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Abstract: Microgrids (MGs) are systems that cleanly, efficiently, and economically integrate Renewable Energy Sources (RESs) and Energy Storage Systems (ESSs) to the electrical grid. They are capable of reducing transmission losses and improving the use of electricity and heat. However, RESs presents intermittent behavior derived from the stochastic nature of the renewable resources available on site. This can cause power-quality issues throughout the electrical grid, which can be solved by different optimization techniques and/or control strategies applied to power converters. This paper offers a detailed review of the literature regarding three important aspects: (i) Power-quality issues generated in MGs both in islanded mode and grid-connected mode; (ii) Optimization techniques used in the MGs to achieve the optimal operating conditions of the Energy Management System (EMS); and (iii) Control strategies implemented in the MGs to guarantee stability, mitigation of power-quality issues, power balance, and synchronization with the grid. It is worth mentioning that in this paper, we emphasize hybrid MGs (HMGs) since they combine the benefits of AC–MGs and DC–MGs while increasing system reliability. As the utility grid moves toward an optimal design of MG structures, this paper will serve as a foundation for future research, comparative analysis, and further development of novel techniques regarding HMGs.

Keywords: hybrid microgrids; renewable energy source; power quality; optimization techniques; control strategies

1. Introduction

The growth of renewable energy exceeded the growth of global energy demand between 2019 and 2020. However, this demand showed a drastic increase in 2022 caused by population growth, high living standards, and infrastructure development. According to the International Energy Agency (IEA), global electricity demand was expected to grow by around 4% by the end of 2022, driven by the global economic recovery. India and countries in Southeast Asia, with an energy consumption rate that will rise to 11% in 2040, will strengthen global energy demand. Therefore, in order to supply this demand, the electrical energy distribution systems must undergo a transformation in the face of the electrical grid of the future, which is composed of digital technologies, renewable energy sources (RESS), and an intelligent grid of distributed generation (DG).
In this context, the popularity of RESs has increased over the years [1], as their integration within the utility grid is an attractive solution. However, maintaining cost-effectiveness and reliability remains a challenge. Therefore, microgrids (MGs) are the most promising solution as a next generation energy system [2]. An MG is defined as a small-scale electrical power system (EPS) made up of a cluster of loads (static, dynamic, flexible, and adjustable, etc.) [3] and RESs that work together through software and devices for the correct energy management; it is also designed to provide the efficiency of a local community's energy supply. It is generally connected to low voltage levels associated with some RESs, such as microturbines, fuel cells (FC), and photovoltaic (PV) systems, along with energy storage systems (ESSs), including flywheels, batteries, supercapacitors (SC), and electric vehicles. The typical diagram of an MG is shown in Figure 1.

![Figure 1. Typical diagram of an MG.](image-url)

Among the main advantages of the MGs are the decentralization of the EPS, inherent flexibility in connecting/disconnecting from the electrical grid, increased system reliability, lower investment cost, great visibility in the green effect because of the integration of renewable sources, the energy-quality improvement of a system, and the reduction of losses in the distribution grid, among others. MGs can be classified as the following: alternating current MGs (AC-MGs), direct current MGs (DC-MGs), and hybrid MGs (DC-AC MGs, or HMGs). Of these classifications, AC-MG is the most widely used configuration that incorporates existing infrastructure, protection, and grid technologies. However, among its most important drawbacks are the need to synchronize the distributed generation units (DGUs) and the losses resulting from the circulation of reactive power. Furthermore, the presence of DC sources presents the problem of conversion to AC using power converters (PC) that decreases the overall efficiency of the system. Thus, the high penetration of DC-based RESs, such as PV systems, FC, ESSs, and loads, has paved the way for DC-MGs. However, these require considerable modifications of the available electrical grid. Both AC-MGs and DC-MGs suffer from inefficiency caused by multiple DC–DC, AC–DC, and DC–AC conversions. Therefore, an HMG is an excellent solution for the creation of intelligent grids within conventional distribution grids, since it combines the advantages of AC–MGs and DC–MGs [4–7]. Nevertheless, HMGs must also face the problem of an accidental or programmed disconnection from the utility grid. As a point of reference, the HMGs must be subject to two typical scenarios, as in any other electrical system of the distribution grid: (1) Situations of minimum and maximum demand; and (2) The management of abnormal operations of their electrical infrastructure. For this reason, this paper explores HMGs.
In recent years, different reviews have been presented that contend with various aspects of HMGs and the associated problems (operations, communications, power quality, stability, energy management, etc.) based on recent studies as part of a global technological development [8–17]. Therefore, the uniqueness of this review is that it provides a comparison with other reviews as it first considers the challenges related to power quality, such as current and voltage harmonic distortion, voltage sag or swell, fluctuations and/or voltage unbalances, the malfunctioning of protection devices, overloads, and failures in electrical equipment [18–26]. Furthermore, this paper also considers the latest and most modern optimization techniques for improving the power output of generators at a particular instant to increase the useful life of ESSs and reduce environmental impact and operating costs. Finally, this paper addresses the control strategies implemented in HMGs, where stability, protection, power balance, smooth transition between modes of operation, power transmission, the synchronization with the utility grid, and the mitigation of power-quality issues are the most important characteristics that must be satisfied. According to the above, this paper comprehensively reviews essential information for researchers to further expand the topic of HMGs.

The major contributions of this paper are cited below.

1. The paper analyzes the integration of AC–MGs and DC–MGs, as well as the use of PCs, through recent studies that contain the latest trends in this field.
2. The paper reviews the main power-quality issues present in HMGs, as well as the most innovative devices used to mitigate each of the issues presented. In addition, it suggests state-of-the-art methods and equipment developed in experimentation laboratories for their implementation in HMGs.
3. The paper presents a critical analysis of a wide variety of optimization techniques used in HMGs to improve power flow and energy generation, reduce uncertainty, and resolve HMG design and topology issues. In addition, it discusses the latest research areas where significant advances can be made regarding HMGs.
4. The paper offers a synthesis of recent control methods and strategies proposed by various researchers to ensure a smooth transition between the HMGs’ operational modes and provide voltage and frequency stability to the electrical grid, as well as improve power quality, minimize operating costs, and ensure effective participation in transitory energy markets.
5. Finally, the paper offers a clear discussion of the key parameters associated with HMGs and provides an in-depth comparison with other current reviews on the topic of HMGs by addressing the main areas of research.

This paper is structured as follows: Section 2 describes the MGs generalities, emphasizing the HMGs. Section 3 describes and analyzes the issues and challenges of power quality, which is key for the integration of HMGs, as well as the techniques and devices used to improve power quality according to current grid codes. Section 4 describes the optimization techniques used in HMGs to improve power flow and energy generation. Section 5 describes the control strategies of the HMGs most used for energy management and control considering the integration of AC and DC subgrids. Section 6 discusses and compares this review with other recent reviews about HMGs. The paper ends with a clear and robust conclusion of the study.

2. Microgrids Generalities

MGs are small-scale EPSs consisting of hybrid RESs, ESSs, PCs, AC–DC buses, AC–DC loads, control units, system monitoring, and software interfaces [27]. They can operate in island mode and connected mode, where all grid setpoints are assumed [28–39]. Several national and international MG projects that consider different RESs have been successfully completed with generation capacities ranging from a few kW to hundreds of MW, as shown in Tables 1 and 2. A brief discussion of the different hybrid RES combinations is presented in these tables.
Table 1. Different types of operational hybrid RESs.

<table>
<thead>
<tr>
<th>Rated Capacity of the RES</th>
<th>Project Details</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 MW (WT), and 35 MV (PV)</td>
<td>Pacific (WT) and Catalina Solar, EE.UU.</td>
<td>[40]</td>
</tr>
<tr>
<td>10 kW (PV), 5 kW (DG), and 50 kWh (BESS)</td>
<td>Kythnos Island, Greece</td>
<td>[41]</td>
</tr>
<tr>
<td>30 MW (GeoT), and 25 MW (PV)</td>
<td>Enel Green Hybrid MicroGrid, EE.UU</td>
<td>[42]</td>
</tr>
<tr>
<td>35 MW (BM), and 22.5 MW (CSP)</td>
<td>TermoSolar Borges, Spain.</td>
<td>[43,44]</td>
</tr>
<tr>
<td>100 MW (WT), 40 MW (PV), 35 MW (BESS)</td>
<td>Zhangbei National, China</td>
<td>[45]</td>
</tr>
<tr>
<td>10 MW (WT + PHESS), and 11 MW (PV)</td>
<td>El Hierro Island, Spain</td>
<td>[46]</td>
</tr>
<tr>
<td>90 kW (WT), 10 kW (WP), and 5 kW (PV)</td>
<td>Dangang Island of Guangdong, China</td>
<td>[47]</td>
</tr>
</tbody>
</table>

PV = Photovoltaic; BESS = Battery Energy Storage System; GeoT = GeoThermal; BM = Biomass; PHESS = Pump Hydro Energy Storage System; BD = Bio Diesel; CSP = Concentrated Solar Thermal Power; WP = Wave Power; WT = Wind Turbine.

Table 2. First MG projects in Mexico.

<table>
<thead>
<tr>
<th>Project Location</th>
<th>Year of Installation</th>
<th>Generator Power (kW)</th>
<th>ESS</th>
<th>Population Served</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ma. Magdalena</td>
<td>1991</td>
<td>4.3 5 18</td>
<td>BESS</td>
<td>168</td>
<td>[48]</td>
</tr>
<tr>
<td>Oyamello</td>
<td>1991</td>
<td>0.76 5 4</td>
<td>BESS</td>
<td>122</td>
<td>[50]</td>
</tr>
<tr>
<td>X-Calak</td>
<td>1992</td>
<td>11.2 60 125</td>
<td>Revers. hydraulic</td>
<td>232</td>
<td>[50]</td>
</tr>
<tr>
<td>El Junco</td>
<td>1992</td>
<td>1.6 10 –</td>
<td>Battery</td>
<td>250</td>
<td>[51]</td>
</tr>
<tr>
<td>Gruñidora</td>
<td>1992</td>
<td>1.2 10 –</td>
<td>–</td>
<td>230</td>
<td>[51]</td>
</tr>
<tr>
<td>Agua Bendita</td>
<td>1993</td>
<td>12.4 20 48</td>
<td>BESS</td>
<td>250</td>
<td>[52]</td>
</tr>
<tr>
<td>Isla Margarita</td>
<td>1997</td>
<td>2.25 15 60</td>
<td>BESS</td>
<td>200</td>
<td>[52]</td>
</tr>
<tr>
<td>San Juanico</td>
<td>1999</td>
<td>17 70 85</td>
<td>Revers. hydraulic</td>
<td>400</td>
<td>[48]</td>
</tr>
</tbody>
</table>

These projects with MGs offer the development of innovative solutions from the technological, regulatory, social, and economic point of view for the aggregation of DGUs, ESSs, and mixed loads adapted to the reality of each region. Most of the MGs shown in Table 1 operate while connected to an electrical grid, although some cases of islanded MGs that stand out for their special design characteristics have also been considered (Table 2). The choice of these MG projects summarized in Tables 1 and 2 are part of the historical evolution and the current situation of the MGs market. As of mid-2019, the total installed, or planned, MG capacity registered in the Navigant Research database was 26.8 GW, spread across 4475 different projects. Within this global set, there is great diversity. By segments, remote MGs, with no or very weak connection to the electrical grid, represent the largest amount in the current market, with 42.3% of the total, followed by the commercial and industrial segment, which represents 25%. By geographical areas, Asia–Pacific and North America are clearly the regions with the greatest weight in the distribution of installed capacity in MGs. It is also expected that during the next few years, it will be in these two geographical areas where the main growth of the market will take place, with expansions well above those expected in Europe, Latin America, the Middle East, or Africa.

In general, the decision to install a MG compared to other alternatives (backup diesel generator, DGUs connected to the grid, gas turbine, etc.) arises from the need for the project to respond to several objectives that a single one of these technologies it cannot solve itself efficiently. Thus, a PV system installation for self-consumption connected to the electrical grid, with or without ESS, can respond to sustainability, cost reduction, and
self-consumption objectives. However, if it is to be accompanied by an improvement in the resilience of the installation, it can be considered to possess an MG structure.

2.1. Classification of the Microgrids

2.1.1. AC–Microgrids (AC–MGs)

Figure 2 shows the diagram of a typical AC–MG. In this system, all distributed generators, including ESSs and loads, are linked to the AC grids buses via a PC. However, it is possible to connect AC generators, like microturbines, diesel, and wind turbines (WTs), to an electrical grid without the need to connect PCs. Alternatively, to connect DC RESs, such as battery-based ESSs (BESS) and PV systems, to the electrical grid, a DC–AC inverter is essential. Therefore, the loads are directly connected to the AC buses. However, AC–MGs possess some inconveniences, such as complex control and synchronization issues with the grid. Nevertheless, this type of MG is the most widely used today.

![AC–MG typical structure](image)

Figure 2. AC–MG typical structure.

