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Review

Comprehensive Analysis of Microgrids Configurations and Topologies

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Abstract: Microgrids have been proposed as a solution to the growing deterioration of traditional electrical power systems and the energy transition towards renewable sources. One of the most important aspects of the efficient operation of a microgrid is its topology, that is, how the components are connected. Some papers have studied microgrid topologies; however, these studies do not perform an exhaustive analysis of the types of topologies, their applications, characteristics, or technical advantages and disadvantages. The contribution of this paper is the integration of the most important functional properties of microgrid topologies in terms of reliability, efficiency, structure, costs, and control methods. The study analyzes 21 topologies divided into six classifications with their respective sub-classifications. The analysis was based on the characteristics of the current (AC or DC), the control mechanisms, the transition between the operating modes, and the operating costs. As a result of the evaluation, it was evidenced that SST-based completely isolated coupled AC topologies, completely isolated two-stage AC decoupled, and multiple microgrids show the best performances. In contrast, the use of two-stage and three-stage partially isolated AC decoupled topologies is not recommended because of their high operating cost and low efficiency and reliability.

Keywords: distributed generation; electrical power system microgrid; network topology; renewable energy

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1. Introduction

Traditional electric power systems (EPS) are characterized by supplying energy to users from centralized generation systems. Currently, these systems are in crisis due to the predominant use of fossil fuels that cause environmental problems. Another problem in these systems is that the power supplies are located far from the demand centers, causing energy and economic losses [1]. Additionally, the long distances between the generation and consumption centers, the obsolescence of EPS elements, and the growth of electricity demand have increased energy quality problems [2,3]. As a solution to these problems, EPS have recently been divided into a small distributed network, known as a microgrid (MG) [4].

MGs have been defined in various ways by specialized literature. The IEEE Std 2030.8-2018 standard defines an MG as the interconnection of a set of distributed energy resources (DER) and loads that act as a particular controllable entity concerning the EPS [5]. According to the IEC TS 62898-1:2017 standard, an MG is an electrical system with energy resources and loads that act as a controllable entity, able of operating in an island or EPS-connected mode [6]. In [7], the authors defined an MG as a small-scale controlled energy system that can operate in island mode or be connected to the EPS in a defined area. Despite the different descriptions, definitions agree on the characteristics of their modes of operation [8].

MGs have become an option to reduce dependency between consumption centers and EPS [1]. According to [9–11], MGs can export and import energy from the EPS and to the EPS using renewable energy sources.

It is expected that in the short- and medium-term the number of MGs may increase due to benefits such as improving power quality and supplying local power when EPS power outages occur [12–14]. However, challenges are posed for MGs due to their bi-directional power flows, EPS structure, configuration type, classification, location, and the varying characteristics of some distributed generation units [15,16].

An MG may change according to their topology and configuration [17]. Connection or disconnection of the DER produces different topologies that may cause variations in the current directions and limits [18,19]. Additionally, improper installation and intermittent behavior of DERs may produce some problems related to frequency variation, voltage instability, power losses increasing, and active and reactive power imbalance. Therefore, a control method that guarantees efficient and safe power transfer is essential [20].

Due to the importance of MGs in the current context of changes in EPS, several researchers have conducted studies on their evolution and challenges. In [2], hybrid MGs based on the interconnection of the current (DC or AC) networks and the EPS were reviewed. However, AC and DC topologies were not considered, nor were selection suggestions. In [21], a system of multiple interconnected hybrid MGs was studied; however, it was not detailed in the characteristics of the topology but in the structure used.

In [22], the authors focused on the obstacles to implementing DC MGs, such as standardization and protection schemes. The study argued that before moving towards protection challenges, it is necessary to understand the architecture of the DC MG. The authors briefly described some DC MG topologies with their advantages and disadvantages. In the study presented in [12], three topologies of MGs were studied that intend to adapt to the marine environment, selecting the most suitable one in a land–sea relay fishing net. In both studies, a limited number of topologies were analyzed.

In [23], MG models and strategies based on four dimensions were assessed: goals and modeling metrics, resilience scenarios, modeling approaches, and strategies and topologies. The network topologies used in each dimension were: (a) MGs as virtual feeders for global resilience, (b) dynamic formation of MGs for global resilience, (c) MGs in island mode for local resilience, and (d) MGs for local resilience. These dimensions only represent the centralized control method; therefore, it did not delve into other types of topologies.

Although the selection of the MG topology is one of the most significant aspects for the efficient incorporation of DER in EPS, studies on the subject are based on diverse and limited criteria that do not allow a comprehensive analysis of the types of topologies, their applications, characteristics, or technical advantages and disadvantages.

Due to the limited and scattered information reported on the main characteristics of MG topologies, this article aims to analyze and compare the main topologies presented in various studies. The evaluation is based on the characteristics of the current (AC or DC), the control mechanisms, the transition between the operating modes, and the operating costs, allowing for the assessment of the technical advantages and disadvantages of each topology. This study intended to contribute to establishing criteria that facilitate the design and selection of the appropriate topologies for EPS expansion projects that include the incorporation of MGs with DER.

The contribution of this paper is the integration of the most important functional properties of MG topologies in terms of reliability, efficiency, structure, costs, and control methods. The research carried out is relevant because MGs are part of possible solutions for the energy transition towards renewable sources and to reverse the growing deterioration of EPS.

This paper is organized as follows. Section 2 describes the classifications of MGs and operation modes. Section 3 discusses the topologies of MGs, classifications, advantages, disadvantages, and finally, the conclusion is presented according to the results.

2. Classification of MGs

An MG is classified as a controllable entity made up of loads and DER that can operate connected to the electricity EPS or in island mode under defined electrical limits [24]. DERs can be integrated into wind generators, photovoltaic (PV) panels, microturbines, and other low-power generators, which are located close to the users [25]. Due to the reduction in prices and the increase in the energy conversion efficiency of DERs, developed countries have reached a certain level of mass use of these resources. However, in many less developed countries, difficulties as high electricity prices, obsolescence of EPS elements, and the lack of attractive economic models have prevented the massive penetration of DERs into electricity systems [26].

The general structure of an MG is represented in Figure 1. This network is connected to the EPS through a point of common coupling (PCC) to exchange energy or operate in island mode in case of maintenance or unintentional island mode scenarios [27].

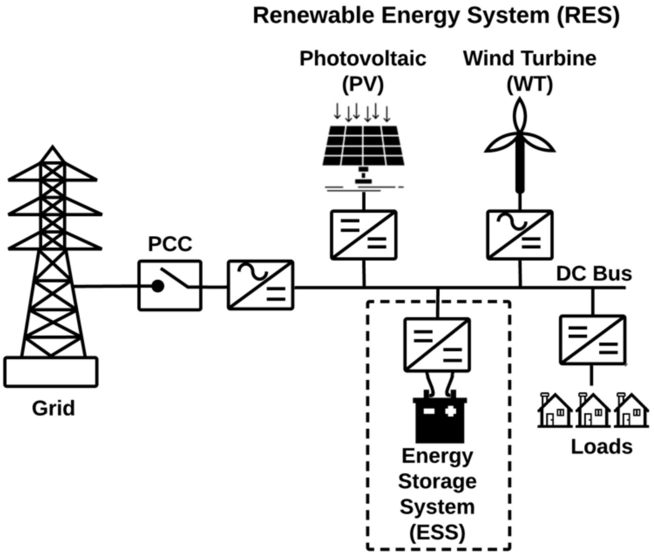

Figure 1. General scheme of an MG [27].

Figure 1 shows that an MG can be represented as a system that integrates a set of loads, DERs units, and energy storage systems (ESS) that allow storing and delivering power. In an MG, the generation units can be selected according to the primary energy available. The main types of generation are PV, wind, hydro, diesel, and hybrid energy [28].

Electricity production based on renewable energies increased from 10% in 2010 to 20% in 2020. This is due to the reduction in the costs of solar and wind technologies and the development of government policies aimed at encouraging the use of these forms of generation [29,30].

Wind generation has not only been proven to be highly profitable, with low operating costs, but it is also adaptable to various places because of abundant and free resources of wind.

Solar generation represents an unlimited resource, which does not generate noise to the population that is near the power plants. It is also highly profitable, and PV cells have also shown a strong increase in efficiency, which allows for greater transformer capacity. Another advantage is that these systems do not have moving parts, nor do they require high maintenance costs [31,32].

MGs have three operation modes. The first mode is connected to the EPS, which handles better stability issues and electricity costs. The second mode is disconnected from the EPS, which converts the EPS into a small grid that supplies the load in emergency or island mode. The third mode is MG shutdown, which is a network security measure to avoid damages to elements [33]. These modes of operation are represented in Figure 2.

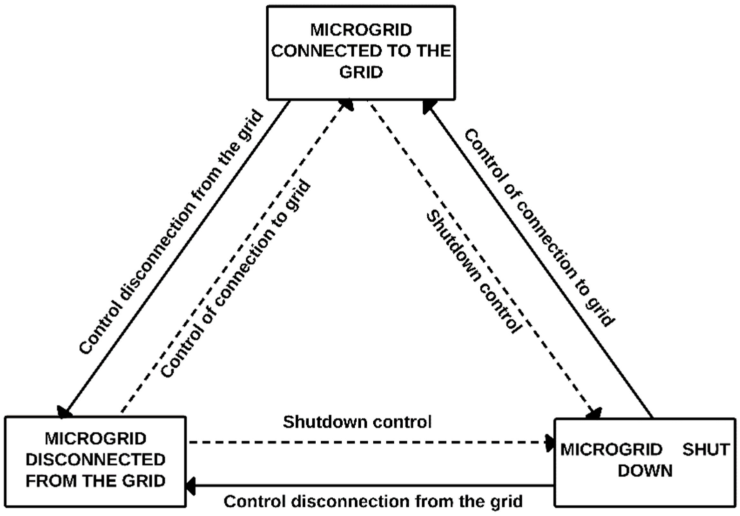

Figure 2. Operation modes of an MG [33].

According to Figure 2, three control mechanisms are used to change from one operation mode to another. The first control mechanism is disconnection from the EPS, in which the MG can turn the operation to island mode. The second control mechanism is connection to the EPS, which allows the MG to operate with the EPS. Finally, the third mechanism is shutdown control, which turns off the MG and stops operation [33,34].

MGs can be classified according to the criteria shown in Figure 3 considering the electricity demand, the capacity of the system, and the type of circuit (AC/DC) [1,33,35].

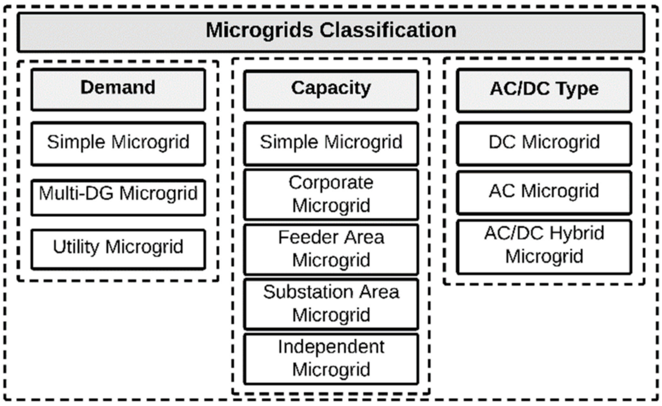

Figure 3. Classification of MGs [33].

