**, *8*, 437–446. [CrossRef]
17. Kim, J.; Jeon, J.; Kim, S.; Cho, C.; Park, J.H.; Kim, H.; Nam, K. Cooperative Control Strategy of Energy Storage System and Microsources for Stabilizing the Microgrid during Islanded Operation. *IEEE Trans. Power Electron.* **2010**, *25*, 3037–3048.
18. Wu, D.; Tang, F.; Dragicevic, T.; Vasquez, J.C.; Guerrero, J.M. A Control Architecture to Coordinate Renewable Energy Sources and Energy Storage Systems in Islanded Microgrids. *IEEE Trans. Smart Grid* **2015**, *6*, 1156–1166. [CrossRef]
19. Díaz, N.L.; Luna, A.C.; Vasquez, J.C.; Guerrero, J.M. Centralized Control Architecture for Coordination of Distributed Renewable Generation and Energy Storage in Islanded AC Microgrids. *IEEE Trans. Power Electron.* **2017**, *32*, 5202–5213. [CrossRef]
20. 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]
21. Guerrero, J.M.; Loh, P.C.; Lee, T.L.; Chandorkar, M. Advanced control architectures for intelligent microgrids—Part II: Power quality, energy storage, and AC/DC microgrids. *IEEE Trans. Ind. Electron.* **2012**, *60*, 1263–1270. [CrossRef]
22. Ahumada, C.; Cárdenas, R.; Sáez, D.; Guerrero, J.M. Secondary Control Strategies for Frequency Restoration in Islanded Microgrids With Consideration of Communication Delays. *IEEE Trans. Smart Grid* **2016**, *7*, 1430–1441. [CrossRef]
23. Liu, G.; Xu, Y.; Tomsovic, K. Bidding strategy for microgrid in day-ahead market based on hybrid stochastic/robust optimization. *IEEE Trans. Smart Grid* **2016**, *7*, 227–237. [CrossRef]
24. Prodan, I.; Zio, E. A model predictive control framework for reliable microgrid energy management. *Int. J. Electr. Power Energy Syst.* **2014**, *61*, 399–409. [CrossRef]
25. Inamdar, S.; Mohanty, R.; Chen, P.; Majumder, R.; Bongiorno, M. On Benefits and Challenges of Nested Microgrids. In Proceedings of the 2019 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Macao, China, 1–4 December 2019; pp. 1–6. [CrossRef]
26. Lasseter, R.H. Smart distribution: Coupled microgrids. *IEEE* **2011**, *99*, 1074–1082. [CrossRef]
27. Liu, G.; Starke, M.R.; Ollis, B.; Xue, Y. Networked Microgrids Scoping Study. ORNL, TN. 2016. Available online: https://info.ornl.gov/sites/publications/files/Pub68339.pdf (accessed on 15 August 2022).
28. Zou, H.; Mao, S.; Wang, Y.; Zhang, F.; Chen, X.; Cheng, L. A Survey of Energy Management in Interconnected Multi-Microgrids *IEEE Access* **2019**, *7*, 72158–72169. [CrossRef]

29. Ouammi, A.; Dagdougui, H.; Dessaint, L.; Sacile, R. Coordinated Model Predictive-Based Power Flows Control in a Cooperative Network of Smart Microgrids. *IEEE Trans. Smart Grid* **2015**, *6*, 2233–2244. [CrossRef]
30. Nikmehr, N.; Najafi Ravadanegh, S. Optimal Power Dispatch of Multi-Microgrids at Future Smart Distribution Grids. *IEEE Trans. Smart Grid* **2015**, *6*, 1648–1657. [CrossRef]
31. Ni, J.; Ai, Q. Economic power transaction using coalitional game strategy in micro-grids. *IET Gener. Transm. Distrib.* **2016**, *10*, 10–18. [CrossRef]