2.1.2. DC–Microgrids (DC–MGs)

The majority of generators of a MG create power in DC, which is converted into AC by means of a PC to adapt to the electrical grid since some equipment needs AC to work. However, the conversion from DC–AC–DC to AC–MG causes losses in the transmission lines, which reduces the efficiency of the system. This can be remedied, though, by using a DC–MG because it reduces the number of PCs in a single conversion process [53]. In [54], the authors affirm that for distribution systems in residential areas, DC–MGs are the best option. Among the main advantages of DC–MGs are the improvement in efficiency and the enormous ease in integrating and optimizing Distributed Energy Resources (DERs). In addition, they solve some control problems; for example, the primary control is considerably simpler because of the absence of reactive power-flow management. Regarding the ease of integrating and optimizing DERs, it is important to note that for both RESs (conventional high efficiency) and ESSs, the vast majority originally operate in DC or need at least one DC stage before interconnection (micro-wind turbines, gas micro-turbines, hydraulic micro-turbines, and flywheels, among others). As a result, using a DC–MG facilitates the interconnection of DERs as it simplifies power conditioning devices and can help mitigate problems arising from frequency regulation and the synchronization present in AC grids.
When the DC–MG operates in island mode, it becomes more resistant to major failures in the main grid. Furthermore, it is much easier to design a DC–MG since there are no problems related to synchronization and reactive power flows. Figure 3 shows the typical configuration of a DC–MG.

![DC–MG typical structure](image)

**Figure 3.** DC–MG typical structure.

### 2.1.3. DC–AC MG or Hybrid MG (HMG)

The HMG is the combination of AC and DC–MGs in the same distribution grid. The main advantages of these MGs are as follows: (i) The coexistence of both types of AC and DC buses, which allow for an easy adaptation and connection to the different types of energy generation and ESSs; and (ii) A high capacity for the integration of different types of loads and power systems. However, in islanded mode, HMGs have a high control complexity because of the difficult synchronization, protection, and power management between the devices that compose the MG [55,56]. Figure 4 shows the typical configuration of an HMG.

### 2.2. Characteristics of the Microgrids

#### 2.2.1. Grid Connection

Although the usual definition of MG refers to those grids connected to electrical grids from which they can be disconnected to work in islanded mode, some authors also include those islanded grids whose distributed operation is similar to that of a MG, as opposed to the more traditional islanded grids whose generation is centralized in one or several diesel generators.

Regarding those MGs connected to the electrical grid, it is also necessary to differentiate between those normally connected to the grid and those normally disconnected. The latter must be planned for a prolonged use of their islanded connection, since they require dispatchable generation (such as diesel generators) or a large storage infrastructure, as opposed to the former that can only use intermittent renewable generation. The continuous use or not of the islanded mode is mainly based on the reliability of the grid to which they...
are connected, although economic reasons could also appear in the future depending on the contractual relationship between the owners of both grids.

Figure 4. HMG typical structure.

2.2.2. Power Source

Power-source types used in an MG, due to their influence on its operation, is also a defining characteristic. DGUs, together with the ESS and the rest of the system elements, must be capable of maintaining the quality and security of supply of the MG, mainly during the islanded mode.

The first way in which it affects the power source is through the characteristics of its supply, mainly if it is a renewable source or not, and if it is dispatchable or not. From the MG management point of view, the RESs allow for the reduction of the cost of its supply, so it will typically seek to maximize its use. From the point of view of security of supply, generation that cannot be dispatched or that has a certain seasonality (for example, mini-hydroelectric) requires that the rest of the components maintain the generation–demand balance.

The second way in which it affects generation is its decentralization. By concept, the MGs must be capable of integrating generation coming from different elements and in different locations of the grid, that is, decentralized. However, in addition to this, the generation can belong to a single user or to different owners (an energy community), related or not to each other. This influences various aspects, from MG management to the contractual relations between the different agents of the same.

2.2.3. ESS

As has been pointed out, the presence or not of ESSs appears linked to the RESs present in the MG: if the MG exclusively uses RESs (or the dispatchable generation does not cover all the demand of the grid), it will require the presence of ESSs. In the case of possessing dispatchable generation, storage tends to be used to optimize the cost of generation and guarantee the exchange of energy with the electrical grid. ESSs can also be useful to cushion the impact on the system when it goes from islanded to connected mode, a maneuver that generates transients that disturb both systems and can cause them to fail.
Regarding its physical layout, and in a similar way to the case of generation, the ESS can be centralized or decentralized. Its property may belong to one or several agents, with a significant impact on the management capacity of MG and on the relations between its agents. Finally, note that the ESS is not limited exclusively to electric ESS, although this is most common in MGs. The presence of thermal ESS makes it possible to optimize the use of the thermal vector, from storing excess heat from cogeneration to preheating water at times of low grid cost or excess renewable generation.

2.2.4. Demand

Demand plays a more important role in MG management than in conventional EPS. As the size of the system is smaller, this means that the demand imposes stricter operating conditions on the MG generation, in particular, when the system operates in islanded mode: in the number of hours that the system can operate in an islanded way, in the critical loads to which a certain quality of supply must be guaranteed, etc. Regarding critical loads, they condition the MG design due to their importance, giving the case that, although they should not require the existence of UPS systems, which the MG usually replaces, they can be incorporated into it in the event of previously existing or installed UPS systems as an additional security measure. Finally, the proximity between generation and demand also facilitates the ability to manage the latter as an active part of the MG as it is able to provide service to other components or users.

2.2.5. Voltage and Frequency

The voltage level is usually low voltage, although some islands have MGs with a medium voltage distribution grid. The most widespread voltage is AC, although some small MGs use DC. Often, the latter only includes buildings or centers that have an MG, although there are also larger grids such as the Okinawa Institute of Science and Technology. There are also MGs that distribute power in both AC and DC, such as the one on the island of Moku or Lo’e. The voltage choice affects all levels of the grid, from the components, which must be adapted to the level and type of voltage chosen, to the control of the grid itself. Voltage levels similar to those of distribution grids are used and, therefore, possess similar components. Regarding the control system, AC grids are usually regulated using the grid frequency as a reference with respect to its reference frequency, while DC grids use the voltage level against the reference voltage level. This reduces the level of complexity of controlling DC systems, which reduces quality issues of components involved. Like voltage, MG frequency is usually the same as the electrical grid to which it will be connected (e.g., 50 Hz in Europe and 60 Hz in the United States). The development of high-frequency MGs has also been proposed. In these grids, the generation systems are connected to a common node from which the generated power is passed on at high frequency and is transmitted to the demand, which generally works at the usual frequency of the distribution grid. These grids have been proposed as a way to facilitate the integration of RESs, since it increases wave quality (it is easier to filter harmonics at high frequencies), improves the efficiency of some components, such as lighting, and reduces the size of devices like transformers. On the contrary, the increase in the reactance of the cables increases the transport losses in the MG and the voltage drops along it, in addition to making its control system more difficult.

2.3. MG Components

In contrast to conventional EPSs, MGs have very specific characteristics. For example, a set that includes generators and loads that are connected to the electrical grid through the Point of Common Coupling (PCC), which acts as a single element facing it. Likewise, the MGs have, in general, low voltage levels, a greater proximity between the generation and consumption points (usually the building itself in which the generation is installed) and, on occasions, interconnections with heat, transport, and other complementary systems (for example, biogas plants for waste management).
The main MG components are the following:

- **Generation:** Like traditional EPSs, MGs admit all types of generation adapted to the power scale. These include diesel generators (typically from backup systems prior to the MG), gas generators, intermittent renewable generation (wind, solar), and non-renewable generation (hydrogen, biogas, mini–hydraulic).
- **Demand:** This is divided between that which is manageable and that which is not, as well as, in the cases that require it, the loads that are critical and the rest. The demand may be interconnected with the rest of the MG systems, such as heat or biogas generation.
- **Grids and subgrids:** Mainly electrical, both overhead and underground, but gas and heat may also be included. All their components are included here: cables, transformers, etc.
- **PCC:** Includes measurement instruments, switches, contactors, synchronization relay, protection and control systems, etc. Due to its sensitivity, and because it does not appear in those islanded MGs, it is included separately from the rest of the electrical grid.
- **Management and control elements:** Including the elements in charge of these regulation processes (Energy Management System–EMS) for the different states of the MG (connected, islanded, and the transition between both).
- **Protection elements:** Normally working individually or coordinated with a few other protection elements.
- **ESS:** Although it is not essential, most MGs include ESSs for the energy management flows between generation and demand; this is particularly important when the MG is regulated in islanded mode.
- **Other components:** Mainly linked to complementary systems.

3. Issues and Challenges of the HMGs

The HMGs have numerous advantages compared with individual AC–MGs and DC–MGs. However, there are also many practical challenges, as well as operational, coordination control, protection, stability, EMS, communication, and electricity market trends that prevent the development of efficient and feasible grids. These challenges are summarized in Table 3.

3.1. Operational Issues

The main operational challenges for HMGs are described below.

- **Power-sharing under different operating conditions** is an important issue regarding the stability of HMGs, which depends not only on the AC subsystem but also on the DC subsystem because of the exchange of power through the PC. Therefore, researchers have analyzed the power distribution in HMGs based on droop control. For example, in [57], the design and operation of an HMG is presented to control the operation of the PC and the power losses during charge/discharge scenarios, concluding that the shared power affects the dynamics of the AC and DC subgrids, which creates a system-wide stability issue. In [58], multiple PCs were implemented to increase system reliability and eradicate the issue of [57]. However, the AC subgrid becomes more susceptible to power exchanges, which reduces the overall performance of the system. Therefore, the implementation of ESSs is proposed to improve power transfer between subgrids [59].

- The parallel operation of multiple PCs is another major issue. The operation of PCs in HMGs has many advantages, with the main one being that it offers greater reliability to the system for high-power applications; see Figure 5. However, the operation of PCs connected in parallel generates serious issues, such as the resynchronization required after different operating modes of the grid, circulating current in parallel operation, and harmonic distortion in the system [60].
• The disconnection between generation and demand can lead to voltage and frequency issues, as HMGs tend to constantly switch from grid-connected mode to islanded mode. In addition, the simultaneous interconnection of a large number of DGUs can be a serious problem, as well as the impact of interconnected PCs on the HMGs.

Table 3. Issues and challenges of the HMGs.

<table>
<thead>
<tr>
<th>Issues and Challenges</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td>• Power quality</td>
</tr>
<tr>
<td></td>
<td>• Coordination control</td>
</tr>
<tr>
<td></td>
<td>• Protection</td>
</tr>
<tr>
<td>Regulation policies</td>
<td>• HMG implementation</td>
</tr>
<tr>
<td>Bidirectional power flow</td>
<td>• Reverse power flow protection</td>
</tr>
<tr>
<td></td>
<td>• Voltage variation</td>
</tr>
<tr>
<td>Operational</td>
<td>• Power generation and demand</td>
</tr>
<tr>
<td></td>
<td>• Disconnection of generators during start-up of islanded mode</td>
</tr>
<tr>
<td></td>
<td>• Low inertia</td>
</tr>
<tr>
<td>Protection</td>
<td>• Grounding</td>
</tr>
<tr>
<td></td>
<td>• Current fault level fluctuations</td>
</tr>
<tr>
<td></td>
<td>• Isolation from the electrical grid</td>
</tr>
<tr>
<td>Power quality</td>
<td>• High THD levels</td>
</tr>
<tr>
<td></td>
<td>• Reactive power compensation</td>
</tr>
<tr>
<td></td>
<td>• Regulatory framework</td>
</tr>
<tr>
<td>AC–DC subgrid coordination</td>
<td>• Energy management scenario</td>
</tr>
<tr>
<td></td>
<td>• Subgrid control</td>
</tr>
</tbody>
</table>

Figure 5. Parallel operation of multiple PCs in HMGs.
### 3.2. Power-Quality Issues

Power quality is a major concern in HMGs, whether operating in islanded mode or grid-connected mode, because of the presence of non-linear and unbalanced loads, which constitute a large part of the system. The presence of these loads creates problems such as harmonic distortion and voltage unbalances, as well as voltage sags/swell in weak grids [61]. Similarly, high levels of harmonic distortion and voltage unbalances are produced by high levels of impedance in the system, as well as load-distribution problems caused by the intermittency of RES, such as wind, solar, and FCs. See Table 4.