According to Figure 3, by considering the electricity demand, MGs can be classified into three types. The first type is the simple MG, which has a single type of distributed generation (DG). The second type is the multi-DG MG composed of several simple MGs. The third type is the utility MG, where loads are prioritized based on user reliability requirements.

The classification according to capacity refers to the type of loads, the power demand, and the area that the MG must supply. According to its extension, the size of the MG defines the availability of the equipment, the operation with the EPS, and the installation and maintenance costs [8]. Table 1 shows the types of MGs according to their capacity.

Table 1. Classification of MGs according to capacity [33].

Type	Capacity (MW)
Simple MG	Less than 2
Corporate MG	Between 2 and 5
Feeder area MG	Between 5 and 20
Substation area MG	Greater than 20
Independent MG	Depending on the loads in remote areas (island, mountainous area, or a village).

According to the type of circuit, the MGs can be classified as AC, DC, and hybrid MGs [36]. This is the most used classification because it considers characteristics of the electric current that is generated, distributed, and consumed [37]. A DC MG has the advantages of storage system integration, higher efficiency because of elimination of DG synchronization, and fewer AC-DC-AC conversions. AC MGs have had a predominance over DC MGs because of the easy transformation of voltage levels with low-frequency transformers, protection, and fault handling. However, AC MGs face challenges with DG timing and reactive power control [38]. On the other hand, studies indicate that 30% of the energy produced in AC is transferred to the DC supply or passes through at least one converter before it is used, a situation that, together with advances in semiconductor technology, allows us to reconsider the implementation of DC MGs [38].

3. MGs Topologies

During the design of an MG, the components and physical arrangement must be considered to achieve a proper transition between the different modes of operation. The connection of the loads, the microgenerators, and the storage elements, require rigorous analysis to obtain the operation and the desired efficiency by the network operator and the user. The way to interconnect all the elements of the network is known as MG topology [39,40].

Topologies can be selected considering the following characteristics [34,41,42]:

- Control mechanisms of the dynamic characteristics of the DGs resources;
- Voltage regulation and frequency for power balance both in island mode and connected to the EPS;
- The transition between operation modes to detect situations that cause changes;
- Economic dispatch to share the load between different DGs;
- Renewable sources are available;
- Minimum impact on the distribution network;
- Coordination between DERs.

The principal classifications of MG topologies are shown in Figure 4. Depending on the type of power supplied, MG topologies are divided into DC, AC, hybrid, and 3-NET [21,43,44]. According to its configuration, MGs are classified into cascade-type and parallel-type MGs.

AC MG systems use the same operating mechanisms as traditional AC power systems, such as frequency, voltage levels, and protection features [45]. DC MGs have been implemented in recent times because of the development of power electronics technology that has increased DC loads and power converters for DC voltage transformation at different levels for different applications [46]. At present, DC MG systems are implemented in special applications such as aviation, automotive, marine, and manufacturing industries; however, an expansion in residential distribution systems is planned [47,48].

Hybrid MG topologies, as seen in Figure 5, can be classified as AC coupling, AC decoupling, and multiple MGs [44].

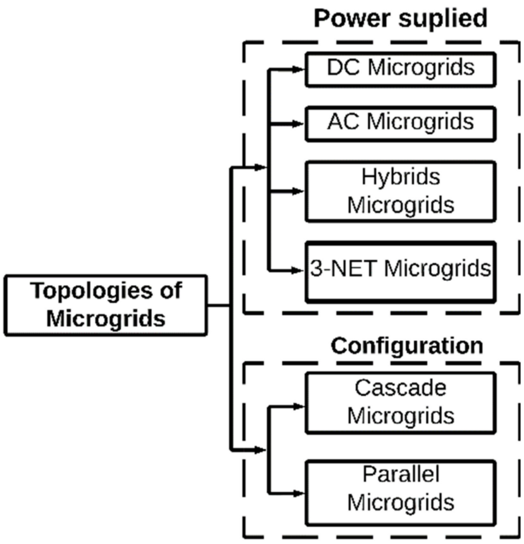

Figure 4. Topologies of MGs.

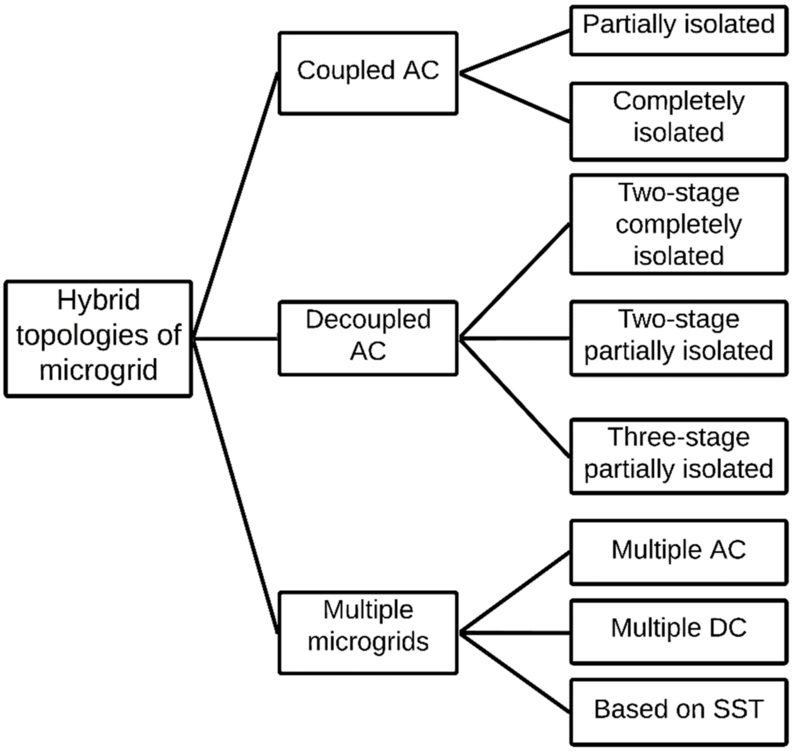

Figure 5. Hybrid topologies of MG [2,21,43].

In the coupled AC topology, the connection to the EPS is made through an AC MG. In the decoupled AC topology, there is not a direct connection between the utility EPS and the AC MG [2]; therefore, it is more expensive. A decoupled MG, in general, is more expensive than coupled MG because higher capacity AC-DC converters are needed [2,49,50]. The multiple MGs' topology corresponds to a network of several MGs AC or DC that are connected to the high-voltage network and other MGs.

The 3-Net MG topology consists of the union of three different types of networks: a high-quality DC network, a low-quality DC network, and an AC network. This topology makes it possible to supply energy in a single MG to elements of different levels of sensitivity concerning changes in the power quality parameters. An example is rural networks that may have loads such as computers, which are very sensitive to voltage disturbances, along with loads such as water heaters, which are not sensitive to these disturbances. Although 3-Net MGs have high reliability, they represent a higher cost in their development and implementation [39].

According to the configuration, MG topologies can be divided into two categories: parallel type and cascade type. The parallel type has been the subject of numerous investigations and is used in applications that include state-of-charge (SOC) balance for storage systems and obtaining optimal economic distribution schemes for DGs [43]. They also include voltage drop control with a maximum power point tracking (MPPT) regulator of PV systems and an optimal DG distribution scheme.

The cascade type is recent and has a relevant function in applications that require the reliable use of DER at a high-voltage level [51]. Furthermore, it is practical in MGs that operate in island mode, where the energy balance between all modules is fundamental [51–53].

3.1. Control Structures of DC and AC MGs

According to the control structures, the AC and DC MGs are divided into two groups as can be seen in Figure 6. The first group is the control methods, and the second group is the load-sharing techniques [54,55].

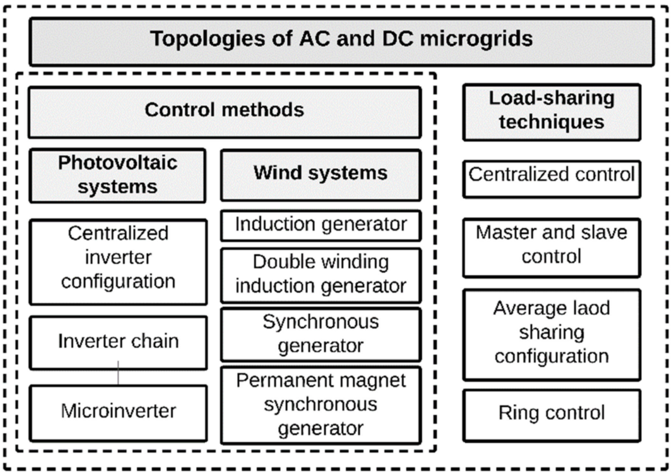

Figure 6. Topologies of AC and DC MGs [33].

In the control structures, the power electronic converters are essential components because they must ensure the adequate supply and distribution of the electrical load without affecting the correct operation of the system [55,56].

3.1.1. Control Method

PV Systems

In PV systems the control methods depend on the type of configuration (i.e., centralized inverter, inverter chain, and microinverter configuration).

Centralized Inverter Configuration

The centralized inverter configuration, presented in Figure 7, has one of the highest efficiencies of all PV systems (over 98%). This configuration is estimated to be used in 44% of PV systems installed in the commercial and utility sectors.

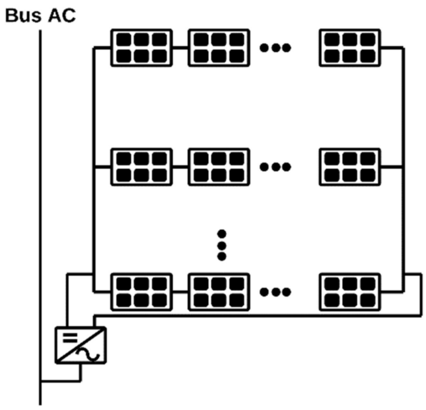

Figure 7. Centralized inverter configuration [55,56].

This configuration is used mainly in residential as well as in small and medium commercial applications offering reliability [57–59]. Additionally, both the implementation and maintenance costs are the lowest of the PV configuration types [57–59]. However, damage to the inverter stops the entire system, so constant maintenance is necessary, and available inverters are required for replacement [57–59]. Some applications using this topology for AC and DC MGs were assessed in [60–62].

Inverter Chain Configuration

The inverter chain represented in Figure 8 has high efficiency (approx. 98%), making it highly profitable. It has power ranges of around 150 kW peak and is estimated to have the highest percentage of use in the market [57–59].