32. Xiao, F.; Ai, Q. New modeling framework considering economy, uncertainty, and security for estimating the dynamic interchange capability of multi-microgrids. *Electr. Power Syst. Res.* **2017**, *152*, 237–248. [CrossRef]
33. Du, Y.; Wang, Z.; Liu, G.; Chen, X.; Yuan, H.; Wei, Y.; Li, F. A cooperative game approach for coordinating multi-microgrid operation within distribution systems. *Appl. Energy* **2018**, *222*, 383–395. [CrossRef]
34. Farzin, H.; Fotuhi-Firuzabad, M.; Moeini-Aghtaie, M. Role of Outage Management Strategy in Reliability Performance of Multi-Microgrid Distribution Systems. *IEEE Trans. Power Syst.* **2018**, *33*, 2359–2369. [CrossRef]
35. Zhang, B.; Li, Q.; Wang, L.; Feng, W. Robust optimization for energy transactions in multi-microgrids under uncertainty. *Appl. Energy* **2018**, *217*, 346–360. [CrossRef]
36. Lahon, R.; Gupta, C.P. Energy management of cooperative microgrids with high-penetration renewables. *IET Renew. Power Gener.* **2018**, *12*, 680–690. [CrossRef]
37. Lahon, R.; Gupta, C.P. Risk-based coalition of cooperative microgrids in electricity market environment. *IET Gener. Transm. Distrib.* **2018**, *12*, 3230–3241. [CrossRef]
38. Li, Y.; Zhao, T.; Wang, P.; Gooi, H.B.; Wu, L.; Liu, Y.; Ye, J. Optimal operation of multimicrogrids via cooperative energy and reserve scheduling. *IEEE Trans. Ind. Inform.* **2018**, *14*, 3459–3468. [CrossRef]
39. Rahbar, K.; Chai, C.C.; Zhang, R. Energy cooperation optimization in microgrids with renewable energy integration. *IEEE Trans. Smart Grid* **2018**, *9*, 1482–1493. [CrossRef]
40. Du, Y.; Li, F. Intelligent Multi-Microgrid Energy Management Based on Deep Neural Network and Model-Free Reinforcement Learning. *IEEE Trans. Smart Grid* **2020**, *11*, 1066–1076. [CrossRef]
41. Jafari, A.; Ganjeh Ganjehlou, H.; Khalili, T.; Bidram, A. A fair electricity market strategy for energy management and reliability enhancement of islanded multi-microgrids. *Appl. Energy* **2020**, *270*, 115170. [CrossRef]
42. Wang, Z.; Chen, B.; Wang, J.; Begovic, M.M.; Chen, C. Coordinated energy management of networked microgrids in distribution systems. *IEEE Trans. Smart Grid* **2015**, *6*, 45–53. [CrossRef]
43. Zamora, R.; Srivastava, A.K. Multi-Layer Architecture for Voltage and Frequency Control in Networked Microgrids. *IEEE Trans. Smart Grid* **2018**, *9*, 2076–2085. [CrossRef]
44. Wang, X.; Wang, C.; Xu, T.; Guo, L.; Li, P.; Yu, L.; Meng, H. Optimal voltage regulation for distribution networks with multi-microgrids. *Appl. Energy* **2018**, *210*, 1027–1036. [CrossRef]
45. Xie, M.; Ji, X.; Hu, X.; Cheng, P.; Du, Y.; Liu, M. Autonomous optimized economic dispatch of active distribution system with multi-microgrids. *Energy* **2018**, *153*, 479–489. [CrossRef]
46. Zhou, X.; Ai, Q.; Yousif, M. Two kinds of decentralized robust economic dispatch framework combined distribution network and multi-microgrids. *Appl. Energy* **2019**, *253*, 113588. [CrossRef]
47. Gao, H.; Xu, S.; Liu, Y.; Wang, L.; Xiang, Y.; Liu, J. Decentralized optimal operation model for cooperative microgrids considering renewable energy uncertainties. *Appl. Energy* **2020**, *262*, 114579. [CrossRef]