#### Table 4. Main power-quality issues in HMGs connected to the electrical grid [53,61–81].

<table>
<thead>
<tr>
<th>Power Quality Issue</th>
<th>Solar</th>
<th>Wind</th>
<th>Hydro</th>
<th>BioDiesel</th>
<th>Biomass</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (sags/swells)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Voltage (over/under)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Voltage unbalances</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Voltage harmonics</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Current harmonics</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Interruptions</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
</tbody>
</table>

#### 3.2.1. Power-Quality Issues in HMGs Connected to the Electrical Grid

In this mode of operation, the most frequent problems are disturbances, grid voltage unbalances, reverse power flow, voltage sags, and harmonic distortion [62–65]. Regarding voltage sags, they represent one of the most serious issues in terms of power quality. These are caused by faults, which lead to instability in the electrical sector and interruption in the operation of the HMGs composed of RESs. Voltage swell is also a serious power-quality issue [66]. Many standards and grid codes impose new regulations about the integration of RES against voltage swells and the ability to withstand voltage sags (Low-Voltage Ride Through (LVRT)) and voltage swells (High-Voltage Ride Through (HVRT)). These regulations require that the HMGs be disconnected from the utility grid in case the voltage sags or swells last for a certain duration [67]. To cite an example, the German standard indicates that in the presence of voltage sags (below their nominal value), the HMGs must remain connected to the utility grid for 0.15 s; otherwise, system shutdown will be mandatory. The same rule indicates that in the presence of voltage swells, the HMG must remain connected (even if it exceeds its nominal value) for 0.1 s; otherwise, disconnection is mandatory [68]. Another phenomenon that occurs regularly in HMGs is voltage unbalance. The voltage unbalance factor (VUF) measures the degree of unbalance in the system [69]. This can have adverse effects on the power electronics of the HMG and on the EPS devices since these will suffer more losses and will be less stable under unbalanced conditions [70]. Therefore, it is necessary to limit the VUF through consistent criteria established in the grid codes and, thus, guarantee a reliable, stable, and balanced integration of the HMGs with the electrical grid [71–76]. Finally, harmonic distortion is another phenomenon with a noticeable presence in HMGs derived from the use of non-linear loads, PCs, computer controllers, and variable speed motors, which are the main causes of the generation of this phenomenon. Most EPSs have some tolerance for harmonic distortion; however, when the harmonic distortion increases, it will undoubtedly lead to communication failure, line loss, overheating, and circuit breaker tripping [77]. Therefore, HMGs must minimize the emission of harmonic distortion according to current standards and codes [53,78–81]. An important index for quantifying the harmonic content of a voltage or current signal is the Total Harmonic Distortion (THD), which expresses the relationship between two magnitudes and the effective value of the harmonic residue or harmonic components with respect to the fundamental component. The THD can be current (THDi) or voltage (THDV), and both must be less than 5%, according to IEEE or IEC standards.
3.2.2. Power Quality Issues in Islanded HMG

The interaction between loads, RESs, and ESSs during HMG transition states can lead to an adverse impact on power quality when the HMG operates in islanded mode; see Figure 6. According to [82], the interaction between the loads and the RESs reduces the value of the impedances in the HMGs, resulting in noticeable voltage variations and a higher probability of power-quality issues.

![Figure 6. Power-quality issues in HMG isolated from electrical grid [82].](image)

In some cases, voltage deviations occur as a consequence of the increase of the voltage harmonics in the HMGs, and this is because of resonances at low frequencies [83]. On the other hand, harmonic distortion continues to be one of the most important power-quality issues in HMGs, even when operating in islanded mode, since not only are the harmonics of the fundamental frequency present, but they also lead to the presence of inter-harmonics, sub-harmonics, and supra-harmonics. For example, in [84–87], the THD_v was calculated from simulations of different HMGs operating in islanded mode with different load types (linear, nonlinear, and mixed). These references show that the highest values of THD_v are in the HMGs that contain non-linear loads. To confront this problem, control strategies are implemented to reduce THD_v in HMGs, which are listed in Table 5. Finally, several studies [88–92] analyze the harmonic distortion in an HMG when it operates in islanded mode and grid connected mode.

Table 5. THD_v (%) on HMG islanded mode for different load and different control strategies.

<table>
<thead>
<tr>
<th>Load</th>
<th>Control Strategy</th>
<th>THD_v [%]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix</td>
<td>Virtual impedance</td>
<td>0.6–8.7</td>
<td>[93–97]</td>
</tr>
<tr>
<td>Non-linear</td>
<td>Harmonic controller</td>
<td>11.38</td>
<td>[98–100]</td>
</tr>
<tr>
<td>Non-linear</td>
<td>Compensation</td>
<td>10.3</td>
<td>[101]</td>
</tr>
<tr>
<td>Non-linear</td>
<td>Fuzzy–PI</td>
<td>4.66</td>
<td>[102]</td>
</tr>
<tr>
<td>Non-linear</td>
<td>Artificial Neural Network</td>
<td>12</td>
<td>[83]</td>
</tr>
</tbody>
</table>

3.2.3. Frequency Variations

The control of the active power in the HMGs in response to the system frequency is achieved through the coordination of the RESs, the diesel generator, the microturbines, and the ESSs. Now, because of the interactions between the loads and the RESs, the frequency variations can be more pronounced, more frequent, and longer in an HMG when operating in islanded mode [103] because the PCs adjust their frequency according to their ranges of maximum active power deviating from the nominal frequency. Thus, a system with a power demand close to its maximum range deviates more from its nominal frequency. This is because an HMG based solely on PV and BESS systems produces a very low inertia.
Conversely, other HMGs that include synchronous generators produce much higher inertia; that can be decisive in the system response. For example, in [104], measurements were calculated for an HMG for almost a year, and the results showed that 89% of the frequency variations were outside the permissible limits: i.e., 42.5 to 57.5 Hz defined in EN 50160 for HMGs operating in islanded mode. Consequently, there were brief interruptions that could have adversely affected certain equipment. Therefore, in an HMG with high-RES penetration, frequency variations usually occur as a consequence of the disconnection of some distributed generators. This is a serious problem as current distribution systems depend on the interconnected system to balance load generation [105,106]. Table 6 summarizes the most-used techniques that regulate the frequency in HMGs. Some of these techniques will be covered in detail in later sections.

### Table 6. Control techniques comparison for frequency regulation in HMGs.

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Droop control</td>
<td>Control HMG frequency deviations.</td>
<td>[107–111]</td>
</tr>
<tr>
<td>Model Predictive Control (MPC)</td>
<td>Effectively predicts the future real power output of the HMG if the system dynamic model and current measurements are available.</td>
<td>[112–116]</td>
</tr>
<tr>
<td>Fuzzy–Logic Control (FLC)</td>
<td>Maintains the voltage on DC bus constant.</td>
<td>[117–120]</td>
</tr>
<tr>
<td>$H_{\infty}$ controller</td>
<td>Provides good performance and keeps the system stable by synthesizing the controllers.</td>
<td>[121–125]</td>
</tr>
<tr>
<td>Hierarchical control</td>
<td>Maintains the system operating at a frequency close to nominal.</td>
<td>[125–131]</td>
</tr>
<tr>
<td>Sliding Mode Controller (SMC)</td>
<td>Regulates the voltage and frequency of the master DGU.</td>
<td>[132–134]</td>
</tr>
<tr>
<td>Demand-side control</td>
<td>Controls the load-side demand.</td>
<td>[135–138]</td>
</tr>
</tbody>
</table>

3.3. Communication Challenges

Communication infrastructure is an important issue regarding the control and management of HMGs as it establishes bidirectional connectivity between HMG components and ensures their safe and optimal operation; see Figure 7. In fact, several of these HMGs continue to employ legacy communication technologies. For that reason, new standards and protocols are being developed that address the unique issues of HMGs. Regarding the above, a good design in the communication systems and good coordination in the protection schemes are essential for achieving a reliable and efficient system in the HMG. Today, wireless communication and fiber optics are presented as alternatives since these systems allow RES and loads to receive and send data through communication links efficiently and reliably. This leads to interconnected devices called Intelligent Electronic Devices (IED) [139] that communicate through a Central Controller (CC) to transfer operational data and perform control actions related to the dispersed geographic locations of the RES, the increase in data traffic, and real-time monitoring and control. All communication networks must satisfy the most important aspects related to data protection, monitoring, control, synchronization, and demand response in HMGs through different bandwidths and acceptable delay times [140]. On the other hand, it has been demonstrated through simulations and experiments that problems exist in the communication networks, such as packet loss, latency, and instability in the operation of the HMG, which can negatively affect the operation of the system in terms of voltage, frequency, and energy losses. Therefore, it is important to have a well-designed communication network in the PC of an HMG [141].
In modern networks, composed of highly complex IEDs, the design of reliable communications and the standardization of the system have a high priority [142]. Some of the available standards that address the networking and communications needs of HMGs are IEC 61850, IEC 61968, DNP3, IEC 60870–5 and IEEE 1646. See Table 7.

Table 7. International standards for HMGs communications [143].

<table>
<thead>
<tr>
<th>Standard</th>
<th>Characteristics</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC 61850 [143]</td>
<td>Exchange of real-time status information and events in substations</td>
<td>DER/HMG</td>
</tr>
<tr>
<td>IEC 61968 [144]</td>
<td>Data exchange between device and networks in the power distribution domain</td>
<td>EMS</td>
</tr>
<tr>
<td>DNP3 [145]</td>
<td>Highly secure communication and authentication interface ideal for data transfer in utilities</td>
<td>Substation Automation</td>
</tr>
<tr>
<td>IEC 60870–5 [146]</td>
<td>It applies remote control concepts by adding headers with appropriate information for the management of its delivery through TCP–IP channels</td>
<td>Control System in HMGs</td>
</tr>
<tr>
<td>IEEE 1646 [147]</td>
<td>Allows building open systems communication interfaces for smart electronic devices</td>
<td>Substation Automation</td>
</tr>
</tbody>
</table>

Related to data protection, it is necessary to integrate a well-established communication system [144,145] that considers operation and maintenance costs, the number of devices, and the necessary bandwidth and coverage. Table 8 shows some of the most-used options for guaranteeing a good communication infrastructure in the HMGs. Finally, to ensure efficient communication structures in the integration of RES with the electrical grid, it is necessary to establish norms and regulations that act in the HMGs’ different modes of operation, mainly in the islanded mode operation since it conflicts with current standards because of the high connection costs for private investors [148]. Another problem to highlight is the installation of bidirectional energy meters necessary to register the energy transfer [149]. For example, [150,151] analyze and compare the regulatory challenges faced by islanded mode HMGs for industrial applications, such as command and control instruments, economic instruments, and information instruments by considering the Distribution System Operator (DSO) model.
### Table 8. Communication infrastructure used in the HMGs.

<table>
<thead>
<tr>
<th>Communication Technology</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Application</th>
</tr>
</thead>
</table>
| Wired                    | • High reliability and security | • High costs  
• Less flexibility with respect to network changes  
• Issues due to the propagation characteristics of EPS elements | Power Line Communication (PLC) |
| Dedicated Wired Networks | • Transmit data at very high speeds  
• Provide reliable decentralized communications [139] | • Need modulators at each user station  
• High installation cost  
• Limit the transmission speed | • Synchronous Optical Networking (SONET)  
• Synchronous Digital Hierarchy (SDH)  
• Ethernet  
• Digital Subscriber Line (DSL)  
• Coaxial cables [146] |
| Wireless                 | • Economically viable  
• Scalable  
• More versatile than wired media  
• High speed  
• Data security | • Prone to environmental interference and transmission attenuation | • Wi-Fi (IEEE 802.11)  
• WiMAX (IEEE 802.16)  
• Bluetooth (IEEE 802)  
• ZigBee (IEEE 802.15)  
• Cellular network communication such as 3/4/5G networks [147,152]. |

### 4. Optimization Techniques

Optimization in the HMGs is directly related to the increase in the power output of the RESs in a given time, the increase in the ESSs’ useful life, and the reduction in environmental impact and operating costs. Therefore, it is necessary to establish constraints, and an objective function, that are related to all these aspects; for example, maintenance, fuel, start and stop, and the commercialization of electrical energy. Thus, in HMGs, optimization techniques can be used at any level to achieve optimal EMS operating conditions and, thus, monitor the operation of electrical, thermal, and mechanical components with both short- and long-term results, which means decreased system costs. Therefore, optimization techniques are necessary in many decision-making tasks in generation programming and in the operation and maintenance of the HMG. Figure 8 shows the optimization techniques most used in HMGs according to various researchers. The aforementioned optimization techniques are described below.

#### 4.1. Linear and Non–Linear Technique

When certain constraints are presented in the system that needs optimal solution, optimization techniques are applied [153]. Some methods used are the following: Linear and Non-Linear Programming (LP and NLP), Mixed Integer Linear and Non-Linear Programming (MILP and MILNP), Quadratic Programming, Linear Least Squares Programming, Dynamic Programming, and artificial intelligence techniques, with the following most important objectives: minimize carbon dioxide emissions, reduce energy consumption, and improve both economy and reliability, among others. Of the mentioned techniques, LP is
used to solve an optimization problem of a linear function under linear constraints. Some algorithms have been developed to solve LP problems, such as the Simplex Method and the Linear Interior Point Solver. On the other hand, NLP programming seeks an extreme value of the objective function under study, subject to some constraints. However, interchangeably, the objective function, its constraints, or both can be nonlinear relationships. When this type of programming presents mixed variables, it is called MILP since its solution is more expensive from the computational point of view.

Figure 8. Optimization techniques most used in HMGs.

Regarding the Quadratic Programming problem, it contains a quadratic objective function in its structure and its linear constraints. Within this framework, quadratic optimization considers the problem with linear equality constraints. To mention a few cases, in [154,155], a problem arose in an HMG located in the CIESOL bioclimatic building of the University of Almeria where the power supplied by the electrical grid was reduced. This problem was solved using the LP technique, reducing the cost of electrical energy by 48.1%. In [156], in order to minimize operating costs and carbon emissions in an HMG, the authors implemented the MILP technique with a new multi-objective solution. To obtain the optimal solution for this programming, there are different commercial modeling platforms on the market, such as GAMS, AMPL [157], and AIMMS [158]. These modeling platforms are armed with deterministic solvers, such as IPOPT, CPLEX, SCIP, BARON, CONOPT, MATLAB, and Python, to name a few.