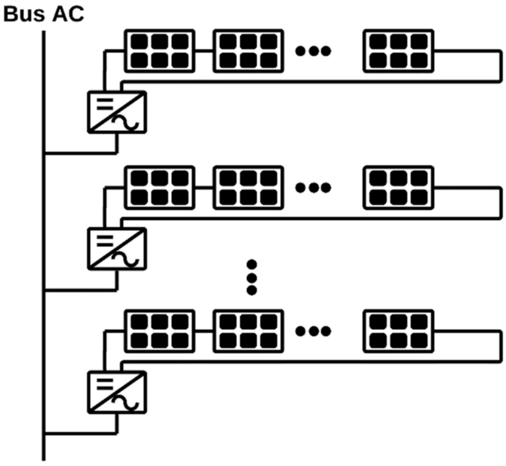

Figure 8. Inverter chains [55,56].

This configuration is reliable, which allows it to be used in residential and some commercial applications. Because there are different inverter cell groupings, the damage of one does not prevent the system from generating power continually [57–59]. However, this configuration is expensive because it requires an inverter for each group of cells, increasing maintenance costs [57–59]. Applications with this configuration were studied in [63–65].

Microinverter Configuration

The microinverter configuration, presented in Figure 9, is the least used. In this configuration, the inverter is connected directly to a battery and converts DC to AC.

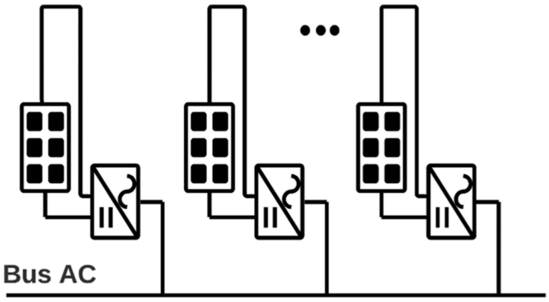

Figure 9. Microinverter [55,56].

The batteries are charged by PV cells and are optimized to be used with a single PV panel [57–59]. In this configuration, installation costs are low, and parts are easy to replace, ensuring continuous use and fast maintenance. In addition, the panels are independent, which means that the failure of one does not affect the total system [57–59]. However, it does not have galvanic isolation between the AC-DC connection, affecting reliability between users [57–59]. In [66,67] various implementations of this architecture were assessed.

Wind Systems

In wind systems, the control methods depend on the technology of the generator used (i.e., induction generator, double-winding induction generator, synchronous generator, and permanent-magnet synchronous generator).

Induction Generator

The induction generator configuration (see Figure 10) can be divided into cage rotor and wound rotor. In addition, it can present multiple configurations according to the use of the loads, such as capacitor banks, frequency converters, and starters. This configuration generates electricity, converting the mechanical energy of the movement of the blades into a magnetic field [31,58].

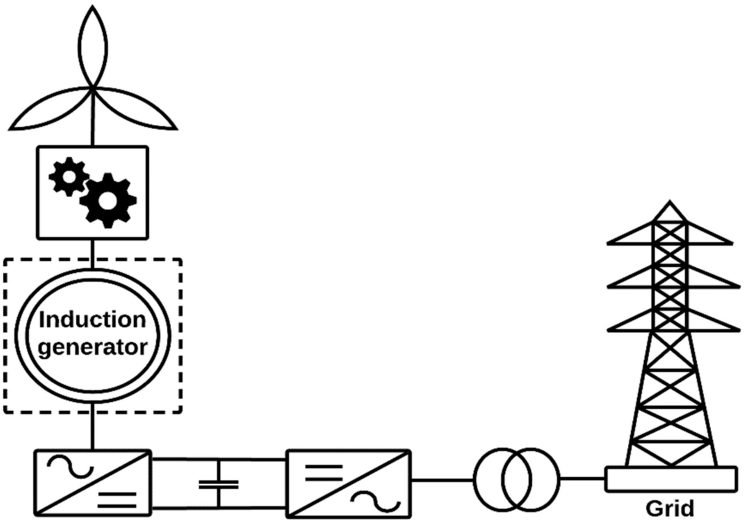

Figure 10. Induction generator [55,56].

This configuration is built robustly, ensuring its prolonged use. Generally, it does not require additional elements and can easily be used in parallel configurations in spaces already used, such as farms and vacant lots [31,58]. However, this configuration has moving parts that require constant maintenance, take up a lot of space, and generally require high starting torque. Additionally, the power factor of this generator can be reduced to low values [31,58]. This topology was used in [68,69].

Double-Winding Induction Generator

The double-winding induction generator is characterized by having a winding that covers the rotor. In this configuration, represented in Figure 11, the stator fulfills the function of controlling the power flow, while the power is controlled from the connection to the rotor [56,70].

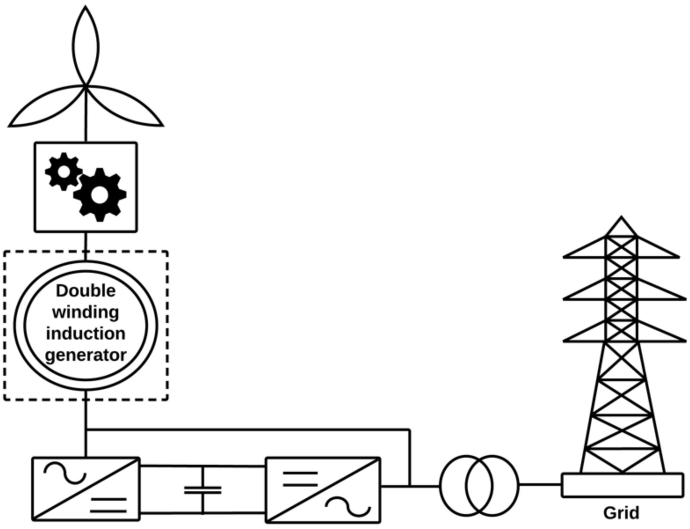

Figure 11. Induction generator [55,56].

This configuration allows greater power generation without overheating and allows the stator to be connected directly to the EPS [56,70]. However, they require additional equipment to control the frequency of the network [56,70].

Synchronous Generator

This configuration, as shown in Figure 12, comprises a fixed stator with a three-phase wound and a rotor with a magnetic field. They also have multiple subdivisions based on construction, excitation mode, and the parts used [70].

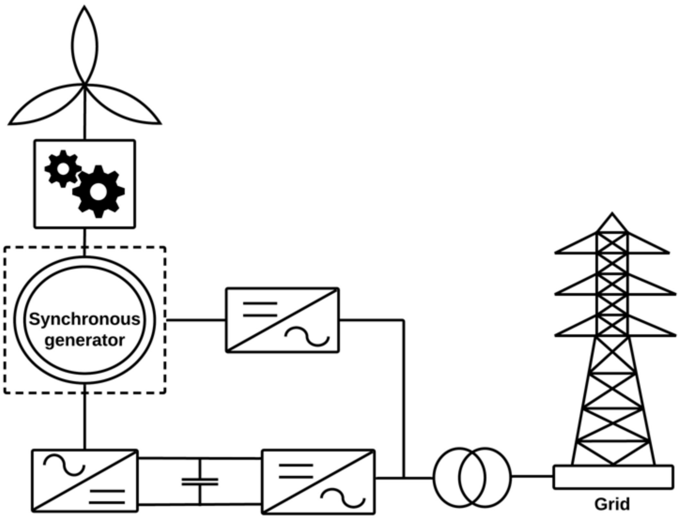

Figure 12. Synchronous generator [55,56].

The synchronous generator has a wide range of configurations, making it suitable for multiple situations and locations. An example is the excitation mode, which can be used as power from the EPS or through a capacitor bank. In [70], a comparative study was performed of each type of synchronous generator according to its subdivisions. The disadvantage of this configuration depends on the selected construction. For example, if a variable speed induction generator with a partial power converter is chosen, an energy loss is produced due to the heat in its gears. In [70], an analysis was performed according to its subdivision.

Permanent-Magnet Synchronous Generator

Figure 13 shows the permanent-magnet synchronous generator configuration.

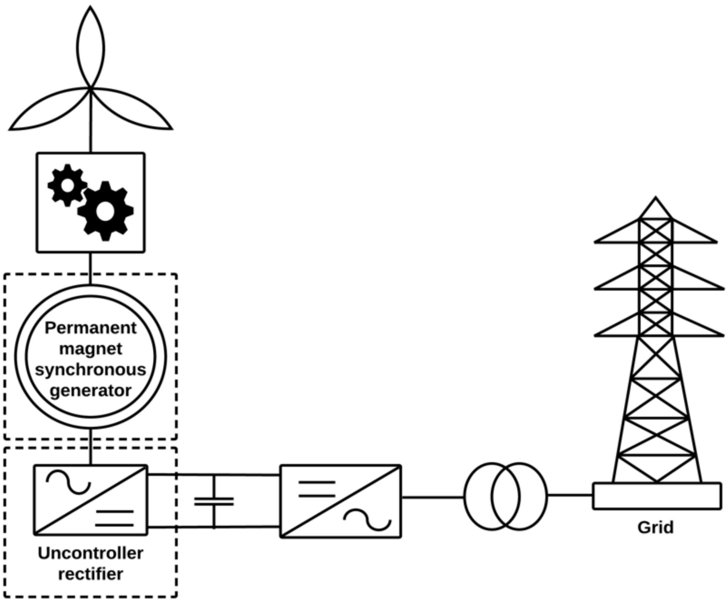

Figure 13. Permanent-magnet synchronous generator [55,56].

This configuration is generally used in offshore wind turbines [71]. Its operating principle is like the synchronous generators, in terms of the dependence of the speed on the energy consumption of the EPS. Due to their construction characteristics, they generate a large amount of power [72,73]. However, its use is limited because it has more complex control systems and a high maintenance cost [72,73].

3.1.2. Load Sharing Techniques

Load sharing techniques are divided according to the type of control (i.e., centralized control, master and slave control, average load sharing control, and ring control).

Centralized control

In centralized control, the loads and DG units connect via a centralized connection or centralized DC bus. In this configuration presented in Figure 14, the main or centralized control has two functions: to link the MG with the user or with the EPS [74,75].

This configuration presents high efficiency at low costs and only requires a converter for connection to the EPS. Additionally, the electronic elements used are simple, and wiring is cheap and simple [74,75]. However, as the principal connection axis is the centralized control, a failure could isolate the MG and convert it to an inoperable network. Additionally, it is very susceptible to a bad network design [74,75].

In [76], a model to a mini-grid project in sub-Saharan Africa was implemented using a centralized control architecture considering multiple connected nodes to optimize the resource, size, nodal location, and generation dispatch. On the other hand, in [77], the centralized control strategy for AC MG connected to the EPS, taking into account the different DGs, was developed. Other applications that use centralized control were discussed in [78,79].