48. Wei, C.; Fadlullah, Z.M.; Kato, N.; Stojmenovic, I. A novel distributed algorithm for power loss minimizing in Smart Grid. In Proceedings of the 2014 IEEE International Conference on Smart Grid Communications, SmartGridComm 2014, Venice, Italy, 3–6 November 2014; pp. 290–295. [CrossRef]
49. Guo, F.; Wen, C.; Mao, J.; Song, Y.D. Distributed Secondary Voltage and Frequency Restoration Control of Droop-Controlled Inverter-Based Microgrids. *IEEE Trans. Ind. Electron.* **2015**, *62*, 4355–4364. [CrossRef]
50. 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]
51. Wang, Z.; Chen, B.; Wang, J.; Kim, J. Decentralized Energy Management System for Networked Microgrids in Grid-Connected and Islanded Modes. *IEEE Trans. Smart Grid* **2016**, *7*, 1097–1105. [CrossRef]
52. Liu, N.; Wang, C.; Cheng, M.; Wang, J. A privacy-preserving distributed optimal scheduling for interconnected microgrids. *Energies* **2016**, *9*, 1031. [CrossRef]
53. Parisio, A.; Wiezorek, C.; Kyntäjä, T.; Elo, J.; Strunz, K.; Johansson, K.H. Cooperative MPC-Based Energy Management for Networked Microgrids. *IEEE Trans. Smart Grid* **2017**, *8*, 3066–3074. [CrossRef]
54. Wang, H.; Huang, J. Incentivizing Energy Trading for Interconnected Microgrids. *IEEE Trans. Smart Grid* **2018**, *9*, 2647–2657. [CrossRef]
55. Liu, T.; Tan, X.; Sun, B.; Wu, Y.; Tsang, D.H. Energy management of cooperative microgrids: A distributed optimization approach. *Int. J. Electr. Power Energy Syst.* **2018**, *96*, 335–346. [CrossRef]
56. Gao, H.; Liu, J.; Wang, L.; Wei, Z. Decentralized Energy Management for Networked Microgrids in Future Distribution Systems. *IEEE Trans. Power Syst.* **2018**, *33*, 3599–3610. [CrossRef]
57. Ma, W.J.; Wang, J.; Gupta, V.; Chen, C. Distributed energy management for networked microgrids using online ADMM with regret. *IEEE Trans. Smart Grid* **2018**, *9*, 847–856. [CrossRef]

58. Amoateng, D.O.; Al Hosani, M.; Elmoursi, M.S.; Turitsyn, K.; Kirtley, J.L. Adaptive Voltage and Frequency Control of Islanded Multi-Microgrids. *IEEE Trans. Power Syst.* **2018**, *33*, 4454–4465. [CrossRef]
59. Dou, X.; Xu, P.; Hu, Q.; Sheng, W.; Quan, X.; Wu, Z.; Xu, B. A distributed voltage control strategy for multi-microgrid active distribution networks considering economy and response speed. *IEEE Access* **2018**, *6*, 31259–31268. [CrossRef]
60. Hussain, A.; Bui, V.H.; Kim, H.M. Resilience-Oriented Optimal Operation of Networked Hybrid Microgrids. *IEEE Trans. Smart Grid* **2019**, *10*, 204–215. [CrossRef]
61. Du, Y.; Wu, J.; Li, S.; Long, C.; Onori, S. Coordinated Energy Dispatch of Autonomous Microgrids With Distributed MPC Optimization. *IEEE Trans. Ind. Inform.* **2019**, *15*, 5289–5298. [CrossRef]
62. Utkarsh, K.; Srinivasan, D.; Trivedi, A.; Zhang, W.; Reindl, T. Distributed Model-Predictive Real-Time Optimal Operation of a Network of Smart Microgrids. *IEEE Trans. Smart Grid* **2019**, *10*, 2833–2845. [CrossRef]
63. Li, Q.; Gao, M.; Lin, H.; Chen, Z.; Chen, M. MAS-based distributed control method for multi-microgrids with high-penetration renewable energy. *Energy* **2019**, *171*, 284–295. [CrossRef]