4.2. Dynamic and Metaheuristic Optimization

Other optimization techniques used in HMG are dynamic optimization and meta-heuristics. The latter is a heuristic method that has specific mechanisms to achieve global optimization, although it does not guarantee it. The Particle Swarm Optimization (PSO) Algorithm is an example of these techniques that is widely used in different areas of social simulation, which uses a population of the search points that moves stochastically in the space, in such a way that the best position that each individual has reached is kept in memory and communicated to all or part of the population, inclining its movement towards the most promising regions detected so far. From this optimization technique, a Multi-Objective PSO (MOPSO) is derived where the PSO is adapted to perform a multi-
objective optimization, which requires that in the updating of the particles, the global best is a non-dominated solution found by the group and that the best personal corresponds to a non-dominated solution found by the particle. Regarding this topic, in [159], the authors propose a MOPSO algorithm that replaces the personal best of each particle through a list containing all non-dominated solutions that it has found. With this, the multicriteria objectives in the HMG are optimized, including the optimal dimensioning of the HMG components, the minimization of the operating cost with respect to renewable generation, and the increase in the reliability of the system [160–164]. In [165–167], the results of the application of the MOPSO technique for applications in HMG are presented. On the other hand, this programming model proposes customers to submit power-demand schedules, as well as monitor prices. The HMG is required to transmit demand forecast information to the electrical grid. In addition, users must participate in energy offers and respond to HMG management signals in real time. An intelligent system can be implemented that independently performs these tasks without the need for them to be carried out by the end user. An HMG is equipped with distributed generation, grid connection, ESSs, and loads. Some works that used this technique are summarized below. In [168], an economic approach is proposed through dynamic programming, which discusses a strategy based on the establishment of prices in real time. In this, consumers compete to minimize costs, which would contribute to an optimal solution for energy consumption. This approach encompasses the critical point of renewable energy consumption by the HMG and the price of energy. Another view of dynamic programming is to propose a dynamic contract mechanism to regulate the control of HMGs based on time. The contract is based on the proposition of purchase commitments at certain times to meet the requirements of the HMG loads while allowing future commitments to be more flexible. A stochastic schedule is used to update the commitments by considering the state of the ESS and a consumption forecast [169]. Finally, the Unit Commitment problem can also be solved with dynamic programming, which aims to minimize CO₂ emissions and the consumption of fossil fuels. To reduce uncertainty in the production of solar energy, an intelligent system calculates the production references of the generators one hour in advance. This raises the reduction of system costs and the optimization of storage systems [170].

4.3. Genetic Algorithm (GA) and Multi-Agent (MAS) Optimization

Within the Multi-Objective Optimization algorithms, there is optimization by the GA to optimally size the components of the HMG at the minimum cost. For example, in [171,172], the authors apply the elitist Non-Dominated Sorting Genetic Algorithm (NSGA–II) to reduce the average peak load and the operating cost through Membership Functions (MF) based on Fuzzy logic-based Energy Management System (FEMS). In [173], NSGA–II addresses the problem of optimal DER dispatch by seeking to minimize generation costs, carbon emissions, and line losses. To schedule the operation between neighboring interconnected HMGs, an EMS is presented with architecture that incorporates the function of an Artificial Neural Network (ANN) to predict both the load and the availability of the DERs in the HMGs. Further applications of NSGA–II are presented in [174–176]. In [177], a methodology is introduced to determine the availability and cost of the energy resource delivered by an HMG with wind and solar generation, as well as a connection to the main electrical grid. The proposed methodology seeks a reliable supply of energy with the least economic investment, for which it makes use of the Multi-Objective Genetic Algorithm (MOGA) as an optimization method.

On the other hand, optimization methods based on a Multi-Agent System (MAS) are complex systems composed of several autonomous agents with only local knowledge and limited capabilities, but which can interact with each other to achieve a global goal. For example, in [178], the authors review the current state of the art of the MAS application in electrical HMGs. This paper focuses on recent MAS developments focusing on work on distributed control of HMGs, electricity market modeling, optimization, and power restoration. Additionally, in [179], the author presents a MAS for the programming of
the generation of an HMG and monitoring of the energetic resources looking for the optimal operation. For over a decade, MAS methods have been used in many energy applications [180]. Finally, in [181], intelligent agents are endowed with functionality so that they can help make energy transfers more economical. In this paper, an HMG that uses multi-agents is designed and its operation validated during power shortages. Agents can make decisions with artificial intelligence by negotiating and cooperating with other agents. The objective of this research is to find the optimal functioning of the different DERs. Currently, many researchers have been commissioned to study MAS models and to apply them to distributed energy systems such as HMGs, recognizing their high potential.

4.4. Fuzzy Logic and Others Techniques

To satisfy the load demand, monitor the ESSs’ charge/discharge and optimize the operation cost considering the high penetration of RESs in the electrical grid; optimization by fuzzy logic is considered. For example, in [182,183], the authors use the Strength Pareto Evolutionary Algorithm (SPEA–II) for Demand Response Management (DRM) and, thus, satisfy maximum demand load and a decrease in customer spending. In [184], a multilevel algorithm is proposed to optimize revenues and expenses and improve the quality of service (QoS) of the data center and the stability of the electrical grid. In [185] a multi-objective algorithm based on the Six Sigma approach is discussed for solving the HMG dimensioning problem consisting of multiple resources and multiple constraints. In [186], the authors propose the fuzzy logic technique for cost and emission optimization using optimal droop control values. This technique is compared with the PSO and MOGA techniques, and the results show a close proximity. In [187], the authors study the interaction between electrical and thermal energy with the help of a power center integrated in an HMG, for which a two-stage stochastic problem is formulated based on a Sample Average Approximation Mechanism. Furthermore, the decomposition technique (Bender) is used to solve multiple cases generated by this mechanism. In [188], a new Dynamic Power Routing (DPR) technique is presented for HMGs operating in islanded mode, which, if integrated with a supervisory controller, will minimize load-shedding and considerably improve system reliability. In [189], the authors analyze the increase in stability in an HMG through the Optimum Power Flow (OPF) using the Interior Point (IP) method, which is employed to discover the issues (technical and economic) associated with an HMG and results in the optimization of system parameters and the interconnection of PCs to maximize load capacity. In [190], the profits of an HMG are improved by implementing the spot price method and, thus, achieving an economic benefit (increased revenue and reduced operating costs) in the operation of the HMG. In [191], the authors propose the Probabilistic Economic Dispatch (ED) tools to reassess the demand forecast using a fuzzy rule-based system, representing the external factors influencing demand, improving the forecast, and, thus, providing a supply of demand constant energy at low cost. In [192], the authors highlight the impact of PHEVs on HMGs by using fuzzy inductive reasoning to forecast short-term power demand, with a forecast horizon of one day using MILP and GAMS software to minimize operating costs. In [193], the authors use the HOMER software to model the HMG in Pakistan to perform demand prediction, with the inputs being the minimum and maximum daily temperature, the time of year, capacity of the day, rainfall, and cloudiness. Thus, they minimize the cost of energy and CO₂ emissions. In [194], the authors use the Multi-Objective Spotted Hyena and Emperor Penguin Optimization (MOSHEPO) technique and compare the results with other strategies, such as GA and MOPSO. The comparison leads to the domain of the MOSHEPO technique for economical load dispatch solutions. There are other methods for solving the problem of flexibility and adaptability in HMGs, such as the Grey Wolf Optimization (GWO) technique, the moth–flame optimization technique, and the gray cumulative prospect theory [195–197]. These techniques are used to minimize the cost of energy, improve RESs’ use, improve power-flow management, minimize operating cost, and reduce CO₂ emissions.
4.5. Optimal Power Flow (OPF) Optimization

Modeling the power flow in an HMG is complex because of the non-linear and non-convex nature of the equations that describe the power flow problem, as well as to quantify the DC and PC equipment that comprise it. Therefore, it is imperative to develop steady-state models, as well as use numerical methods, to obtain the appropriate solution. Some cases of this optimization technique are cited below. In [198], an optimal programming strategy for an HMG is proposed using the second-order cone programming relaxation method to perform a linear transformation to minimize the total cost of the proposed HMG. In [199], the authors use the coupling relationship between a PV and a WT system where an integrated optimization model is established in HMGs. In [200], the increase in the use of renewable energy and the reduction of the operating cost of an HMG are studied. In addition, it emphasizes the need to coordinate the load of the grid for which the authors use an Improved Memetic Algorithm (IMA) that provides shorter execution time and excellent results compared with the Basic Memetic Algorithm (BMA). In [201], a decentralized model is proposed for an optimal power flow. Thus, it achieves the autonomous operation of the HMG with the help of the power-injection control of the PC and the Kriging model, which uses the Analytic Target Cascading (ATC) method. The results show that the Kriging model applied to the power transformer with ATC provides a better fit with the power-loss functions, solving large-scale decentralized and centralized power flow problems.

4.6. Robust and Stochastic Optimization

Another point to consider is the participation of users in management, the sale of energy, and decision-making based on energy prices in the HMGs. This increases the uncertainty in the production and consumption of energy, as well as in the control of the on/off decisions of the dispatchable central, in the amount of charge/discharge of the ESS and in the commercialization of the energy with the electrical grid. Therefore, the main methods used to handle these uncertainties are stochastic optimization and robust optimization. The latter has been widely used to resolve uncertainties in HMGs because it uses probability density functions. Therefore, certain types of variants have been proposed for the standard robust optimization, resulting in Adaptive Robust Optimization (ARO) that overcomes the drawbacks of static robust optimization. Citing some examples, in [202–204], the uncertainty of wind load and generation, as well as the market price in HMGs that operate in islanded mode and connected to the grid, is analyzed through a robust optimization approach. The authors in [205] used the ARO for the operation of HMGs with a safety constraint, while considering the uncertainties in the loads and the intermittent renewable energies. Since robust optimization does not manage the interrelationships between uncertainties, stochastic optimization is employed. In [206], the authors introduced this optimization to reduce operating system costs and the amount of unattended power in the HMG [207–209].

In [210,211], a novel methodology for the probabilistic estimation of the stochastic model of the BESS’s state of charge is proposed. For this, a computational tool is structured that links the DIgSILENT PowerFactory and Python programs. This application allows, in a probabilistic way, for the evaluation of the operation of the HMG by considering the availability of the intermittent primary resource of renewable energy sources and the variability of electrical demand. As a result of this investigation, the stochastic models of the State of Charge (SoC) of the BESS are determined for each time period. In [212], an EMS is developed that considers the behavior of a gasifier-generator system through the use of mathematical models in the generation of electricity based on biomass in an HMG, including conventional and unconventional sources of electricity generation, BESS, demand response, and grid connection for economic power supply to the load. Thus, the mathematical formulation was performed for both the optimization objective function, as well as the constrains of the sources and loads that composes the HMG. Furthermore, an algorithm was implemented in MATLAB–Simulink® for the execution of simulations and obtaining results, which showed that the management system satisfactorily operates the
islanded HMG and grid-connected mode by taking advantage of the biomass source to meet the load in an environment of economic operation, combining each of the sources and storage that make up the system. In [213], the authors present a robust two-stage optimal dispatch model that manages state variables, such as DG cost, energy exchange, charging/discharging of the BESS, and the output power of the PCs and manages to reduce the model and achieve an optimal shipment regardless of uncertainties through the column generation algorithm and constraints. In [214], the authors used a Modified Crow Search (MCSA)-based Algorithm using the stochastic power flow model to determine the uncertainty of active and reactive loads, as well as wind and solar power generation and the cost of energy produced. In [215], the authors compare two approaches that use Petri nets to design and implement a system that schedules HMG power dispatch in real time. For this study, constraints such as costs, grid supply, load demand, and power losses are considered.

To add value to this study, the management of random climatic variables is suggested, such as wind speed and solar radiation for the generation of electrical energy. To analyze the uncertainties related to wind and solar energy, load demand and the dispatch of HMGs, the authors in [216] suggested applying a stochastic model based on a Modified Flower Pollination Algorithm (MFPA). The simulation results demonstrate that the performance of MFPA was better than that obtained with GA and several other algorithms. For the management of resilience in cooperative HMGs, a control algorithm has been developed in [217] using stochastic predictive control techniques where the authors predict the energy generated in both photovoltaic and wind, the price prediction for both the purchase and sale of energy in the daily market, and the estimated consumption of both critical and non-critical load, all this using the Chaotic Particle Swarm Optimization (CPSO) technique. In [218], the analysis, design, and comparison of distributed predictive control techniques were performed that allow managing constraints and uncertainties in the process of RESs’ natural intermittency for the optimal management of electrical energy in HMGs. The controllers have been validated by testing a distributed system composed of two HMGs: one powered by solar energy, and the other by wind energy. The results obtained from the performance comparison between some distributed controllers have allowed for the choosing of a controller based on three scenarios, it seeks the solution to the optimization problem in a finite number of scenarios, and it presents better conditions to deal with its own stochastic nature of energy systems. In [219], the authors use a robust dispatch technique based on Interval–Partitioned Uncertainty (IPU) to shut down uncontrollable renewable generators with the Big M method, which uses the Column-and-Constraint Generation (C–CG) algorithm for robust three-level optimization and minimizes the conservativeness of the results without compromising the robustness of the system. In [220], the authors employ a piecewise linearization and struggles strategy, combined with the Newton–Gregory quadratic interpolating polynomial technique to address the uncertainty in the optimization model interpolating polynomial technique to address the uncertainty in the optimization model based on the risk developed by the HMG. Finally, in [221], the authors propose a deterministic coordinate programming model and then apply a hybrid stochastic interval method to address the uncertainties in the HMG. Clearly, the research trend is shifting toward BESS optimization and PHEV charging integration. Table 9 summarizes the main characteristics of the previously described optimization techniques used in HMGs.