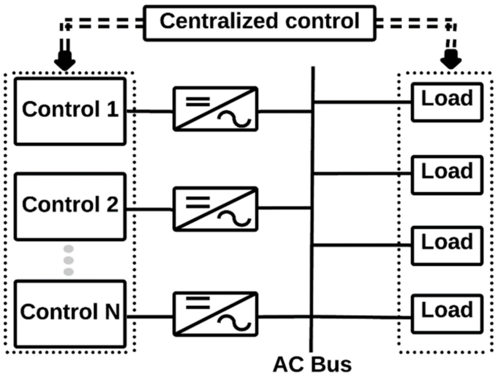

Figure 14. Centralized control [55,56].

Master and Slave Control

In the configuration shown in Figure 15, a voltage inverter works as master control and adopts the reactive power control method (PQ). When the system works in island mode, the inverter adopts the voltage–frequency control method (V/F) [54,80,81]. In this configuration, the master unit can be classified into three subcategories: battery energy storage system (BESS), DG, and a combination of BESS-DG [54,80,81]. This type of control allows excellent energy performance and voltage recovery at the MG/EPS PCC [80,81].

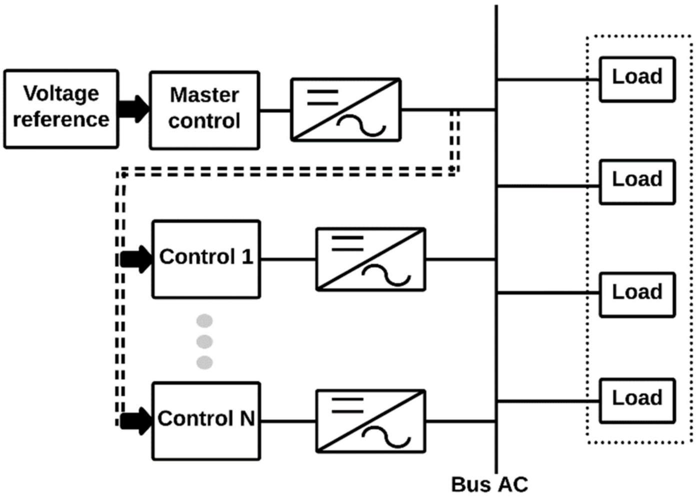

Figure 15. Master–slave control [55,56].

According to Figure 15, the complete system depends on the master control. When this mater control fails, the configuration stops working, requiring constant monitoring and maintenance [80,81]. In [82], master–slave wave farm systems and control methods were investigated.

Average Load Sharing Control

In the average load sharing control (see Figure 16), each inverter shares the load regulation process. A common bus related to current is used to calculate the average of the current. Each time a current cycle occurs, the system performs a new calculation to average the load. It has two main configurations: single-inverter and parallel-inverter system [83].

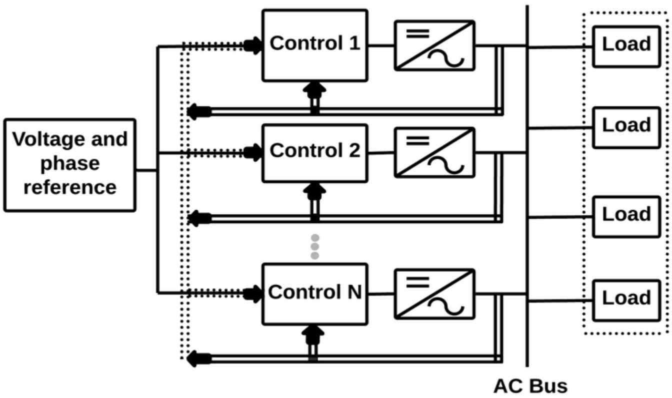

Figure 16. Average load sharing [55,56].

This configuration makes the system reliable due to its ability to distribute the control actions among all inverters. Additionally, it also presents an optimal performance in the current and voltage variables [83]. However, it can be affected by the line impedance effect, producing some power losses [83].

In [84], a distributed control scheme, with current sharing and average voltage regulation in DC MGs, was proposed. The contribution is that the proposed control scheme achieves average voltage regulation without the need for voltage measurements. On the other hand, in [85,86] a hierarchical control strategy was used for DC MGs with DG.

Ring Control

As can be seen in Figure 17, in this strategy control, a loop is created where a module with its inverter is connected in series to another inverter, using a bus that controls the voltage output. Additionally, a connection is made between the last and the first modules to complete the loop [83].

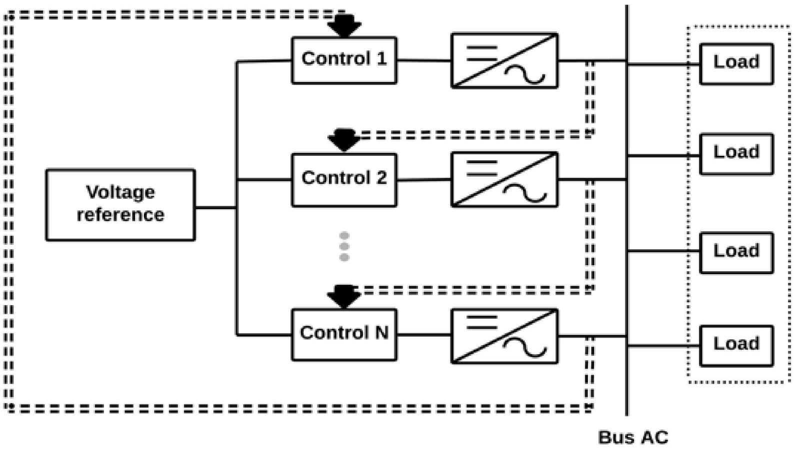

Figure 17. Ring control [55,56].

This configuration presents a good response to changes in the system, and it allows for the obtainment of a stable output voltage [83]. However, if an inverter fails, the performance of the system is compromised, leading to the possibility of completely disabling the network. It also presents limitations in the electrical capacity [83,87]. A ring DC MG control architecture was used to manage load balancing and power distribution in [88–90].

3.2. Hybrid MG Topologies

Hybrid MG topologies are divided into AC coupled, AC decoupled, and multiple MGs with their respective subcategories. Each of these topologies is discussed below.

3.2.1. Coupled AC

AC coupled MGs can have partially isolated or completely isolated configurations. The characteristics of each configuration are described below.

Partially Isolated Configuration

This configuration is generally used to interconnect several asynchronous AC networks. The most typical applications of these topologies are large-scale PV and wind farms. In this configuration (see Figure 18) the AC MG is connected to the EPS in normal operation mode, and low-capacity AC-DC converters are used to handle the energy flow between the EPS and the DC network [2,49,50].

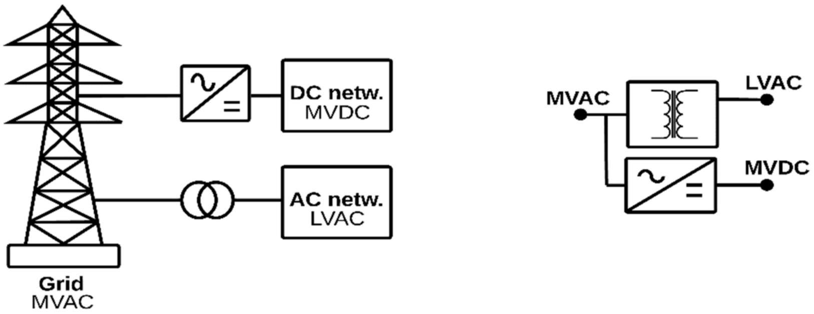

Figure 18. Partially isolated configuration [2].

The AC-DC converter that connects the DC network to the EPS is not behind the transformer; therefore, the nominal power of the transformer reduces because it must conduct the flow of energy from the AC network. Therefore, galvanic isolation does not exist for the DC network unless a second transformer is added [2]. In this configuration, the protection of devices for DC medium voltage (MV) networks is unusual, and their cost is expensive, so it is not often used because MV networks DC are rarely used in MGs [2].

Completely Isolated Configuration

This configuration presented in Figure 19 is divided into three main stages and is more common than the partially isolated configuration. The micro-source stage is the first one, where DG units, ESS, and the DC link are connected. The second one is the combined source, where the inverter and the AC link are located to connect them. Finally, the third stage is the MG, where the low-voltage interconnections and the EPS are carried out [2,49,50].

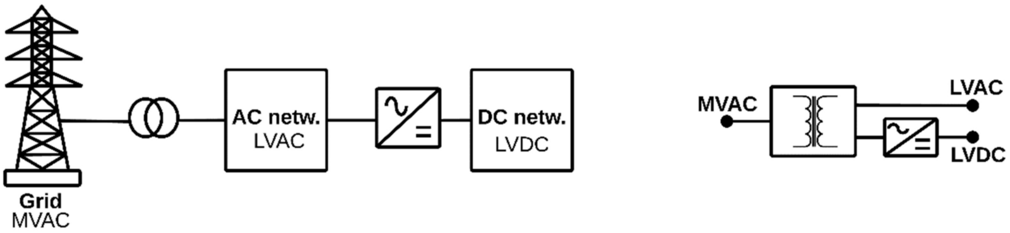

Figure 19. Completely isolated configuration [2].

This configuration compared to conventional configurations strengthens the reliability and flexibility of the distribution network. In addition, its plug-and-play-based system benefits the incorporation of next-generation, charging, or storage devices [2].

A transformer between MGs and the EPS is used at the PCC. It supplies galvanic isolation to the MG and decreases the voltage to create AC and DC low-voltage networks [2]. Although this configuration is suitable for incorporating DG units in the network, many converters are required to connect the DG AC units to the DC network. However, connecting DG units to the network would improve the efficiency of the configuration [2].

3.2.2. Decouple AC

AC decoupled MGs are divided into the following configurations: two-stage completely isolated, two-stage partially isolated, and three-stage partially isolated configuration. The characteristics of each configuration are described below.

Two-Stage Completely Isolated Configuration

In this configuration, shown in Figure 20, a solid-state transformer (SST) is at the input, supplying galvanic isolation to the MG.

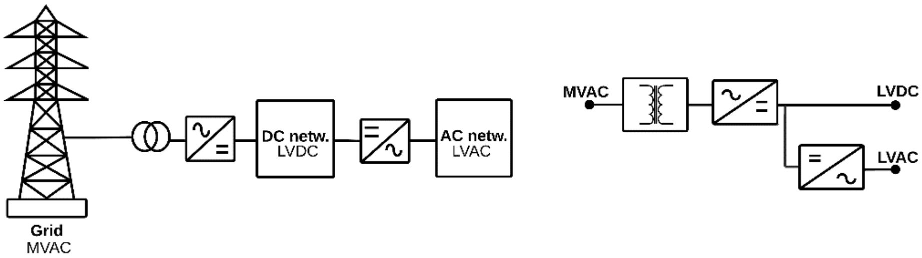

Figure 20. Two-stage completely isolated configuration [2].

This configuration avoids the stability or timing problems that occur when DG units are integrated into the traditional EPS. Additionally, the system works securely with several DG units [2]. However, tight control of interface converters can affect system stability [2,49,50].