64. Wang, L.; Zhang, B.; Li, Q.; Song, W.; Li, G. Robust distributed optimization for energy dispatch of multi-stakeholder multiple microgrids under uncertainty. *Appl. Energy* **2019**, *255*, 113845. [CrossRef]
65. Wu, X.; Xu, Y.; Wu, X.; He, J.; Guerrero, J.M.; Liu, C.C.; Schneider, K.P.; Ton, D.T. A Two-Layer Distributed Cooperative Control Method for Islanded Networked Microgrid Systems. *IEEE Trans. Smart Grid* **2020**, *11*, 942–957. [CrossRef]
66. Wang, Y.; Mao, S.; Nelms, R.M. On hierarchical power scheduling for the macrogrid and cooperative microgrids. *IEEE Trans. Ind. Inform.* **2015**, *11*, 1574–1584. [CrossRef]
67. Bahramara, S.; Moghaddam, M.P.; Haghifam, M.R. Modelling hierarchical decision making framework for operation of active distribution grids. *IET Gener. Transm. Distrib.* **2015**, *9*, 2555–2564. [CrossRef]
68. Farzin, H.; Fotuhi-Firuzabad, M.; Moeini-Aghtaie, M. Enhancing Power System Resilience Through Hierarchical Outage Management in Multi-Microgrids. *IEEE Trans. Smart Grid* **2016**, *7*, 2869–2879. [CrossRef]
69. Tian, P.; Xiao, X.; Wang, K.; Ding, R. A Hierarchical Energy Management System Based on Hierarchical Optimization for Microgrid Community Economic Operation. *IEEE Trans. Smart Grid* **2016**, *7*, 2230–2241. [CrossRef]
70. Marzband, M.; Parhizi, N.; Savaghebi, M.; Guerrero, J.M. Distributed Smart Decision-Making for a Multimicrogrid System Based on a Hierarchical Interactive Architecture. *IEEE Trans. Energy Convers.* **2016**, *31*, 637–648. [CrossRef]
71. Wang, Z.; Chen, B.; Wang, J.; Chen, C. Networked microgrids for self-healing power systems. *IEEE Trans. Smart Grid* **2016**, *7*, 310–319. [CrossRef]
72. Lv, T.; Ai, Q. Interactive energy management of networked microgrids-based active distribution system considering large-scale integration of renewable energy resources. *Appl. Energy* **2016**, *163*, 408–422. [CrossRef]
73. Wang, D.; Guan, X.; Wu, J.; Li, P.; Zan, P.; Xu, H. Integrated Energy Exchange Scheduling for Multimicrogrid System with Electric Vehicles. *IEEE Trans. Smart Grid* **2016**, *7*, 1762–1774. [CrossRef]
74. Kou, P.; Liang, D.; Gao, L. Distributed EMPC of multiple microgrids for coordinated stochastic energy management. *Appl. Energy* **2017**, *185*, 939–952. [CrossRef]
75. Liu, Y.; Guo, L.; Wang, C. A robust operation-based scheduling optimization for smart distribution networks with multi-microgrids. *Appl. Energy* **2018**, *228*, 130–140. [CrossRef]
76. Bui, V.H.; Hussain, A.; Kim, H.M. A multiagent-based hierarchical energy management strategy for multi-microgrids considering adjustable power and demand response. *IEEE Trans. Smart Grid* **2018**, *9*, 1323–1333. [CrossRef]
77. Dehghanpour, K.; Nehrir, H. An Agent-Based Hierarchical Bargaining Framework for Power Management of Multiple Cooperative Microgrids. *IEEE Trans. Smart Grid* **2019**, *10*, 514–522. [CrossRef]
78. Zou, S.; Ma, Z.; Yang, N. Decentralised hierarchical coordination of electric vehicles in multi-microgrid systems. *IET Gener. Transm. Distrib.* **2019**, *13*, 2899–2906. [CrossRef]