Table 9. Most-used power-flow optimization algorithms in HMGs.

<table>
<thead>
<tr>
<th>Techniques</th>
<th>Characteristics</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear and nonlinear</td>
<td>• Solve an optimization problem of a linear function under linear constraints.</td>
<td>[153–158,222]</td>
</tr>
<tr>
<td></td>
<td>• Search an extreme value of the objective function under study, subject to some constraints.</td>
<td></td>
</tr>
</tbody>
</table>
Table 9. Cont.

<table>
<thead>
<tr>
<th>Techniques</th>
<th>Characteristics</th>
<th>Ref.</th>
</tr>
</thead>
</table>
| GA and improved GA as SPGA, NSGA-II, etc. | • Optimally manages the power in the HMGs, seeking the best economic and ecological solution, meeting the requirements of energy demand.  
• Applicable to other types of systems and combine with other algorithms.  
• It is usually slow and complicated. | [171,173–177] |
| PSO and improved PSO as MOPSO | • Due to its simplicity, the execution time of the algorithm is not a variable to be taken into account.  
• It is possible to “relax” the constraints in order to reach better optimums.  
• Cannot effectively solve the discrete and combinatorial optimization problems | [159–167] |
| Fuzzy Logic | • Improve EMS and power-sharing between Interconnected Multiple Microgrids and, in turn, overall system performance.  
• It avoids the use of large groups of data obtained from studies and surveys and also reduces the error committed against the use of a polynomial adjustment. | [208,212,223] |
| Multi–Agent System (MAS) | • Apply to complex systems composed of many variables  
• Deal with decentralized management operating with defined objectives  
• Reduce operating costs that include different sources of generation | [178–181] |
| Optimal Power Flow (OPF) | • Reduce losses and minimize cost  
• Deal with power flow modeling | [198–201] |
| Robust and Stochastics | • Allows user participation in management, energy trading and decision-making based on energy prices  
• Realize uncertainties on their merits considering deterministic upper and lower bounds | [202–221] |
| Other techniques | • Consider non-linear characteristics  
• Minimizes energy cost by using renewable energy sources | [168,194–201] |

5. Control Strategies

This section will address the issue of control strategies by emphasizing HMGs because they require more complex strategies compared with conventional distribution grids since they integrate AC and DC subgrids. It is worth mentioning that many of these strategies were originally studied for AC and DC–MGs independently but could also be feasible for HMGs with major or minor modifications. Figure 9 shows the most studied control strategies applied to HMGs, and their advantages and disadvantages are described in Table 10. Generally, stability, protection, power balance, smooth transition between operating modes, power transmission, synchronization with the electrical grid, and optimization are the characteristics that a control strategy must meet in the environment of
HMGs [28,125]. As mentioned throughout this paper, HMGs are a feasible solution for the integration of RESs, ESSs, and loads in the same grid. They address various issues: power quality [53,61–106], optimization techniques [153–222], available software tools [224–227], protection devices [228–231], etc. On the other hand, considering the responsibilities assumed by the different levels of control, the HMG can be controlled in a centralized, decentralized, distributed, or hierarchical manner. In the centralized approach, the Hybrid Microgrid Central Controller (HMGCC) is responsible for optimizing the operation of the HMG and determining the amount of power that the HMG must import or export from the upstream distribution system. However, the HMGCC must consider market prices for electricity, grid-security concerns, and ancillary services requested by the DSO when making decisions.

On the contrary, when fully decentralized control is implemented, the CC assumes responsibilities and competes or collaborates to optimize production, meet demand, and provide the maximum possible export to the grid, all conducted while considering real-time market prices. As for distributed control, it does not have a CC and only performs neighboring communication to transmit local information. Finally, the hierarchical control structure contains a local- and higher-level controller, so the voltage stability can change, and the environmental emission, energy conservation, and operating cost reduce the EPS’s resilience. The previously mentioned control strategies are described below.

5.1. Centralized Control Strategy

Among the most notable advantages of centralized control, the standardized procedures and their simple implementation stand out. The studies in [232–234] present the CC of an HMG based on two main functions: (i) Direct and uninterruptible communication with the DSO and the electricity market; and (ii) Facilitating the exchange of information with the local controllers of the HMG, as well as the data processing. It is important to mention that local controllers cannot communicate with each other, nor can they act on their own, but they collect data from HMG’s DGUs. Furthermore, in the centralized control scheme, the CC makes dispatch decisions for all DGs and ESSs, according to the objective function and constraints. It is important to note that power distribution and voltage regulation are centrally controlled, and commands are distributed over a low-bandwidth communication link. When it comes to controllers with a wide bandwidth, these are distributed to each local inverter, allowing fewer disturbances. This is similar to when it is a
single inverter with a single controller of high bandwidth. However, in this control strategy, it offers low reliability because they are interconnected at a single point. Therefore, the researchers suggest employing this control strategy in small HMGs with a control that can be achieved with a low-bandwidth communication structure. Master–slave control is a method used in the centralized control strategy, which is responsible for the regulation of the common bus voltage because the generators supply power according to the needs of the load and, thus, provide a higher level of coordination in multilayer control by allowing the HMGs to operate simultaneously [235]. When the HMG is connected to the grid, the master unit operates with P/Q constant power control as the reference standard is supplied by the grid. When the HMG changes from connected mode to islanded mode, the master unit switches to V/f control mode to serve as a reference to the smaller units: the slaves [236].

Table 10. Main advantages and disadvantages of the optimization algorithms in HMGs.

<table>
<thead>
<tr>
<th>Control Strategy</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional methods</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Droop control</td>
<td>Manages the decentralized energy of the DGUs.</td>
<td>Load-dependent frequency variation.</td>
<td>[110]</td>
</tr>
<tr>
<td>Nonlinear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sliding Mode Control</td>
<td>Low cost, relaxed scalability, and improves grid stability</td>
<td>Need for an ESS and a load shedding strategy.</td>
<td>[133]</td>
</tr>
<tr>
<td>Port-Hamiltonian</td>
<td>Manage load balancing and efficient power distribution and stabilize voltage.</td>
<td>Requires passive-based control of damping and interconnect assignment.</td>
<td>[237]</td>
</tr>
<tr>
<td>Lyapunov</td>
<td>Present robustness of the LRC against parametric uncertainties</td>
<td>Requires extra components to detect slow and fast modes for dynamic stability.</td>
<td>[238]</td>
</tr>
<tr>
<td>Adaptive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine Learning</td>
<td>Operational flexibility of the HMG different components and reduction of the impact of uncertainties.</td>
<td>Less sensitive to process parameter changes and system disturbance.</td>
<td>[201]</td>
</tr>
<tr>
<td>MPC</td>
<td>Ensures upload constraints are met and the economic optimization of the HMG.</td>
<td>Modelling difficulties, sensitivity to load parameter variation and high computational burden.</td>
<td>[239]</td>
</tr>
<tr>
<td>Robust</td>
<td>H2/H∞</td>
<td>Enables more reliable power supply for sensitive loads in the absence of grids.</td>
<td>Steady state deviations in the frequency and voltage set-point.</td>
</tr>
<tr>
<td>Fuzzy Logic</td>
<td>Reduce grid fluctuation and increase the ESS lifecycle.</td>
<td>Fine-tuning its parameters is relatively difficult due to the nature of the system.</td>
<td>[187]</td>
</tr>
<tr>
<td>Intelligent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSO</td>
<td>Improvement in the local energy efficiency and reduction in the energy consumption costs.</td>
<td>Absence of constraint management strategies.</td>
<td>[162–167]</td>
</tr>
<tr>
<td>GA</td>
<td>Global optimization, robustness, search speed, computational accuracy and convergence.</td>
<td>They can be difficult to optimize and can be time-consuming to run.</td>
<td>[173–176]</td>
</tr>
</tbody>
</table>

Sustainability 2023, 15, 9847

23 of 53
<table>
<thead>
<tr>
<th>Control Strategy</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual Impedance</td>
<td>Provide active stabilization and disturbance avoidance, and ancillary services.</td>
<td>Load current transients are only partially reproduced.</td>
<td>[240–242]</td>
</tr>
<tr>
<td>Primary</td>
<td>Can effectively deal with all kinds of wind speed and ac load mutation and restrain the frequency variation on AC side.</td>
<td>It does not consider the simultaneous effect of DC power control on connected converters on the DC–link side in the presence of ESS.</td>
<td>[243–245]</td>
</tr>
<tr>
<td>Power Flow</td>
<td>Determines the minimum operating costs considering the limitations of the DGUs.</td>
<td>Uncertainty of parameter selection and slow convergence rate.</td>
<td>[199]</td>
</tr>
<tr>
<td>Multi-agent</td>
<td>Helps make energy transfers more economical in the event of power outages.</td>
<td>Complex systems composed of several autonomous agents with only local knowledge and limited capabilities.</td>
<td>[180]</td>
</tr>
<tr>
<td>SMC</td>
<td>Offers robustness for sudden variations in power sources and loads, low cost, and relaxed scalability.</td>
<td>Poor robustness against variation of plant dynamic.</td>
<td>[246]</td>
</tr>
<tr>
<td>MPC</td>
<td>Fast control dynamic response and good performance for systems involving non-linearities.</td>
<td>Need for an accurate model of the process to predict the control methodology.</td>
<td>[247]</td>
</tr>
<tr>
<td>Predictive Control</td>
<td>Ensures the quality of electrical services and minimizes component profitability.</td>
<td>Communication delays under uncertainty parameters increase the system sensitivity.</td>
<td>[240–242,248]</td>
</tr>
<tr>
<td>EMS</td>
<td>Provide a more effective exploration of the search space and simplifies the generation of high-quality optimal solutions.</td>
<td>Low accuracy in several applications due to the leaders' stochastic movement</td>
<td>[161–163]</td>
</tr>
</tbody>
</table>

5.2. Decentralized Control Strategy

HMGs are organized as agents to cover internal demand and exchange energy with the electrical grid and with other HMGs by using a decentralized control strategy in which there is no CC figure since each controller local generates its own control variables. It is worth mentioning that among the advantages of this control is that it is easy to connect and use. Other advantages include the following: low computational cost, extensive fault control, and high efficiency in power-flow management from a single point [249]. In [250], a decentralized control architecture for HMGs is presented together with a real-time decision-making environment based on agents capable of operating in an interconnected or islanded mode. The results show that this control is insufficient in the treatment of information about DGUs. However, it is concluded that it is the most reliable control since there is no need for communication links between the different units of the system. Figure 10 graphically shows the centralized and decentralized control of an HMG, and Table 11 summarizes the main characteristics of centralized and decentralized control architectures applied to HMGs.
5.2. Decentralized Control Strategy

HMGs are organized as agents to cover internal demand and exchange energy with the electrical grid and with other HMGs by using a decentralized control strategy in which there is no need for communication links between the different units of the system. Figure 10 shows graphically the centralized and decentralized control of an HMG.

Table 11. Characteristics important of centralized and decentralized control applied to HMGs.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Centralized Control</th>
<th>Decentralized Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of owners</td>
<td>Single owner</td>
<td>Multiple owner</td>
</tr>
<tr>
<td>Tasks</td>
<td>Uncertainly</td>
<td>Reduction of energy costs</td>
</tr>
<tr>
<td>Operating personal</td>
<td>Not Available</td>
<td>Available</td>
</tr>
<tr>
<td>Complexity</td>
<td>Not complicated algorithms</td>
<td>Complicated algorithms</td>
</tr>
<tr>
<td>Installation of new equipment</td>
<td>Experienced technician</td>
<td>Plug-and-play</td>
</tr>
<tr>
<td>Communication</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Market participation</td>
<td>Not all units collaborate</td>
<td>All units collaborate</td>
</tr>
</tbody>
</table>

5.3. Distributed Control Strategy

Currently, the design of novel, distributed control systems applied to the HMG have become popular in the scientific community. These control systems must achieve reliable, efficient, high-performance, and enhanced safety [251]. This type of control is distributed throughout the grid, increasing system reliability as compared with centralized control strategies [246,252]. In [253], a distributed algorithm for the balance of the SOCs is presented, which uses a non-linear controller in sliding mode to locally regulate the SOC of each BESS to the same value, which is the global average estimated by means of an observer. In [254], a distributed control based on the MAS theory is designed to guarantee robustness with respect to any plug-and-play event, as well as connection failure and parametric variations. In brief, this type of control provides high reliability and reduced cost compared with a decentralized control strategy. Furthermore, this control strategy does not require a CC because the control is distributed along with the HMG [255].

5.4. Hierarchical Control Strategies

Hierarchical control has four levels: zero level control, primary control, secondary control, and tertiary control. The interaction of these multilayer controls is important for obtaining a reliable control model to share power between DGs, thus improving power quality, minimizing operating costs, and ensuring effective participation in transitive power markets [256].

Zero-level control is the name of the internal control of each of the converters. This controller operates in less than 5 ms and requires high processing speed and low computational cost. The zero-level control is associated with the external loop of the VSCs (Voltage Source Converters), where the objective is defined by the operating mode of the HMG. On the one hand, in the grid-connected mode, the VSCs must perform power management of the integrated resource. On the other hand, when operating in islanded mode from the grid, the VSCs must guarantee the stability of the voltage and frequency. Two of the most
popular strategies are classical vector control and PQ theory. The dynamic performance of these controls is fast enough to be considered in the other stages. However, steady-state performance and control limits require further analysis for proper integration with the other stages.