Two-Stage Partially Isolated Configuration

The two-stage partially isolated topology (see Figure 21) (as the AC coupled partially isolated topology), is less usual than the other topologies because the protection of the devices for the DC MV network is not as usual, and their cost is relatively high.

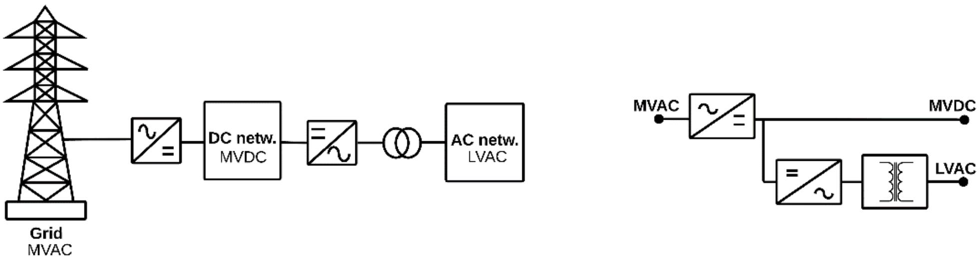

Figure 21. Two-stage partially isolated configuration [2].

This topology presents a simple perspective on the generation of the DC MG regarding the conversion stages. The SST, which is placed in the AC LV network, uniquely guarantees the isolation of this network [2,49,50].

Three-Stage Partially Isolated Configuration

This configuration, represented in Figure 22, provides DC MV and LV networks as well as an AC LV network [2]. Additionally, it employs a DC MT network as the two-stage partially isolated configuration.

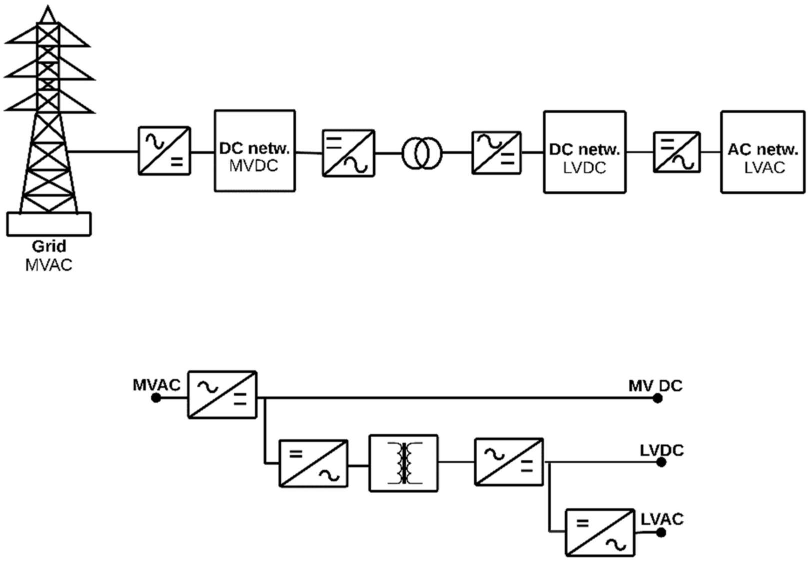

Figure 22. Three-stage partially isolated configuration [2].

The usage of a medium-frequency (MF) transformer in the DC-DC stage supplies galvanic isolation of the LV side of the MG and the size of the devices is extremely reduced [2]. Moreover, the use of an MF transformer makes it suitable for small- or large-scale integration of DG units, ESS, or loads. Nevertheless, it must improve reliability and efficiency while it reduces price and size devices [2,49,50].

3.2.3. Multiple MGs

Multiple MGs are autonomous, independently managed, and operated systems that allow the use of DG units and loads efficiently. Each MG may have some functions or capacity such as excess renewable generation, which could benefit other MGs in the same area and at different times [91].

AC—DC

Figure 23 shows the structure of multiple MGs AC and DC.

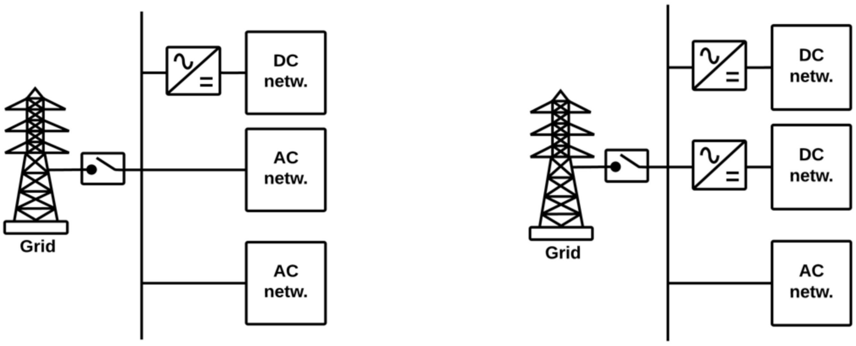

Figure 23. Multiple AC-DC MGs [21,43].

Neighboring MGs connected can increase their performance in backup, reliability, economic dispatch, and power quality [43]. However, the energy management of multiple MGs system is a complex problem since the DG units within each multiple MG, the energy exchange between the multiple MGs, and the energy exchange between the EPS and the MGs must be coordinated. The development of multiple MG systems is limited by the current energy management capacity [54,91].

Based on SST

The configuration based on SST (see Figure 24) uses an SST that acts as a power router, which can perform all the functions of a conventional transformer [43].

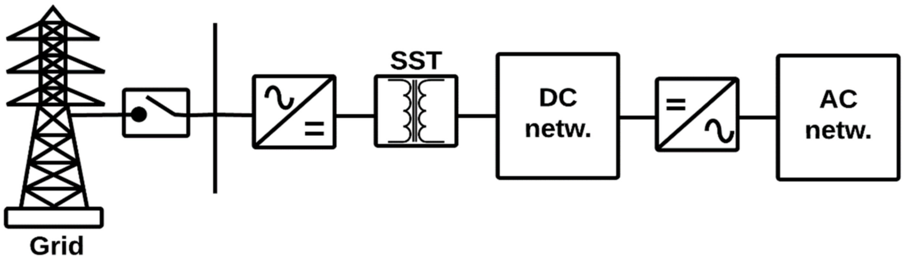

Figure 24. Based on SST [43].

This configuration can coordinate the power exchange between neighboring AC and DC MGs. It offers high-power quality and allows a reduction in the number of faults [43,92,93]. However, the three-phase unbalance problem can cause adverse impacts on the power quality of the SST [92,93]. Applications that integrated SSTs and DG were studied in [94–96].

3.3. 3-NET

This configuration is based on the union of three different networks, as seen in Figure 25. The first one is a high-quality DC network, the second one is a low-quality DC network, and the third one is an AC network connected to the EPS through a PCC. This configuration is essential for situations where there are constant interruptions and concerns about power quality [39,97].

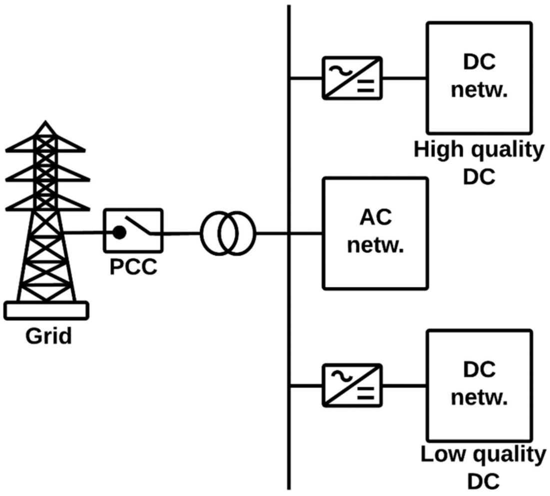

Figure 25. 3-NET [39].

The reliability offered by this configuration is very high. In addition, many loads can be connected to any of the types of networks. For example, it would be feasible to connect a heater to the low-quality DC network and sensitive electronic devices to the high-quality DC network. However, the design and implementation costs of this network are high, and high power losses can be presented [39,97].

Currently, it is necessary to develop flexible MGs capable of operating both connected to the EPS and in island mode. Therefore, studies about MG topologies, architectures, planning, and configurations are necessary. A challenge of this configuration is the need to integrate new technologies of power electronics, telecommunications, generators, and ESS, among others [47].

3.4. Classification by Configuration

The topologies according to their configuration can be classified as cascade and parallel types. The characteristics of each type are discussed below.

3.4.1. Cascade Type

The cascade-type configuration [98,99], also known as series-type configuration, is observed in Figure 26 [100]. This configuration offers an efficient solution using DG in high voltage. It also allows a high-quality power supply due to frequency regulation [52,53]. Generally, most ESS are located in a localized area, where centralized control is in common use [81].

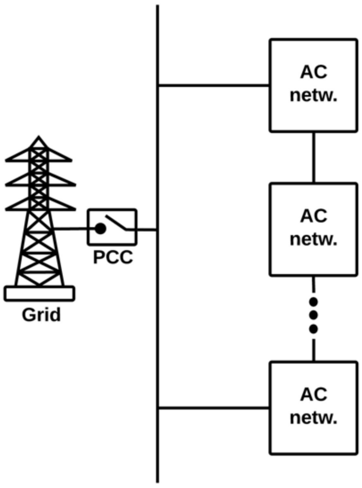

Figure 26. Cascade type [100].

This configuration allows easy increasing the voltage without the use of expensive and huge transformers [51]. One stage for power conversion is required to integrate the low-voltage devices into the MG [53,101]. It is easy and flexible to implement, especially for connecting PV systems to the EPS, MGs, and battery management [101,102]. However, increasing the number of cascaded MGs makes it more difficult to install the ESS in a localized area. The cost of communication through a sophisticated and expensive centralized control depends on a large bandwidth which becomes a complex situation [51].

3.4.2. Parallel Type

The parallel-type configuration [103,104] (see Figure 27) uses droop control, does not require physical communication links, and is easy to implement [62]. However, all local controllers need to communicate with a central controller, which weakens the reliability and scalability of the system if adequate control strategies are not adopted [53,105].

When the MG is connected to the EPS, DG units are controlled as current sources to maintain operating with the EPS [53]. In island mode, the decentralized control methods, which mainly include droop control and its variants, are used to achieve frequency synchronization and power-sharing [53]. Additionally, it allows increasing the power capacity and efficiency of the system and reduces the ripple of the output current [105]. However, a two-stage DC/AC power conversion is required to integrate the low-voltage devices into the MG [53,101]. The accuracy of the power distribution is very sensitive to the output impedance of the inverters. The harmonic power in the case of non-linear loads is poorly compensated, and not connecting the inverters at the same time to the bus affects the power distribution [106].