79. Du, Y.; Wu, J.; Li, S.; Long, C.; Onori, S. Hierarchical Coordination of Two-Time Scale Microgrids with Supply-Demand Imbalance. *IEEE Trans. Smart Grid* **2020**, *11*, 3726–3736. [CrossRef]
80. Zhang, Q.; Dehghanpour, K.; Wang, Z.; Huang, Q. A Learning-Based Power Management Method for Networked Microgrids under Incomplete Information. *IEEE Trans. Smart Grid* **2020**, *11*, 1193–1204. [CrossRef]
81. Mehri Arsoon, M.; Moghaddas-Tafreshi, S.M. Peer-to-peer energy bartering for the resilience response enhancement of networked microgrids. *Appl. Energy* **2020**, *261*, 114413. [CrossRef]
82. Zhao, T.; Wang, J.; Lu, X. An MPC-aided Resilient Operation of Multi-Microgrids with Dynamic Boundaries. *IEEE Trans. Smart Grid* **2020**, *12*, 2125–2135. [CrossRef]
83. Garcia-Torres, F.; Bordons, C.; Tobajas, J.; Márquez, J.J.; Garrido-Zafra, J.; Moreno-Muñoz, A. Optimal Schedule for Networked Microgrids Under Deregulated Power Market Environment Using Model Predictive Control. *IEEE Trans. Smart Grid* **2020**, *12*, 182–191. [CrossRef]
84. Chen, J.; Chen, C.; Duan, S. Cooperative optimization of electric vehicles and renewable energy resources in a regional multi-microgrid system. *Appl. Sci.* **2019**, *9*, 2267. [CrossRef]
85. Nguyen, H.K.; Khodaei, A.; Han, Z. A big data scale algorithm for optimal scheduling of integrated microgrids. *IEEE Trans. Smart Grid* **2018**, *9*, 274–282. [CrossRef]
86. Hussain, A.; Bui, V.H.; Kim, H.M. Robust optimization-based scheduling of multi-microgrids considering uncertainties. *Energies* **2016**, *9*, 278. [CrossRef]

87. Qiu, H.; You, F. Decentralized-distributed robust electric power scheduling for multi-microgrid systems. *Appl. Energy* **2020**, *269*, 115146. [CrossRef]
88. Bazmohammadi, N.; Tahsiri, A.; Anvari-Moghaddam, A.; Guerrero, J.M. A hierarchical energy management strategy for interconnected microgrids considering uncertainty. *Int. J. Electr. Power Energy Syst.* **2019**, *109*, 597–608. [CrossRef]
89. Yan, M.; Shahidehpour, M.; Paaso, A.; Zhang, L.; Alabdulwahab, A.; Abusorrah, A. Distribution Network-Constrained Optimization of Peer-to-Peer Transactive Energy Trading among Multi-Microgrids. *IEEE Trans. Smart Grid* **2020**, *12*, 1033–1047. [CrossRef]
90. John, T.; Lam, S.P. Voltage and frequency control during microgrid islanding in a multi-area multi-microgrid system. *IET Gener. Transm. Distrib.* **2017**, *11*, 1502–1512. [CrossRef]
91. Golsorkhi, M.S.; Hill, D.J.; Karshenas, H.R. Distributed voltage control and power management of networked microgrids. *IEEE J. Emerg. Sel. Top. Power Electron.* **2018**, *6*, 1892–1902. [CrossRef]
92. Hossain, M.J.; Mahmud, M.A.; Milano, F.; Bacha, S.; Hably, A. Design of Robust Distributed Control for Interconnected Microgrids. *IEEE Trans. Smart Grid* **2016**, *7*, 2724–2735. [CrossRef]
93. Xu, Q.; Zhao, T.; Xu, Y.; Xu, Z.; Wang, P.; Blaabjerg, F. A Distributed and Robust Energy Management System for Networked Hybrid AC/DC Microgrids. *IEEE Trans. Smart Grid* **2019**, *11*, 3496–3508. [CrossRef]