The primary control must act quickly in a time frame of up to 50 ms and is implemented locally in the VSCs. When the operating mode of the HMG is islanded, it must ensure stable operation for voltage and frequency, in conjunction with zero-level control. The most important goal of primary control is to reach a stable equilibrium point. Therefore, this control must be fast, simple, and reliable. Usually, a proportional control implemented locally in each converter is used. See Figure 11.

Secondary control should operate around 500 ms and depend on the previous control stages. Its objective is to improve the power quality and frequency in an HMG so that it operates at nominal values. The secondary control shares some characteristics of the primary and tertiary controls. Therefore, a properly designed secondary control must include the variation in frequency and regulation constants of the primary control. On the other hand, it requires the capacity constraints of the tertiary control [257]. See Figure 11.

The tertiary control (Figure 11) coordinates the interaction of the HMG with the EPS through the VSCs. Where most of the intermittently distributed generation can interconnect through a PC. This strategy is widely used to share the power generated from synchronous generators in the conventional grid. Voltage/frequency control in power systems applied to HMGs when operating in islanded mode. Active power distribution in the variables denotes the conjugate value.

![Figure 11. Primary, secondary, and tertiary control strategies for HMGs. The asterisk (*) interposed in the variables denotes the conjugate value.](image)

Secondary control should operate around 500 ms and depend on the previous control stages. Its objective is to improve the power quality and frequency in an HMG so that it operates at nominal values. The secondary control shares some characteristics of the primary and tertiary controls. Therefore, a properly designed secondary control must include the variation in frequency and regulation constants of the primary control. On the other hand, it requires the capacity constraints of the tertiary control [257]. See Figure 11.

The tertiary control (Figure 11) coordinates the interaction of the HMG with the EPS and optimizes the operation to minimize operating costs and losses while respecting operating constraints. This type of control reconciles both generation and demand and defines the reference power to the VSCs as grid followers. Compared to secondary control, the tertiary control is lower and can be considered as a steady-state problem. The tertiary control must be executed in real time and automatically without constant human supervision. Therefore, fast, robust, and efficient algorithms are required to guarantee convergence [228]. The control layers of the hierarchical control scheme are detailed below.

5.4.1. Primary Control

In [258], a classification of control techniques applicable to HMGs is presented in which a general categorization of control functions for DERs is established. Three types of primary control levels are presented: (i) Grid-forming; (ii) Grid-feeding/following; and (iii) grid-supporting, as well as between interactive and non-interactive strategies (Table 12). In the case of HMG isolated mode operation, one must use ESSs to maintain the power...
balance between generation and demand. Furthermore, unpredictable behaviors of RESs must be corrected. Therefore, it is necessary to control the power balance, which is one of the most complex problems in isolated HMGs because it requires that at least one of the DERs units (ESSs or RESs) assume the grid-forming role, becoming responsible for setting the amplitude and frequency of the local grid voltage. For this, two main approaches have been used to define the voltage and frequency of the local grid: single master (one unit in the grid-forming mode of operation), or multi-master (different units connected in parallel all working in the grid-forming mode of operation).

Table 12. Classification of control strategies for the coupling of DERs.

<table>
<thead>
<tr>
<th>Control Methods</th>
<th>Following-Grid Controllers</th>
<th>Forming-Grid Controllers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Interactive</td>
<td>Power delivery (with or without MPPT)</td>
<td>Voltage and frequency</td>
</tr>
<tr>
<td>Interactive</td>
<td>Dispatch of active and reactive power</td>
<td>control</td>
</tr>
<tr>
<td>Control Methods</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Normally in an operation islanded mode, the ESS units assume the role of grid-forming. In this case, the RESs can be integrated into the HMG in grid-following mode, as grid-following units using control for the MPPT to obtain the maximum possible power [258–262]. In this context, for grid-forming control, the DG and ESS systems must guarantee the voltage and frequency stability of the HMGs [263,264]. In [265], a comprehensive survey review of the grid-forming control strategies for multiple PCs is conducted, where the following classification is observed: (i) Communication network between devices; and (ii) Non-communication network. One of the most-used control strategies in this connection network is droop-based control [35,233,246,250,252–254,266–269], which is described below.

Droop Control

One of the most used controls in the primary hierarchical control strategies is the Conventional Droop Control (CDC), where most of the intermittently distributed generators that operate with MPPT are used in the power-sharing control scenario for which an improved control strategy based on droop with power distribution was designed for HMGs where the DC–MG and AC–MG can interconnect through a PC. This strategy is widely used to share the power generated from synchronous generators in the conventional grid. Voltage/frequency control in power-sharing is the essential function of control systems applied to HMGs when operating in islanded mode. Active power distribution throughout the system must be precisely achieved by regulating the active power of the PC. Additionally, when the PC delivers reactive power to the AC–MG, it adds some more complexity to the control system of an HMG so the existing droop control uses the frequency offset to calculate the reference active power for the PCs, which is usually a current-controlled PC. Droop control consists of \( P_\omega \) and \( QV \) droop controls that are, respectively, expressed in (1) below [270]:

\[
\begin{align*}
\omega_i &= \omega_{ref} + \Delta \omega_{i,adj} + \kappa_{i,P}(P_{i,sett} - P_i) \\
V_{i,pk} &= V_{i,sett} + I_{i,RMS}Z_{vir} - V_i - \kappa_{i,Q}Q_i
\end{align*}
\]

(1)

where the subscript \( i = \{1, 2, \ldots, N = 3\} \) denotes the DGUs index set, \( \omega_i \) is the \( i \)th DGU frequency, \( \omega_{ref} \) is the HMG reference frequency, \( \Delta \omega_{i,adj} \) is the \( i \)th frequency adjustment factor of the DGU. This value is obtained from the overload control strategy, \( \kappa_{i,P} > 0 \) is the droop control gain, \( P_{i,sett} \) is the \( i \)th DGU active power, which is obtained by the secondary active power controller, and \( P_i \) is the \( i \)th DGU active power output. Additionally, \( V_i \) is the \( i \)th DGU output voltage, \( V_{i,sett} \) is the \( i \)th DGU voltage set-point, \( I_{i,RMS} \) is the RMS current of the controller, \( Z_{vir} \) is the virtual impedance, \( \kappa_{i,Q} > 0 \) is the \( i \)th DGU gain of droop control, and \( Q_i \) is the \( i \)th DGU output reactive power.
When the DGUs operate as inverters, then $V_{i,pk}$ is the maximum voltage at the inverter terminals. When it comes to the genset $V_{i,pk} = V_{cmd}$ indicates the input voltage to the control block of the synchronous generator, $V_f$. If there are two inverters interfaced with the DGUs, then these act as controlled three-phase AC voltage sources, which are the instantaneous voltages for each phase (i.e., $v_a$, $v_b$, and $v_c$), as is shown in the following [271]:

$$
\begin{align*}
  v_a &= V_{i,pk} \sin(\omega_i t + 0^{\circ}) \\
  v_b &= V_{i,pk} \sin(\omega_i t - 120^{\circ}) \\
  v_c &= V_{i,pk} \sin(\omega_i t + 120^{\circ})
\end{align*}
$$

(2)

To calculate the $QV$–droop control value for each one of the DGUs, we have the following expression:

$$
V_{\max, DGU} = V_{req, DGU} - V_{\text{meas, DGU}} - m_{Q, DGUs} Q_{\text{meas, DGU}}
$$

(3)

where $V_{req, DGU} = V_{set, DGU}$ and $V_{\text{meas, DGU}}$ are, respectively, the DGU voltage amplitude and the instantaneously measured voltage of the DGU. Furthermore, $m_{Q, DGU}$ is the characteristic slope of the $QV$–droop gain and $Q_{\text{meas, DGU}}$ is the instantaneous reactive power of the DGU. For this case, $m_{Q, DGU}$ is obtained as (4):

$$
m_{Q, DGU} = \frac{\Delta V_{DGU}}{\Delta Q_{DGU}} = \frac{\Delta V_{DGU}}{Q_{\max, DGU} - Q_{\min, DGU}}
$$

(4)

It is important to note that the main objective of the $QV$ droop control strategy is to adjust the value of the voltage magnitude so that the DGU injects the necessary amount of reactive power [272]. When the DGU operates as an inverter, then the ESS, which is designed as a three-phase controlled–voltage source, will have a minimum real power limit. If this limit is positive, it means that the ESS is in discharging mode. To calculate the characteristic slope of the ESS, $m_{P, ESS}$, the following expression is used.

$$
m_{P, ESS} = \frac{\Delta V_{ESS}}{\Delta P_{ESS}} = \frac{2\pi f_{ESS}}{P_{\max, ESS} - P_{\min, ESS}}
$$

(5)

In [273], the authors discussed control of an HMG using the droop control method and a decentralized EMS that considers multiple subgrids. The HMG has a variety of three-phase inverters, local loads, and line impedances. The results show power-sharing delivered to the loads without the use of specific communication lines between the inverters. In addition, by implementing various control loops, the intention was to correctly manage the energy exchanged by the elements of the HMG, adjust it to European standards, and allow a connection to the grid. In [274], the authors incorporate the parallel operation of several bidirectional converters to transfer power from the DC side to the AC side of the HMG and vice versa, fitting the slope of the curve relating frequency to active power by using virtual impedances. In [275], the authors propose a primary control strategy to share active power using a Virtual Synchronous Machine (VSM) to improve the AC and DC bus frequency of an HMG and, thus, improve system stability and power quality. To address these issues, in [276], the authors propose adjustable inertia in integrated circuits to analyze the dynamic performance and the impact of operating points on the load impedance modulus. The study includes droop control for the voltage and frequency variables and inertia support for the AC and DC buses of the HMG. In [239], the authors propose decentralized load distribution and power management methods for HMGs to generate desired values of the PCs, while the active and reactive power error and the joint delay the droop control. In [247], the authors used a Modified Droop Control (MDC) to control the power of the PV system, while in [277], the analysis of an HMG is presented, which is modeled as a Hamiltonian system and presents conditions in which the system will be stable. It is important to mention that the necessary constraint for performing control in the converter is that the voltage and phase are immediately available, which
is generated by an independent control. This limits it because it does not consider the dynamics of the PCs.

Model Predictive Control (MPC)

Predictive models involving current and power (Model Predictive Current Power (MPCP)), as well as predictive models of voltage and power (Model Predictive Voltage Power (MPVP)), are applied in HMGs that are used in issues of power generation, fluctuations, demand power, battery state of charge, and efficient power management. MPC is responsible for guaranteeing compliance with the constraints, the operating conditions, and the exchange of power flows between the elements of the HMG and the charging station, following the objectives provided by the tertiary controller. In addition, it manages the use of ESSs, such as batteries and PHEVs, and ensures that charging constraints (charging type and time) are met. Furthermore, it handles the economic optimization of the HMG by managing the sale and purchase of energy [278]. For example, in [279], the authors suggest using several PCs connected in series with a static VAR compensator for HMG applications to perform P–δ and Q–P–V droop control. Additionally, the PC manages to mitigate the harmonic components by determining the impedance in the voltage source, which in turn has two thyristors that are activated in each half cycle. Nothing is discussed in these references about stability and circulating current issues. Figures 12 and 13 show the schematic diagram of the MPC used in the primary control of an AC–MG operating in islanded mode seen at the converter level and at the electrical grid level.

![Schematic diagram of converter-level MPC](image)

**Figure 12.** Schematic diagram of converter-level MPC. $X^*$ denotes the first conjugate of the function.

![Schematic diagram of grid-level MPC](image)

**Figure 13.** Schematic diagram of grid-level MPC.

Converter–Level MPC

By discretizing the dynamics of a specific circuit, the predictive model is obtained. This is achieved by estimating or measuring variables such as voltage, current, or power (see Equation (5)).

$$\dot{x}(k+1) = f(x(k), u(i))$$

where $x(k)$ indicates the dynamics of the circuit at $k$ instant; $u(i)$ are the switching states of the converter; and $f(\cdot)$ is the function applied to the voltage and/or current variables considering Kirchhoff’s Law. The Euclidean distance for the cost function is considered,
which consists of the “ordinary” distance between two points, that is, between the predicted and nominal values (see Equation (6)).

$$g = \sum (w_j|x^* - \hat{x}(k + 1)|)$$  \hspace{1cm} (6)

where $x^*$ is the control reference, i.e., denotes the desired values of voltage, current, power, etc.; $w_j$ is the weighting coefficients \[240\]. Solving the search algorithm applied to an MPC is easy because its switching states are limited \[241\], and it is applicable for different converter topologies \[242–244,248,280,281\].

**MPC for Grid Level**

The parts that constitute a Grid-level MPC are the resolution algorithm, cost function, and predictive model as seen in Figures 12 and 13. This optimizes the performance of both the restricted systems and the operating states based on forecasts, which are generated from the predictive model and transcend the cost function. As each sampling time is completed, the optimal control sequence is calculated during a given time horizon for each element of the system.

Finally, this type of control satisfactorily minimizes the uncertainties of the system and integrates optimal control, process control with dead times, and multivariable processes using future references when available. All of this is achieved through the application of a strategy with a finite control horizon, which allows for the consideration of constrains and non-linear processes.