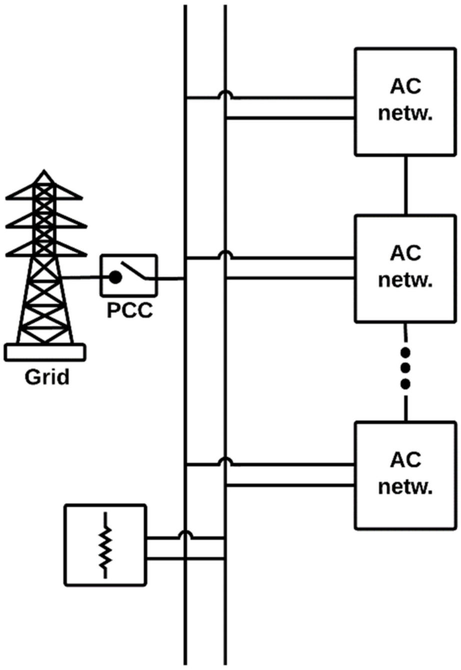

Figure 27. Parallel type [53,105].

3.5. Summary of the MG Characteristics

Table 2 summarizes each topology assessed, references, advantages, disadvantages, and application.

Table 2. Summary of the MG characteristics.

Topology	Advantage	Disadvantage	Application	Reference
Centralized inverter	Reliability. Widely used. Low cost.	Depends on the power inverter. Constant maintenance	Commercial: MV and HV.	[57–62,83]
Inverter chain	Efficiency. Peak power. Reliability.	High cost.	Residential. Commercial: LV, MV.	[57–59,63–65,83]
Microinverter	Maintenance. Cost. Independent panels.	Non-galvanic isolation in ac-dc connection	Residential. Commercial: LV.	[57–59,66,67,83]
Induction generator	Robust. Additional electronics. Easy parallel connection. Installation area.	Constant maintenance. Installation area. Starting torque is required. Power factor	High and low power. Variable speed generators.	[31,58,68,69]
Double-winding induction generator	Power. No overheating. Stator connection.	Load dependency. Network frequency	High and low power. Variable speed generators.	[56,70]
Synchronous generator	High flexibility. Wide range of configurations.	Subject to the generator selected	Industrial. Generating stations.	[56,70]
Permanent-magnet synchronous generator	Power.	Control system's maintenance cost	Offshore wind turbines Generator stations	[71–73]
Centralized control	Efficient. Cost. Use one power converter. Simple electronics.	Depends on the converter Susceptible to design.	Residential. Commercial: LV and MV.	[74–79]

Table 2. *Cont.*

Topology	Advantage	Disadvantage	Application	Reference
Master–slave control	Performance. Voltage in the PCC.	Constant monitoring. Constant maintenance. Depends on the master control.	Commercial: LV and HV. Power storage in capacitors.	[54,80–82]
Average load sharing	Reliability. Performance	Impedance effect. Power losses.	Parallel power systems. Power storage in capacitors.	[83–86]
Ring control (3C)	Response time. Robust. Stability.	Electrical capacity. A faulty inverter disables the network completely.	Parallel power systems. Power storage in capacitors. Uninterrupted systems.	[83,87–90,107]
Partially isolated coupled AC	Size of the power converter	Uncommon. Costs.	Interconnection of several AC networks. Remote or large-scale wind or PV farms.	[2,49,50]
Completely isolated coupled AC	Flexibility. Reliability. Plug-and-play system. Galvanic isolation.	Number of power converters	Integration of DG units into the EPS.	[2,49,50]
Two-stage completely isolated decouple AC	Galvanic isolation. Stability. Synchronization Reliability.	Regulation of power converters.	Integration of DG units into the ESPS	[2,49,50]
Two-stage partially isolated decouple AC	SST conversion stages	Uncommon. Costs.	Integration of DG units into the EPS.	[2,49,50]
Three-stage partially isolated decouple AC	MF transformer.	Efficiency. Reliability.	MV, LV networks. Small- or large-scale integration of DG, ESS, or loads.	[2,49,50]
Multiple AC—DC	Power backup. Reliability. Power quality.	Energy management. Energy exchange between MGs.	LV networks	[54,91]
SST	Power quality. The number of failures. The power is exchanged between neighboring AC-DC MGs.	Three-phase imbalance.	Integration of DG units into the EPS.	[43,54,91–96]
3-NET	Efficiency. Reliability. The number of loads.	Cost. Loss of power demand.	Residential and Commercial: LV and MV networks.	[39,47,97]
Cascade type	Electricity supply. Frequency control implementation.	The number of MGs. Storage units. Communication. Bandwidth.	High-voltage applications. Energy storage applications. PV applications. Battery management.	[51–53,81,98–102]
Parallel type	Power capacity. Efficiency. The ripple of the output current. Reliability.	Power share.	Frequency synchronization.	[53,101,103–106]

During the selection of the topologies, the mechanisms to control the dynamic characteristics of the DG resources, the frequency and voltage regulation, the energy balance, the transition between the operation modes, and the economic dispatch must be considered. These characteristics allow the EPS to supply the energy demanded by the loads in a reliable and coordinated manner with minimal impact on the distribution networks.

Based on the analysis performed of the topologies, it can be inferred that hybrid MG topologies, such as SST-based completely isolated coupled AC, two-stage completely isolated decoupled AC, and multi-MGs, have proven to be feasible to operate in combination with the EPS. In contrast, two- and three-stage partially isolated AC decoupled topologies still have a challenge in terms of the need to reduce operating costs, and improve efficiency and reliability, for this reason, this topology is rarely used.

4. Conclusions

Currently, EPS face challenges due to the obsolescence of their components and the need to carry out an energy transition towards renewable sources. One way to face these problems has been the development of MGs that promise to be a good alternative solution due to their flexibility, efficiency, and capacity for dynamic operation in conjunction with EPS.

The form of connection of the energy sources and the loads, as well as the possible connection alternatives between the MGs themselves and the EPS, constitute one of the most important aspects in the operation of the MGs. These forms of connection are called topologies, and it is one of the most relevant research fields within the current conjuncture of the development of new forms of management of EPS.

In this study, 21 MG topologies were analyzed, taking as reference the characteristics of the current (AC or DC), the control mechanisms, the transition between the operating modes, and the operating costs.

As a result of the evaluation, it was evidenced that the use of hybrid MG topologies is recommended, specifically, the SST-based completely isolated coupled AC, the two-stage completely isolated decoupled AC, and multiple MGs. These topologies have the advantage that they are feasible for the incorporation of DG units in the EPS and for improving the flexibility and reliability of the distribution network.

It was also observed that two -and three-stage partially isolated AC decoupled topologies have high operating costs and have low efficiency and reliability; therefore, they should continue to be improved.

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References

1. Meng, L.; Sanseverino, E.R.; Luna, A.; Dragicevic, T.; Vasquez, J.C.; Guerrero, J.M. Microgrid supervisory controllers and energy management systems: A literature review. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1263–1273. [CrossRef]
2. Unamuno, E.; Barrena, J.A. Hybrid ac/dc microgrids—Part I: Review and classification of topologies. *Renew. Sustain. Energy Rev.* **2015**, *52*, 1251–1259. [CrossRef]
3. Gómez, Y.A.G.; Garcia, N.T.; Velasco, F.E.H. Acondicionador Unificado de Calidad de la Potencia en Topología Dual iUPQC para Compensación Activa de Sobretensiones Transitorias. *INGE CUC* **2017**, *13*, 112–117. [CrossRef]
4. Patnaik, B.; Mishra, M.; Bansal, R.C.; Jena, R.K. MODWT-XGBoost based smart energy solution for fault detection and classification in a smart microgrid. *Appl. Energy* **2021**, *285*, 116457. [CrossRef]
5. IEEE. IEEE Standard for the Testing of Microgrid Controllers. *IEEE Study* **2018**, *2018*, 1–42. [CrossRef]
6. IEC. *IEC TS 62898-1:2017 | Microgrids—Part 1: Guidelines for Microgrid Projects Planning and Specification*; IEC: Geneva, Switzerland, 2017; Volume 33.