94. Du, Y.; Wu, J.; Li, S.; Long, C.; Paschalidis, I.C. Distributed MPC for coordinated energy efficiency utilization in microgrid systems. *IEEE Trans. Smart Grid* **2019**, *10*, 1781–1790. [CrossRef]
95. Zhao, B.; Wang, X.; Lin, D.; Calvin, M.M.; Morgan, J.C.; Qin, R.; Wang, C. Energy management of multiple microgrids based on a system of systems architecture. *IEEE Trans. Power Syst.* **2018**, *33*, 6410–6421. [CrossRef]
96. Nikmehr, N.; Najafi Ravadanegh, S. Reliability evaluation of multi-microgrids considering optimal operation of small scale energy zones under load-generation uncertainties. *Int. J. Electr. Power Energy Syst.* **2016**, *78*, 80–87. [CrossRef]
97. Yoo, H.J.; Nguyen, T.T.; Kim, H.M. Multi-frequency control in a stand-alone multi-microgrid system using a back-to-back converter. *Energies* **2017**, *10*, 822. [CrossRef]
98. Keshta, H.E.; Ali, A.A.; Saied, E.M.; Bendary, F.M. Real-time operation of multi-micro-grids using a multi-agent system. *Energy* **2019**, *174*, 576–590. [CrossRef]
99. Liu, Y.; Qu, Z.; Xin, H.; Gan, D. Distributed Real-Time Optimal Power Flow Control in Smart Grid. *IEEE Trans. Power Syst.* **2017**, *32*, 3403–3414. [CrossRef]
100. Zhou, J.; Zhang, H.; Sun, Q.; Ma, D.; Huang, B. Event-based distributed active power sharing control for interconnected AC and DC microgrids. *IEEE Trans. Smart Grid* **2018**, *9*, 6815–6828. [CrossRef]
101. Liu, Y.; Li, Y.; Xin, H.; Gooi, H.B.; Pan, J. Distributed Optimal Tie-Line Power Flow Control for Multiple Interconnected AC Microgrids. *IEEE Trans. Power Syst.* **2019**, *34*, 1869–1880. [CrossRef]
102. Hans, C.A.; Braun, P.; Raisch, J.; Grune, L.; Reincke-Collon, C. Hierarchical Distributed Model Predictive Control of Interconnected Microgrids. *IEEE Trans. Sustain. Energy* **2019**, *10*, 407–416. [CrossRef]
103. Liu, W.; Gu, W.; Xu, Y.; Wang, Y.; Zhang, K. General distributed secondary control for multi-microgrids with both PQ-controlled and droop-controlled distributed generators. *IET Gener. Transm. Distrib.* **2017**, *11*, 707–718. [CrossRef]
104. Liu, W.; Gu, W.; Wang, J.; Yu, W.; Xi, X. Game theoretic non-cooperative distributed coordination control for multi-microgrids. *IEEE Trans. Smart Grid* **2018**, *9*, 6986–6997. [CrossRef]
105. Liu, Y.; Li, Y.; Gooi, H.B.; Jian, Y.; Xin, H.; Jiang, X.; Pan, J. Distributed Robust Energy Management of a Multimicrogrid System in the Real-Time Energy Market. *IEEE Trans. Sustain. Energy* **2019**, *10*, 396–406. [CrossRef]
106. Rahbar, K.; Chai, C.C.; Zhang, R. Real-time energy management for cooperative microgrids with renewable energy integration. In Proceedings of the 2014 IEEE International Conference on Smart Grid Communications, SmartGridComm 2014, Venice, Italy, 3–6 November 2014; pp. 25–30. [CrossRef]
107. Shafiee, Q.; Dragicevic, T.; Vasquez, J.C.; Guerrero, J.M. Modeling, stability analysis and active stabilization of multiple DC-microgrid clusters. In Proceedings of the 2014 IEEE International Energy Conference (ENERGYCON), Cavtat, Croatia, 13–16 May 2014; pp. 1284–1290.