**Virtual Impedance Control**

Virtual impedance control is mainly used to provide active stabilization and disturbance avoidance, as well as ancillary services to the HMG \[245,282\]. The virtual impedance for an inverter-based DGU unit is implemented in (7):

$$v^*_{odq\_ref} = v_{odq\_ref} - Zv^*_{i odq}$$

$$\begin{cases} v^*_{od\_ref} = v_{od\_ref} - Rv^*_{i od} + Xv^*_{i oq} \\ v^*_{oq\_ref} = v_{oq\_ref} - Rv^*_{i oq} + Xv^*_{i od} \end{cases} \hspace{1cm} (7)$$

where $v^*_{odq\_ref}$ is the reference value for $\hat{v}_{odq}$ and $v_{odq\_ref}$ is the output voltage of droop controller. If the virtual impedance is considered in (7), then the expression will be:

$$i_{odq\_ref}(t) = K_{i odq}(t) + k_{p\_odq} (v_{odq\_ref}(t) - \hat{v}_{odq}(t)) + k_{i\_odq} \int (v_{odq\_ref}(t) - \hat{v}_{odq}(t)) dt + j\omega_b C_f \hat{v}_{odq}(t)$$ \hspace{1cm} (8)

where $\omega_b$ indicates the nominal angular frequency and $C_f$ is the output filter capacitance. Therefore, implementing virtual impedance results in the following system state matrix:

$$v(t) = \frac{1 + m}{2} \cos((\omega_0 t)) \cos(\omega_0 t)$$ \hspace{1cm} (9)

Expanding Equation (9), we have:

$$v(t) = V \cos(\omega_0 t) + \frac{m}{2} \cos((\omega_0 + \omega_m)t) + \frac{m}{2} \cos((\omega_0 - \omega_m)t)$$ \hspace{1cm} (10)

This equation represents a modulated signal containing three frequencies, namely $\omega_0$, $\omega_0 + \omega_m$, and $\omega_0 - \omega_m$. For example, in \[283\], the authors use an adaptive virtual impedance control for voltage and frequency regulation of an HMG, as shown in Figure 14. In \[284–286\], this type of control is used to control the power distribution of the PCs through the decoupling of active and reactive power, avoiding the circulation of power flow between the PCs connected to each other, etc. In \[287\], the authors propose a model to guarantee adequate power decoupling and $P$-$f$ and $Q$-$V$ ratios, by using a virtual impedance.
in each inverter, which consists of a current feedback loop multiplied by the virtual impedance value.

![Virtual Impedance Control Diagram](image)

**Figure 14.** Application of the virtual impedance control for the voltage and current control in HMGs.

**Virtual Inertia Control**

There are few research papers that describe the problems related to voltage and frequency in electrical grids by considering a high penetration of RES in HMG applications through virtual inertial control. If these issues are not addressed, they will result in other types of issues such as transient stability. To combat this problem, DGUs based on synchronous machines are used to reduce the maximum frequency deviation at the expense of increasing the oscillation duration (because of inertia). Additionally, inverter-based DGUs have been used to reduce rotor angle deviations and improve the voltage profile on the demand-side, so adding the concept of virtual inertia sounds quite logical. Some examples in the literature are cited below. In [288], an exhaustive review of the various techniques and topologies of the implementation of virtual inertia is provided, where it is shown that similar inertial responses can be achieved, relating the parameters of these topologies through time and inertia constants. In addition, the authors present a discussion of research issues and directions, indicating future research needs for the integration of virtual inertial systems. In [289], a virtual inertia-based control is modeled to be implemented in an HMG in order to improve the controller performance for large system-frequency deviations. The proposed control is tested by simulating an HMG connected to the grid with two DGUs and two synchronous generators, all with similar powers. The results of the simulation carried out in MATLAB–Simulink® illustrate the improvement of the transient stability of the frequency. Other authors [290] study small signal stability, including the effect of connecting PHEVs to charging stations within the HMG by considering the virtual inertia control. The stability of the HMG obtained after implementing the proposed control is analyzed in the OPAL-RT real-time simulator. In relation to the previous discussion, Table 13 shows the different control strategies implemented in different research papers. As previously discussed, most control strategies that do not require a communication network are based on droop control techniques. However, other strategies can be found where a communication network is not required [291–293].

**Table 13.** Control techniques implemented in the primary control for applications in HMGs.

<table>
<thead>
<tr>
<th>No.</th>
<th>Method</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Conventional/modified droop control</td>
<td>[239,247,270–277]</td>
</tr>
<tr>
<td>2</td>
<td>Virtual impedance control</td>
<td>[245,282–287]</td>
</tr>
<tr>
<td>3</td>
<td>MPC</td>
<td>[244,278]</td>
</tr>
<tr>
<td>4</td>
<td>Virtual inertia control</td>
<td>[288–293]</td>
</tr>
</tbody>
</table>

5.4.2. Secondary Control

There is fairly extensive literature on primary and tertiary control. However, there are few theoretical developments regarding secondary control. The most complete and
up-to-date review on the subject is presented in [294]. This review includes both centralized and distributed versions [233,295–297] where the centralized versions involve a complex communication network between elements, while the distributed scheme allows for simpler but less robust communications. Note that the secondary control shares some characteristics of the primary and tertiary controls. Therefore, a properly designed secondary control must include the variation in frequency and regulation constants of the primary control. On the other hand, it requires including the capacity constraints of the tertiary control. Therefore, optimization-based controls, such as the MPC or the Receding Horizon Control, are ideal for this type of application. The latter is based on a very simple idea: solve an optimization problem at each time step. Therefore, the optimization model must represent the HMG very precisely and be simple enough to be evaluated in an agile way to guarantee convergence.

Another of the main objectives of this level of control is to return the system to a stable state precisely and be simple enough to be evaluated in an agile way to guarantee convergence. One of the main objectives of this level of control is to return the system to a stable state at each time step. Therefore, the optimization model must represent the HMG very precisely and be simple enough to be evaluated in an agile way to guarantee convergence.

Depending on the architecture and state of HMG, the levels of control assume different degrees of responsibility. For example, for centralized control, the management of the HMG is performed from the HMGCC [298]. For this, variables such as active and reactive power of the DGUs, ESS, and critical loads are collected. In addition, market conditions, security concerns, requests for higher control units (for example, the SCADA of the electrical grid), and the need for a robust communication network capable of uniting all the components are taken to account for control levels [299]. However, this is complicated by the fact that most of the connected devices are in different locations, making it difficult to interconnect. Through this resource, though, energy management is optimized in small-scale HMGs where few DGUs are installed. The mathematical model of this type of control is expressed as follows:

\[ \dot{v}_i(t) = -\kappa_1 \sum_{j \in N_i} a_{ij} \text{sgn}(\mathbb{P}_i(t) - \mathbb{P}_j(t)) \]

\[ \mathbb{P}_i(t) = v_i(t) + r_i(t) = v_i(t) + P_{i,\text{opt}}(t) \]  

where \( i = \{1, 2, \ldots, N\} \) indicates the DGUs index set, \( \kappa_1 > 0 \) indicates a design parameter, \( a_{ij} \) is the entry of the adjacency matrix, \( \dot{v}_i(t) \in \mathbb{R}^N \) represents an intermediate state variable, \( r_i(t) = P_{i,\text{opt}}(t) \in \mathbb{R}^N \) is the time-varying reference signal for the \( i \)th DGU acquired by the distributed secondary controller. From the above, it can be summarized that this type of control conditions all the components of the communication network, \( G \), to reach a consensus, and, likewise, entrusts the \( i \)th agent to track its time-varying optimal power dispatch reference, \( P_{i,\text{opt}} \). This will help restore the DGUs frequencies to the HMG reference frequency. Note that \( \text{sgn}(\cdot) \) is a multi-valued function as expressed in (12):

\[ \text{sgn}(\mathbb{X}) = \begin{cases} 
1 & \text{if } \mathbb{X} > 0 \\
0 & \text{if } \mathbb{X} > 0 \\
-1 & \text{if } \mathbb{X} > 0
\end{cases} \]  

For the correct initialization of the intermediate state variable considering an \( i \)th DGU, we have:

\[ v_i(0) = 0 \quad \rightarrow \quad \sum_{i=1}^{N} v_i(0) = 0 \]  

Considering (11), we have a distributed secondary control system:

\[ \mathbb{P}_{i,\text{req}}(t) = P_i(t) \]

\[ \mathbb{P}_{i,\text{opt}}(t) = \mathbb{P}_{i,\text{opt}}(t) - \kappa_1 \sum_{j \in N_i} a_{ij} \text{sgn}(P_i(t) - P_j(t)) \]  

(14)
where $\tilde{P}_{\text{req}}(t)$ is the primary controller reference signal.

Some examples of this type of control are listed below. In [300], a secondary control for unbalanced grids is presented with a PC-centric approach for the shared power of the RESs and the ESSs and, thus, guarantees the correct functioning of the HMG in both modes of operation. In [301], a hierarchical control scheme was proposed that includes levels of primary and secondary control Group ICE, composed of local controllers for the primary control, designed an appropriate design for the central secondary controller in such a way that the compensation of the voltage imbalance in the PCC between the HMG and the electrical grid can be managed, in addition to providing a balanced distribution of active and reactive power between the controlled devices. In this research, an algorithm for the OPF is developed to obtain optimal reference values for active voltages and powers in an HMG. According to the authors, PC control works successfully regardless of how the DGUs are managed. Other similar studies are investigated in [96,302–304].

However, for a non-centralized approach, energy management responsibilities fall to the RESs and ESSs. This means that the control is implemented in the CC to prevent the communication network from operating with higher-level control strategies (tertiary, etc.) [305]. However, in disturbances, the HMG will be able to function normally by simply disconnecting the faulty unit. This is what makes this control scheme attractive. Within the secondary techniques, distributed control is the most studied scheme because of its good performance in communication since it provides a relatively simple communication network. Some examples are cited below. In [306], an optimal voltage control strategy was proposed for keeping the voltage magnitudes of the selected nodes within an allowed range and also achieving a precise reactive power distribution. This was attained by implementing the most appropriate techniques for this type of function; for example, consensus or agent-based techniques. These techniques provide good efficiency compared with others thanks to the interaction between RESs and ESSs. The study conducted in [307] proposed a cooperative secondary control for isolated HMGs viewed as multi-agent systems that communicate with each other through a wireless connection. In this study, the authors affirm that ESSs play a very important role in HMGs, especially in secondary control, which turns out to be the best control scheme since it reduces multi–agent coordination errors. In [308], a distributed secondary control strategy has been proposed to manage the operation of a set of distributed HMGs in an isolated environment, in addition to maintaining the correct connection with the common bus that unites all HMGs through a MAS and techniques based on consensus, which should avoid overloads and deep discharges in the BESSs. The study suggests that a decentralized EMS, based on the theory of MAS, can have important benefits, such as the autonomous nature of HMGs for power generation in non-interconnected areas. The system simulation was performed using OpenDSS-G and Python. The research concludes that with the MAS theory, more reliable DG systems can be created because of their autonomous decision-making capacity and can cover electrical demands from neighboring HMGs. In [309], the author proposes the control of the operation mode of a set of HMGs interconnected through a common bus but isolated from the electrical grid to protect the useful life of the BESSs by means of a distributed averaging technique for the frequency and voltage. The authors propose the design of an architecture based on MAS because of the extensive use that this type of model has in EMS of HMGs, facilitating its modeling and the design of control systems.

As observed in the references shown, a large number of consensus-based distributed strategies have been proposed to address the problem of real-time optimization in HMGs by considering the availability of DG reactive power, and algorithms have been applied through simple consensus. For example, in [130,310], the authors analyze the voltage deviations caused by droop-based primary control using a consensus technique. In [311], the authors seek to regulate the voltage to reduce energy losses through reactive power compensation and thus eradicate the problem presented by microgenerators connected to the electrical grid. This is carried out by applying a control strategy based on Intelligent Agents (IED), which adjusts the amount of reactive power injected into the grid by con-
sensus. In [237], the authors propose an HMG made up of a large number of DGUs and controllable loads. A consensus-based distributed intelligence strategy is applied to the HMG, which considers each DGU as a private entity and associated with some available agent with limited communication. Simulations were carried out considering test grids of IEEE 30 nodes and IEEE 119 nodes. Finally, in [312], the authors seek to restore the frequency deviation by means of a decentralized secondary control strategy where it is concluded that these control strategies do not need communication systems and, therefore, a plug-and-play connection of all DGUs can be guaranteed.

5.4.3. Tertiary Control

The application of this control is very diverse. For example: (i) It deals with optimizing the operation of the HMG; (ii) It facilitates the connection of the HMG with the electrical grid; and (iii) It controls the active and reactive power of each one of the DGUs based on technical, parametric, and economic criteria [238]. In the distributed approach, the equal incremental cost criterion can also be established using a consensus algorithm, which solves economic load dispatch issues. This is expressed as follows:

$$\lambda_i(t) = u_i^1(t) = -\kappa_2 \sum_{j \in N_i} a_{ij} \text{sgn} \left( \lambda_i(t) - \lambda_j(t) \right)$$

Subject to

$$\lambda_i(0) = 2\gamma_i P_i(0) + \beta_i$$
$$\sum_{i=1}^{N} P_i(0) = P_D$$

(15)

where $\kappa_2 < 0$, and $0 < \sigma < 1$ are design parameters, $u_i^1$ is the incremental cost consensus control input for the $i$th DGU. Therefore, all DGUs are related to those parameters i.e., $\lambda_j = \lambda_i = \lambda_{ij,pat}, \forall i, j = \{1, 2, \ldots, N\}$, using the distributed economic dispatch algorithm.