7. Hossain, A.; Pota, H.R.; Hossain, J.; Blaabjerg, F. Evolution of microgrids with converter-interfaced generations: Challenges and opportunities. *Int. J. Electr. Power Energy Syst.* **2019**, *109*, 160–186. [CrossRef]
8. Álvaro, R.; Menéndez, J. *Casos de Microrredes*; Orkestra: País Vasco, Spain, 2020; Volume 73.
9. Gaona, E.E.; Mancera, P.A.; Trujillo, C.L. Sensores inalámbricos aplicada a una Microrred en modo "Isla" Routing Algorithm with topology reconfiguration for Wireless Sensor Network applied to microgrid in Island mode. *Rev. UIS Ing.* **2016**, *15*, 93–104. [CrossRef]
10. Patnaik, B.; Mishra, M.; Bansal, R.C.; Jena, R.K. AC microgrid protection—A review: Current and future prospective. *Appl. Energy* **2020**, *271*, 115210. [CrossRef]
11. Komala, K.; Kumar, K.P.; Cherukuri, S.H.C. Storage and non-Storage Methods of Power balancing to counter Uncertainty in Hybrid Microgrids—A review. *J. Energy Storage* **2021**, *36*, 102348. [CrossRef]
12. Chen, X.; Ju, Y.; Zhang, R. Land-sea relay fishery networked microgrids under the background of cyber-physical fusion: Characteristics and key issues prospect. *Inf. Process. Agric.* **2021**. Available online: https://login.ezproxy.cuc.edu.co/login?qurl=https://www.sciencedirect.com%2fscience%2fjournal%2faip%2f22143173 (accessed on 9 March 2021). [CrossRef]
13. Ajoulabadi, A.; Ravadanegh, S.N.; Mohammadi-Ivatloo, B. Flexible scheduling of reconfigurable microgrid-based distribution networks considering demand response program. *Energy* **2020**, *196*, 117024. [CrossRef]
14. Che, L.; Zhang, X.; Shahidehpour, M.; AlAbdulwahab, A.; Abusorrah, A. Optimal Interconnection Planning of Community Microgrids with Renewable Energy Sources. *IEEE Trans. Smart Grid* **2017**, *8*, 1054–1063. [CrossRef]
15. Martin-Martínez, F.; Miralles, A.S.; Rivier, M. A literature review of Microgrids: A functional layer based classification. *Renew. Sustain. Energy Rev.* **2016**, *62*, 1133–1153. [CrossRef]
16. Gadanayak, D.A. Protection algorithms of microgrids with inverter interfaced distributed generation units—A review. *Electr. Power Syst. Res.* **2021**, *192*, 106986. [CrossRef]
17. Ortiz, L.; González, J.W.; Gutierrez, L.B.; Llanes-Santiago, O. A review on control and fault-tolerant control systems of AC/DC microgrids. *Heliyon* **2020**, *6*, e04799. [CrossRef]
18. Laaksonen, H. Protection Principles for Future Microgrids. *IEEE Trans. Power Electron.* **2010**, *25*, 2910–2918. [CrossRef]
19. Hooshyar, A.; Iravani, R. Microgrid Protection. *Proc. IEEE* **2017**, *105*, 1332–1353. [CrossRef]
20. Hannan, M.; Tan, S.Y.; Al-Shetwi, A.Q.; Jern, K.P.; Begum, R. Optimized controller for renewable energy sources integration into microgrid: Functions, constraints and suggestions. *J. Clean. Prod.* **2020**, *256*, 120419. [CrossRef]
21. 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]
22. Chandra, A.; Singh, G.K.; Pant, V. Protection techniques for DC microgrid—A review. *Electr. Power Syst. Res.* **2020**, *187*, 106439. [CrossRef]
23. Wang, Y.; Rousis, A.O.; Strbac, G. On microgrids and resilience: A comprehensive review on modeling and operational strategies. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110313. [CrossRef]
24. Wei, P.; Chen, W. Microgrid in China: A review in the perspective of application. *Energy Procedia* **2019**, *158*, 6601–6606. [CrossRef]
25. Jiayi, H.; Chuanwen, J.; Rong, X. A review on distributed energy resources and MicroGrid. *Renew. Sustain. Energy Rev.* **2008**, *12*, 2472–2483. [CrossRef]
26. Nichols, D.; Stevens, J.; Lasseter, R.; Eto, J.; Vollkommer, H. Validation of the CERTS microgrid concept the CEC/CERTS microgrid testbed. In Proceedings of the 2006 IEEE Power Engineering Society General Meeting, Montreal, QC, Canada, 18–20 June 2006; IEEE: Piscataway, NJ, USA, 2006; p. 3.
27. Issa, W.R.; El Khateb, A.H.; Abusara, M.A.; Mallick, T.K. Control Strategy for Uninterrupted Microgrid Mode Transfer During Unintentional Islanding Scenarios. *IEEE Trans. Ind. Electron.* **2018**, *65*, 4831–4839. [CrossRef]
28. Priyadharshini, N.; Gomathy, S.; Sabarimuthu, M. A review on microgrid architecture, cyber security threats and standards. *Mater. Today Proc.* **2020**. Available online: https://login.ezproxy.cuc.edu.co/login?qurl=https://doi.org%2f10.1016%2fj.matpr.2020.10.622 (accessed on 4 December 2020). [CrossRef]
29. Cole, W.; Gates, N.; Mai, T. Exploring the cost implications of increased renewable energy for the U.S. power system. *Electr. J.* **2021**, *34*, 106957. [CrossRef]
30. US EIA. *February 2020 Monthly Energy Review*; EIA: Washington, WA, USA, 2020.
31. Lakatos, L.; Hevessy, G.; Kovács, J. Advantages and Disadvantages of Solar Energy and Wind-Power Utilization. *World Future* **2011**, *67*, 395–408. [CrossRef]
32. Shahzad, U. A Quantitative Comparison of Wind and Solar Energy | Umair Shahzad—Academ-ia.edu. *Durreesamin J.* **2016**, *7*. Available online: https://www.academia.edu/32941924/A_Quantitative_Comparison_of_Wind_and_Solar_Energy (accessed on 4 December 2020).
33. Fusheng, L.; Ruisheng, L.; Fengquan, Z. Composition and classification of the microgrid. In *Microgrid Technology and Engineering Application*; Academic Press: Cambridge, MA, USA, 2016; pp. 11–27. [CrossRef]
34. Bordons, C.; Garcia-Torres, F.; Valverde-Isorna, L. Gestión Óptima de la Energía en Microrredes con Generación Renovable. *Rev. Iberoam. Automática E Inf. Ind.* **2015**, *12*, 117–132. [CrossRef]
35. Ortiz, L.; Orizondo, R.; Águila, A.; González, J.W.; López, G.J.; Isaac, I. Hybrid AC/DC microgrid test system simulation: Grid-connected mode. *Heliyon* **2019**, *5*, e02862. [CrossRef]

36. Dagar, A.; Gupta, P.; Niranjan, V. Microgrid protection: A comprehensive review. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111401. [CrossRef]
37. García, E.E.G.; Trujillo, C.L.R.; Cubides, H.E.R. Infraestructura de comunicaciones en microrredes eléctricas. *Redes Ing.* **2014**, *5*, 28–38. [CrossRef]
38. Pourbehzadi, M.; Niknam, T.; Aghaei, J.; Mokryani, G.; Shafie-Khah, M.; Catalão, J.P.S. Optimal operation of hybrid AC/DC microgrids under uncertainty of renewable energy resources: A comprehensive review. *Int. J. Electr. Power Energy Syst.* **2019**, *109*, 139–159. [CrossRef]
39. Nguyen, M.Y.; Yoon, Y.T. A Comparison of Microgrid Topologies Considering Both Market Operations and Reliability. *Electr. Power Compon. Syst.* **2014**, *42*, 585–594. [CrossRef]
40. Basak, P.; Chowdhury, S.; Dey, S.H.N. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. *Renew. Sustain. Energy Rev.* **2012**, *16*, 5545–5556. [CrossRef]
41. De Madrid, C.; De, G.; Inteligentes, R.; Energía, D.; Comunicación, Y. *La Suma de Todos Guía de Redes Inteligentes de Energía y Comunicación*; IDEA: Madrid, Spain, 2004.
42. Fuentes, A. Estudio de Viabilidad y Requisitos Técnicos Necesarios Para la Implantación de una Micro-Red Eléctrica. Ph.D. Thesis, Universidad Argentina de la Empresa, Buenos Aires, Argentina, 2007.
43. Gupta, A.; Doolla, S.; Chatterjee, K. Hybrid AC–DC Microgrid: Systematic Evaluation of Control Strategies. *IEEE Trans. Smart Grid* **2018**, *9*, 3830–3843. [CrossRef]
44. Lotfi, H.; Khodaei, A. Hybrid AC/DC microgrid planning. *Energy* **2017**, *118*, 37–46. [CrossRef]
45. Baran, M.; Mahajan, N. DC distribution for industrial systems: Opportunities and challenges. *IEEE Trans. Ind. Appl.* **2003**, *39*, 1596–1601. [CrossRef]
46. Xu, L.; Chen, D. Control and Operation of a DC Microgrid with Variable Generation and Energy Storage. *IEEE Trans. Power Deliv.* **2011**, *26*, 2513–2522. [CrossRef]
47. Guerrero, J.M.; Vasquez, J.C.; Matas, J.; de Vicuna, 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]
48. Justo, J.J.; Mwasilu, F.; Lee, J.; Jung, J.-W. AC-microgrids versus DC-microgrids with distributed energy resources: A review. *Renew. Sustain. Energy Rev.* **2013**, *24*, 387–405. [CrossRef]
49. Nehrir, M.H.; Wang, C.; Strunz, K.; Aki, H.; Ramakumar, R.; Bing, J.; Miao, Z.; Salameh, Z. A Review of Hybrid Renewable/Alternative Energy Systems for Electric Power Generation: Configurations, Control, and Applications. *IEEE Trans. Sustain. Energy* **2011**, *2*, 392–403. [CrossRef]
50. Nejabatkhah, F.; Li, Y.W. Overview of Power Management Strategies of Hybrid AC/DC Microgrid. *IEEE Trans. Power Electron.* **2015**, *30*, 7072–7089. [CrossRef]
51. Shi, G.; Han, H.; Liu, Y.; Su, M.; Liu, Z.; Sun, Y. A Common Second Frequency Control of Island Cascaded-type Microgrid. In Proceedings of the 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 29 September–3 October 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 5407–5410.
52. Sun, Y.; Shi, G.; Li, X.; Yuan, W.; Su, M.; Han, H.; Hou, X. An f-P/Q Droop Control in Cascaded-Type Microgrid. *IEEE Trans. Power Syst.* **2018**, *33*, 1136–1138. [CrossRef]
53. Ge, X.; Han, H.; Xiong, W.; Su, M.; Liu, Z.; Sun, Y. Locally-distributed and globally-decentralized control for hybrid series-parallel microgrids. *Int. J. Electr. Power Energy Syst.* **2020**, *116*, 105537. [CrossRef]
54. Khan, H.A.U.; Al Hosani, M.; Zeineldin, H. Topology planning for autonomous MMGs: An ordered binary decision diagram-based approach. *IET Smart Grid* **2020**, *3*, 60–68. [CrossRef]
55. Hernández Mora, J.; Trujillo Rodríguez, C.; Vallejo Lozada, W. Modelo de un sistema fotovoltaico interconectado. *Tecnura* **2013**, *17*, 26–34. [CrossRef]
56. Trujillo Rodriguez, J. Hernandez Mora OFC. In *Sistemas Fotovoltaicos y Sistemas Eólicos en Microrredes*; UD E, Caldas U; Microrredes Electr. Primera, UD: Bogotá, Colombia, 2015; pp. 61–83.
57. Hayman, A.K. Development of a High-Efficiency Solar Micro-Inverter. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2008.
58. Alvarez, J.M.G.; Targarona, J.C.G. Generación eólica empleando distintos tipos de generadores considerando su impacto en el sistema de potencia. *Dyna* **2011**, *78*, 95–104.
59. ISE PRIFORSES. *Photovoltaics Report*; Fraunhofer: Freiburg, Germany, 2020.
60. Mongrain, R.S.; Ayyanar, R. Control of nonideal grid-forming inverter in islanded microgrid with hierarchical control structure under unbalanced conditions. *Int. J. Electr. Power Energy Syst.* **2020**, *119*, 105890. [CrossRef]
61. Brandao, D.I.; Araujo, L.; Caldognetto, T.; Pomilio, J.A. Coordinated control of three- and single-phase inverters coexisting in low-voltage microgrids. *Appl. Energy* **2018**, *228*, 2050–2060. [CrossRef]
62. Pinto, J.O.C.P.; Moreto, M. Protection strategy for fault detection in inverter-dominated low voltage AC microgrid. *Electr. Power Syst. Res.* **2021**, *190*, 106572. [CrossRef]
63. Chang, C.-Y.; Zhang, W. Distributed control of inverter-based lossy microgrids for power sharing and frequency regulation under voltage constraints. *Automatica* **2016**, *66*, 85–95. [CrossRef]
64. Andishgar, M.H.; Gholipour, E.; Hooshmand, R.-A. An overview of control approaches of inverter-based microgrids in islanding mode of operation. *Renew. Sustain. Energy Rev.* **2017**, *80*, 1043–1060. [CrossRef]