108. Tah, A.; Das, D. An Enhanced Droop Control Method for Accurate Load Sharing and Voltage Improvement of Isolated and Interconnected DC Microgrids. *IEEE Trans. Sustain. Energy* **2016**, *7*, 1194–1204. [CrossRef]
109. Werth, A.; Kitamura, N.; Tanaka, K. Conceptual study for open energy systems: Distributed energy network using interconnected DC nanogrids. *IEEE Trans. Smart Grid* **2015**, *6*, 1621–1630. [CrossRef]
110. Abdali, A.; Noroozian, R.; Mazlumi, K. Simultaneous control and protection schemes for DC multi microgrids systems. *Int. J. Electr. Power Energy Syst.* **2019**, *104*, 230–245. [CrossRef]
111. Qiu, H.; Zhao, B.; Gu, W.; Bo, R. Bi-Level Two-Stage Robust Optimal Scheduling for AC/DC Hybrid Multi-Microgrids. *IEEE Trans. Smart Grid* **2018**, *9*, 5455–5466. [CrossRef]
112. 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.* **2011**, *58*, 158–172. [CrossRef]
113. Mohiti, M.; Monsef, H.; Anvari-moghaddam, A.; Guerrero, J.; Lesani, H. A decentralized robust model for optimal operation of distribution companies with private microgrids. *Int. J. Electr. Power Energy Syst.* **2019**, *106*, 105–123. [CrossRef]
114. Lv, T.; Ai, Q.; Zhao, Y. A bi-level multi-objective optimal operation of grid-connected microgrids. *Electr. Power Syst. Res.* **2016**, *131*, 60–70. [CrossRef]

115. Wang, D.; Qiu, J.; Reedman, L.; Meng, K.; Lai, L.L. Two-stage energy management for networked microgrids with high renewable penetration. *Appl. Energy* **2018**, *226*, 39–48. [CrossRef]
116. Nikmehr, N.; Najafi-Ravadanegh, S.; Khodaei, A. Probabilistic optimal scheduling of networked microgrids considering time-based demand response programs under uncertainty. *Appl. Energy* **2017**, *198*, 267–279. [CrossRef]
117. Sandgani, M.R.; Sirouspour, S. Priority-Based Microgrid Energy Management in a Network Environment. *IEEE Trans. Sustain. Energy* **2018**, *9*, 980–990. [CrossRef]
118. Jadhav, A.M.; Patne, N.R.; Guerrero, J.M. A Novel Approach to Neighborhood Fair Energy Trading in a Distribution Network of Multiple Microgrid Clusters. *IEEE Trans. Ind. Electron.* **2019**, *66*, 1520–1531. [CrossRef]
119. Gazijahani, F.S.; Salehi, J. Stochastic multi-objective framework for optimal dynamic planning of interconnected microgrids. *IET Renew. Power Gener.* **2017**, *11*, 1749–1759. [CrossRef]
120. Wang, Z.; Wang, J. Self-Healing Resilient Distribution Systems Based on Sectionalization into Microgrids. *IEEE Trans. Power Syst.* **2015**, *30*, 3139–3149. [CrossRef]
121. Zhang, W.; Xu, Y. Distributed Optimal Control for Multiple Microgrids in a Distribution Network. *IEEE Trans. Smart Grid* **2019**, *10*, 3765–3779. [CrossRef]
122. Yang, X.; He, H.; Zhang, Y.; Chen, Y.; Weng, G. Interactive Energy Management for Enhancing Power Balances in Multi-Microgrids. *IEEE Trans. Smart Grid* **2019**, *10*, 6055–6069. [CrossRef]
123. Jalali, M.; Zare, K.; Seyedi, H. Strategic decision-making of distribution network operator with multi-microgrids considering demand response program. *Energy* **2017**, *141*, 1059–1071. [CrossRef]
124. Esmaeili, S.; Anvari-Moghaddam, A.; Jadid, S. Retail market equilibrium and interactions among reconfigurable networked microgrids. *Sustain. Cities Soc.* **2019**, *49*, 101628. [CrossRef]
125. Sen, S.; Kumar, V. Microgrid control: A comprehensive survey. *Annu. Rev. Control.* **2018**, *45*, 118–151. [CrossRef]
126. Sam, A.A. Nested Microgrids: Operation and Control Requirement. 2018. Available online: https://www.cired-repository.org/handle/20.500.12455/1054 (accessed on 15 August 2022).
127. Liu, K.; Liu, T.; Tang, Z.; Hill, D.J. Distributed MPC-Based Frequency Control in Networked Microgrids with Voltage Constraints. *IEEE Trans. Smart Grid* **2019**, *10*, 6343–6354. [CrossRef]
128. Che, L.; Shahidehpour, M.; Alabdulwahab, A.; Al-Turki, Y. Hierarchical coordination of a community microgrid with AC and DC microgrids. *IEEE Trans. Smart Grid* **2015**, *6*, 3042–3051. [CrossRef]
129. Hussain, A.; Bui, V.H.; Kim, H.M. A Resilient and Privacy-Preserving Energy Management Strategy for Networked Microgrids. *IEEE Trans. Smart Grid* **2018**, *9*, 2127–2139. [CrossRef]