65. Khan, A.A.; Beg, O.A.; Alamaniotis, M.; Ahmed, S. Intelligent anomaly identification in cyber-physical inverter-based systems. *Electr. Power Syst. Res.* **2021**, *193*, 107024. [CrossRef]
66. Trujillo, C.; Velasco, D.; Figueres, E.; Garcerá, G.; Ortega, R. Modeling and control of a push–pull converter for photovoltaic microinverters operating in island mode. *Appl. Energy* **2011**, *88*, 2824–2834. [CrossRef]
67. Khan, O.; Xiao, W. Review and qualitative analysis of submodule-level distributed power electronic solutions in PV power systems. *Renew. Sustain. Energy Rev.* **2017**, *76*, 516–528. [CrossRef]
68. Awan, M.A.I.; Raza, A.; Riaz, M.; Khalil, L.; Bhatti, K.L. Integration of sub-gradient based coordinate for multiple renewable generators in microgrid. *Mater. Today Proc.* **2021**, *47*, S64–S73. [CrossRef]
69. Willenberg, D.; Winkens, A.; Linnartz, P. Impact of wind turbine generator technologies and frequency controls on the stable operation of medium voltage islanded microgrids. *Electr. Power Syst. Res.* **2020**, *189*, 106760. [CrossRef]
70. Li, H.; Chen, Z. Overview of different wind generator systems and their comparisons. *IET Renew. Power Gener.* **2008**, *2*, 123–138. [CrossRef]
71. Rosslyn-Smith, W.; De Abreu, N.V.A.; Pretorius, M. Exploring the indirect costs of a firm in business rescue. *S. Afr. J. Account. Res.* **2019**, *34*, 24–44. [CrossRef]
72. Gaonkar, D.N. Investigation on Electromagnetic Transients of Distributed Generation Systems in the Microgrid. *Electr. Power Compon. Syst.* **2010**, *38*, 1486–1497. [CrossRef]
73. Thakur, D.; Jiang, J. Design and Construction of a Wind Turbine Simulator for Integration to a Microgrid with Renewable Energy Sources. *Electr. Power Compon. Syst.* **2017**, *45*, 949–963. [CrossRef]
74. Wunder, B.; Ott, L.; Kaiser, J.; Han, Y.; Fersterra, F.; Marz, M. Overview of different topologies and control strategies for DC micro grids. In Proceedings of the 2015 IEEE First International Conference on DC Microgrids (ICDCM), Atlanta, GA, USA, 7–10 June 2015; IEEE: Piscataway, NJ, USA, 2015; pp. 349–354.
75. Wunder, B.; Ott, L.; Han, Y.; Kaiser, J.; Maerz, M. Voltage Control and Stabilization of Distributed and Centralized DC Micro Grids. In Proceedings of the PCIM Europe 2015; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany, 19–20 May 2015; pp. 1–8.
76. Dunham, H.; Cutler, D.; Mishra, S.; Li, X. Cost-optimal evaluation of centralized and distributed microgrid topologies considering voltage constraints. *Energy Sustain. Dev.* **2020**, *56*, 88–97. [CrossRef]
77. Jmii, H.; Abbes, M.; Meddeb, A.; Chebbi, S. Centralized VSM control of an AC meshed microgrid for ancillary services provision. *Int. J. Electr. Power Energy Syst.* **2020**, *115*, 105450. [CrossRef]
78. Chandra, A.; Singh, G.K.; Pant, V. Protection of AC microgrid integrated with renewable energy sources—A research review and future trends. *Electr. Power Syst. Res.* **2021**, *193*, 107036. [CrossRef]
79. Carvalho Silveira, J.P.; dos Santos Neto, P.J.; dos Santos Barros, T.A.; Ruppert Filho, E.; Chandra, A.; Singh, G.K. Power management of energy storage system with modified interlinking converters topology in hybrid AC/DC microgrid. *Int. J. Electr. Power Energy Syst.* **2021**, *130*, 106880. [CrossRef]
80. Chen, X.; Wang, Y.H.; Wang, Y.C. A novel seamless transferring control method for microgrid based on master-slave configuration. In Proceedings of the 2013 IEEE ECCE Asia Downunder, Melbourne, VIC, Australia, 3–6 June 2013; IEEE: Piscataway, NJ, USA, 2013; pp. 351–357.
81. Wanichrojanarat, C.; Wirasanti, P. Control Strategy for Seamless Transition of Microgrid Using Battery Energy Storage System. In Proceedings of the 2018 53rd International Universities Power Engineering Conference (UPEC), Glasgow, UK, 4–7 September 2018; pp. 1–6. [CrossRef]
82. Yan, Z.; Zhang, X.P. Master-slave wave farm systems based on energy filter with smoothed power output. *Glob. Energy Interconnect.* **2018**, *1*, 559–567. [CrossRef]
83. Roslan, M.A.; Ahmed, K.H.; Finney, S.J.; Williams, B.W. Improved Instantaneous Average Current-Sharing Control Scheme for Parallel-Connected Inverter Considering Line Impedance Impact in Microgrid Networks. *IEEE Trans. Power Electron.* **2010**, *26*, 702–716. [CrossRef]
84. Trip, S.; Han, R.; Cucuzzella, M.; Cheng, X.; Scherpen, J.; Guerrero, J. Distributed Averaging Control for Voltage Regulation and Current Sharing in DC Microgrids: Modelling and Experimental Validation. *IFAC-PapersOnLine* **2018**, *51*, 242–247. [CrossRef]
85. Benahmed, S.; Riedinger, P.; Pierfederici, S. Distributed-based Integral Action for Current Sharing and Average Voltage Regulation in DC Microgrids. *IFAC-PapersOnLine* **2021**, *54*, 52–59. [CrossRef]
86. Yuan, M.; Fu, Y.; Mi, Y.; Li, Z.; Wang, C. Hierarchical control of DC microgrid with dynamical load power sharing. *Appl. Energy* **2019**, *239*, 1–11. [CrossRef]
87. Wu, T.-F.; Chen, Y.-K.; Huang, Y.-H. 3C strategy for inverters in parallel operation achieving an equal current distribution. *IEEE Trans. Ind. Electron.* **2000**, *47*, 273–281. [CrossRef]
88. Toub, M.; Iii, R.D.R.; Maaroufi, M.; Aniba, G. Decentralized Hamiltonian Control of Multi-DER Isolated Microgrids with Meshed Topology. *Energy Procedia* **2019**, *157*, 1253–1265. [CrossRef]
89. Zafeiratou, I.; Prodan, I.; Lefèvre, L.; Piétrac, L. Meshed DC microgrid hierarchical control: A differential flatness approach. *Electr. Power Syst. Res.* **2020**, *180*, 106133. [CrossRef]
90. Mohammadi, S.; Ojaghi, M.; Jalilvand, A.; Shafiee, Q. A pilot-based unit protection scheme for meshed microgrids using apparent resistance estimation. *Int. J. Electr. Power Energy Syst.* **2021**, *126*, 106564. [CrossRef]

91. 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]
92. Agrawal, A.; Nalamati, C.S.; Gupta, R. Hybrid DC–AC Zonal Microgrid Enabled by Solid-State Transformer and Centralized ESD Integration. *IEEE Trans. Ind. Electron.* **2019**, *66*, 9097–9107. [CrossRef]
93. Li, Y.; Sun, Q.; Qin, D.; Cheng, K.; Li, Z. Power Control of a Modular Three-Port Solid-State Transformer With Three-Phase Unbalance Regulation Capabilities. *IEEE Access* **2020**, *8*, 72859–72869. [CrossRef]
94. Ullah, S.; Haidar, A.M.; Hoole, P.; Zen, H.; Ahfock, T. The current state of Distributed Renewable Generation, challenges of interconnection and opportunities for energy conversion based DC microgrids. *J. Clean. Prod.* **2020**, *273*, 122777. [CrossRef]
95. Mishra, D.K.; Ghadi, M.J.; Li, L.; Hossain, J.; Zhang, J.; Ray, P.K.; Mohanty, A. A review on solid-state transformer: A breakthrough technology for future smart distribution grids. *Int. J. Electr. Power Energy Syst.* **2021**, *133*, 107255. [CrossRef]
96. Huang, L.; Li, Y.; Cui, Q.; Xie, N.; Zeng, J.; Shu, J. Research on optimal configuration of AC/DC hybrid system integrated with multiport solid-state transforms and renewable energy based on a coordinate strategy. *Int. J. Electr. Power Energy Syst.* **2020**, *119*, 105880. [CrossRef]
97. Nguyen, M.Y.; Nguyen, V.T.; Yoon, Y.T. Three-wire network: A new distribution system approach considering both distributed generation and load requirements. *Int. Trans. Electr. Energy Syst.* **2013**, *23*, 719–732. [CrossRef]
98. Sahoo, B.; Routray, S.K.; Rout, P.K. A new topology with the repetitive controller of a reduced switch seven-level cascaded inverter for a solar PV-battery based microgrid. *Eng. Sci. Technol. Int. J.* **2018**, *21*, 639–653. [CrossRef]
99. Cheng, Z.; Li, Z.; Li, S.; Gao, J.; Si, J.; Das, H.S.; Dong, W. A novel cascaded control to improve stability and inertia of parallel buck-boost converters in DC microgrid. *Int. J. Electr. Power Energy Syst.* **2020**, *119*, 105950. [CrossRef]
100. Hou, X.; Sun, Y.; Zhang, X.; Zhang, G.; Lu, J.; Blaabjerg, F. A Self-Synchronized Decentralized Control for Series-Connected H-Bridge Rectifiers. *IEEE Trans. Power Electron.* **2019**, *34*, 7136–7142. [CrossRef]
101. Ge, X.; Han, H.; Yuan, W.; Sun, Y.; Su, M.; Zhang, X.; Hai, K.L. An Integrated Series-Parallel Microgrid Structure and its Unified Distributed Control. In Proceedings of the 2018 IEEE 4th Southern Power Electronics Conference (SPEC), Singapore, 10–13 December 2018; pp. 1–6.
102. Hou, X.; Sun, Y.; Han, H.; Liu, Z.; Yuan, W.; Su, M. A fully decentralized control of grid-connected cascaded inverters. *IEEE Trans. Sustain. Energy* **2019**, *10*, 315–317. [CrossRef]
103. Srinivasan, M.; Kwasinski, A. Control analysis of parallel DC-DC converters in a DC microgrid with constant power loads. *Int. J. Electr. Power Energy Syst.* **2020**, *122*, 106207. [CrossRef]
104. Li, P.; Guo, T.; Zhou, F.; Yang, J.; Liu, Y. Nonlinear coordinated control of parallel bidirectional power converters in an AC/DC hybrid microgrid. *Int. J. Electr. Power Energy Syst.* **2020**, *122*, 106208. [CrossRef]
105. Boddapati, V.; Kumar, T.S.; Prakash, N.; Gunapriya, B. Current droop control of parallel inverters in an autonomous microgrid. *Mater. Today Proc.* **2021**, *45*, 2034–2039. [CrossRef]
106. Guerrero, J.; De Vicuna, L.G.; Matas, J.; Castilla, M.; Miret, J. Output Impedance Design of Parallel-Connected UPS Inverters with Wireless Load-Sharing Control. *IEEE Trans. Ind. Electron.* **2005**, *52*, 1126–1135. [CrossRef]
107. Yang, Y.; Huang, C.; Zhou, D.; Li, Y. Fault detection and location in multi-terminal DC microgrid based on local measurement. *Electr. Power Syst. Res.* **2021**, *194*, 107047. [CrossRef]