As a control, that can work in both modes of operation. The functions it performs in each are explained below: the estimate of short-term load changes, the forecast of generation and energy storage capacity, as well as the specific demands established and the price signals provided by the electricity market, are considered in the analysis of the operation of the MG in the mode connected to the electrical grid. Additionally, it manages the flow of active and reactive energy between the HMG and the electrical grid by regulating voltage and frequency. For this to be possible, it is necessary to use a centralized strategy where the tertiary control is located in the HMGCC, which can be the SCADA system, or a distributed technique where all the control is located in the CCs and, thus, optimize some variables, such as efficiency, economic benefit, simplicity of control, power quality, etc. [313]. In islanded mode, the tertiary control level is in charge of restoring the secondary control reserve and managing eventual electrical congestion. It is also responsible for the injection of power according to the availability of the resource and to the demand. The interactions between all DGUs at this level have the need for communication because of all the functions that are developed independently of the HMG’s state of operation.

For example, in [314], there is a centralized tertiary control for the EMS of an HMG operating in islanded mode. This research focuses on finding the optimal energy dispatch to maximize the economic benefits, coming from RESs, ESSs, or the electrical grid. Furthermore, this strategy considers the electricity price forecast, generation, and energy demand profiles to optimize the entire system: the interaction with the grid and the ESS/DG interaction. This model is integrated from the models corresponding to a distribution grid (single phase), PV systems, WTs, BESSs, and a vehicle fleet that works as an ESS. The efficiency and effectiveness of the OPF algorithms for tertiary control are analyzed and verified through their application to different variants of two case studies. Some of these variants consider real weather data of solar irradiation and wind speed. In [315], an optimal tertiary control for an HMG is proposed based on MILP that works in both modes of operation to solve an OPF problem. The study is based on achieving a tertiary control of an HMG for the stability and reliability of the established system and uses MATLAB-Simulink® software for the simulation and visualization of results. In addition, various centralized tertiary management strategies can be identified in the literature [316,317].
On the other hand, there are some approaches where the tertiary control level is located in the HMG in a distributed manner, as studied in [318]. In the tertiary control, the master–slave technique is used, which, unlike the primary and secondary control that uses the master to ensure the reliable operation of the HMG, it is the slaves that have operability by injecting the available power. The meaning of this strategy is valid when the HMG is operating in islanded mode, where the slaves that inject power attain the reference given by the master. For example, in [319], the authors propose a gossip-based tertiary control algorithm that sits directly on the CC. In addition, a case study is presented where the three hierarchical levels are integrated into the CC. In this approach, a tertiary consensus control strategy has been implemented in which each DG follows a global objective function for the distributed optimization problem. With the consensus algorithms, it is intended that all the DGs have the same state of information to achieve the best performance in the HMG. Due to the above, the current trend forces to increase the use of centralized tertiary control strategies for HMG applications since they provide greater flexibility in their operation.

5.4.4. Non-Linear Control Strategies

In the last decades, several controllers based on different approaches have been proposed with the objective to relax the restrictive conditions on the parameters of the load, the voltage path, and the voltage reference of the HMGs, guaranteeing the exponential stability of the desired equilibrium point. These approaches are implemented in non-linear control strategies where control schemes stabilize the voltage in DC networks that are affected by non-linear loads, which result from combining constant impedance, as well as current and different types of power loads. For example, in [320], the authors present a non-linear control architecture applied to an HMG composed of a PV system, an ESS, an electrical grid, and consumer demand. This system is intended to manage load-balancing and efficient power distribution. The model they use is based on port-Hamiltonian (PH) with differential flatness and parameterization of B-splines. The results show that this novel approach can stabilize the voltage of HMGs. In [321], a novel EMS and control structure is proposed for an HMG composed of a PV and FC system and a BESS and SC system. The proposed model uses two types of control methods, PID and Flatness, to obtain a constant voltage for AC and DC loads. They also used the PSO method to obtain the highest energy from solar radiation available by MPPT. The model was simulated in the MATLAB–Simulink® program, which represented the system. In the end, the authors conclude that this model can be applied to HMGs for power-stability studies. In [322], the stability of the HMGs is analyzed based on small signal linearization techniques. The authors propose mathematical methods based on Lyapunov, which estimate the asymptotic stability domain of the studied system. Additionally, stability studies of DC/AC droop-controlled inverters, AC/DC and DC/DC converters, and motor controllers are explored. Finally, the paper mentions areas that future research could address to improve large-signal stability studies in HMGs. In [323], a non-linear hierarchical control strategy is proposed and applied to an HMG composed of a PV system, a BESS, and supercapacitor–based ESS to satisfy the constraints of the grid codes. In this paper, it is intended to stabilize the DC voltage of the HMG despite the large variations in production and consumption based on non-linear control algorithms designed for the use of temporary separation between different components of the ESS. The simulation results allow operating margins to be maintained around the voltage reference. In [324], the authors propose a non-linear control strategy based on a combination of Lyapunov theory and Input–Output Feedback Linearization (IOFL) to provide stable operation for an HMG under unbalanced generations of AC drives. The HMG is composed of BESS lithium, PV system, and bidirectional DC/DC power converters. HMG is modeled in the MATLAB–Simulink® software, which verified the accuracy and capacity of the proposed non-linear control strategy. One of the most outstanding results is that the control input of the BESS lithium bidirectional DC/DC power converter consists of both control inputs of the inverter connected to the DC–link, which led to effective dynamic parts for the control inputs. In [325], the authors provide a
non-linear control approach based on ISS–Lyapunov for HMG considering the Plug and Play philosophy. In addition, a new non-linear scheme to Constant Power Load (CPL) based on the backstepping technique is addressed. The objective of this study is to provide frequency support to the AC grid while maintaining the stability of the DC grid, especially in grids with a high penetration of RESs and ESSs. The modeling of the HMG and the controllers were developed in the MATLAB–Simulink® software. The authors conclude that topics such as voltage support for AC grids, power-quality constraints, and more sophisticated power-converter topologies need to be included in future work.

Table 14 summarizes the main functions of the control levels of the hierarchical control architecture where each level is responsible for controlling the HMG on a different scale. Additionally, Table 15 illustrates the general summary between different control strategies available for HMGs. Figure 15 presents the classification of the hierarchical control strategies mentioned previously in this section.

Table 14. Main function of hierarchical control levels.

<table>
<thead>
<tr>
<th>Control</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary</td>
<td>Participation in transitive markets</td>
</tr>
<tr>
<td>(global control)</td>
<td>Management of both modes of operation</td>
</tr>
<tr>
<td></td>
<td>Coordination of several MGs</td>
</tr>
<tr>
<td></td>
<td>Failure analysis</td>
</tr>
<tr>
<td></td>
<td>Optimization of variable: cost, efficiency, etc.</td>
</tr>
<tr>
<td>Secondary</td>
<td>Voltage/frequency, active and reactive power control</td>
</tr>
<tr>
<td>(HMG control)</td>
<td>Improves the voltage and frequency quality</td>
</tr>
<tr>
<td></td>
<td>Requires the use of communication network</td>
</tr>
<tr>
<td></td>
<td>Synchronization with the main electrical grid</td>
</tr>
<tr>
<td>Primary</td>
<td>Protection devices</td>
</tr>
<tr>
<td>(local control)</td>
<td>Power-sharing</td>
</tr>
<tr>
<td></td>
<td>Transient stability in both modes of operation</td>
</tr>
<tr>
<td></td>
<td>Voltage/frequency stability in islanded mode</td>
</tr>
</tbody>
</table>

Figure 15. Classification of the HMG control strategies.
### Table 15. Comparison between different control strategies.

<table>
<thead>
<tr>
<th>Control Strategy</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Location</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centralized</td>
<td>• Harmonic signals rejection.</td>
<td>• Loss of flexibility and expandability.</td>
<td>Small size HMGs</td>
<td>Master–slave control</td>
</tr>
<tr>
<td></td>
<td>• Compensates for unbalances</td>
<td>• Requires computational resource.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Improves MG stability with inertia emulation and oscillation damping</td>
<td>• Information congestion.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decentralized</td>
<td>• Simple control.</td>
<td>• Limited performance.</td>
<td>Local information only</td>
<td>Droop control</td>
</tr>
<tr>
<td></td>
<td>• Does not depend on digital technology.</td>
<td>• Reliability, and effectiveness depends on sensors.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Accuracy varies depend on configuration</td>
<td>• Accuracy varies depend on configuration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed</td>
<td>• Suitable for short transmission lines, accurate load sharing.</td>
<td>• Inadequate communication.</td>
<td>BESS and DC/DC PC</td>
<td>Coordinated control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Unsuitable for long transmission lines, security.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Weak communication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hierarchical</td>
<td>• Reliable and robust for UDGs.</td>
<td>• Complex control structure.</td>
<td>Complex modern system</td>
<td>Agent based control</td>
</tr>
<tr>
<td></td>
<td>• Advance control and management.</td>
<td>• Complex communication</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Standardized configuration in HMGs.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 6. Discussion with Recently Conducted Reviews

Due to the continuous development of new DGUs, issues are generated in the planning of the EPS and the protection of relays of the electrical grid, affecting the power quality of the distribution grids. This affects the normal operation of electrical equipment, reducing its useful life while causing economic losses derived from a large-scale power supply. As mentioned above, disturbances can appear in the form of long-term voltage fluctuations, as well as deviations in RMS values of nominal voltage and frequency, voltage unbalances, and harmonic distortion issues. To deal with these problems, primary and/or secondary control schemes or strategies are applied, which regulate the voltage and stabilize the frequency levels within a certain allowable range by the grid codes.

In recent years, different reviews have been presented that address various aspects of HMGs. For example, regarding the power-quality issue, reference [326] proposes a review of new control techniques to be implemented in the Unified Power Quality Conditioner (UPQC) to improve power quality in the HMG. In [327], the presented study reviews and compares the problems, solutions, and standards of power quality in HMGs by considering...
the following main problems: voltage sags, voltage swell, voltage and current harmonic distortion, system unbalances, and fluctuations. Furthermore, reference [328] critically reviews the definitions and power quality indicators specified in IEC 61000 and IEEE Std. 1159 and discusses the causes and consequences of power quality problems in HMGs. Reference [329] presents a detailed review of the uncertainties associated with HMGs, considering RESs to guarantee their optimal operation. In [330], the main power-quality issues that HMG developers face in guaranteeing a sustainable EPS are mentioned. In HMGs with DGUs based on PV systems, they generate a large current harmonic content [331]. This is caused by the presence of a large number of non-linear loads [332], with PV inverters being the devices that produce harmonics [333] and high-frequency harmonics (supraharmonic). At the same time, the connection of the non-linear loads on the load side also creates harmonic distortion issues. In [334], the authors analyzed an HMG composed of PV systems and linear and non-linear loads for harmonic distortion studies. In the study, the authors varied the levels of renewable penetration and concluded that the THD was around 4% for linear loads and 5.06% for non-linear loads.

Considering all these studies, we can mention that monitoring power quality in distribution grids has become a major concern. A proper measurement and analysis of electromagnetic disturbances in the grids shows both the contribution of the HMG to the deterioration of power quality and the influence of utility grid disturbances on the performance parameters of the HMG. Finally, as a technical point of view of this study, it is important to understand that power-quality issues in HMGs cannot be fully reflected through a single power-quality standard. Therefore, it is extremely important to select an efficient control method to guarantee the stable operation of the HMG and good power quality.

Regarding these reasonable control methods, there are optimization techniques applied to HMGs for optimal management of power quality. Great advances have been made in the development of power converters for DGUs and, to a lesser extent, algorithms and control strategies have been developed to ensure power quality. HMG dynamics, particularly when operating in islanded mode, can be markedly different than those used in a conventional EPS. The main functions of these algorithms are to control the voltage frequency as well as the active and reactive power. For example, in [335], a review of different well-established mathematical optimization techniques is presented and applied to one of the complex processes of HMG: planning. In [336], the most recent and efficient techniques used to optimize green HMGs from an economical and reliable perspective are reviewed to achieve a clean, economical, and highly reliable system. In [337], the bibliometric analysis of an HMG is reviewed, and future research topics with a view to improving ESSs are highlighted. In [338], an exhaustive review of the optimization and control techniques that can analyze the transient stability in HMGs operating in islanded mode and grid–connected mode by considering RESs is presented. Thus, it identifies and guides future studies on related topics.

In [339], a general description of various optimization techniques applied to the controls of an HMG is presented, as well as a detailed review of meta-heuristic optimization algorithms based on elementary Intelligent System and PSO algorithms. Similarly, in [340], a review of optimization techniques is described, mainly the metaheuristics that include Ant Colony Optimization (ACO), GA, PSO, Simulated Annealing (SA), and Differential Evolution (DE), etc., which are applied to HMGs to guarantee economical and reliable load dispatch. In [224], an exhaustive review of the energy management techniques of the RESs that comprise the HMGs is presented. Subsequently, a review of different forms (variants) [341] and hybrid forms [342] of PSO was introduced to solve the problems in economic dispatch issues.

The key issues about the control strategies for the mitigation of power-quality issues in HMG are addressed in this document where the main issues faced as stability and voltage unbalances are described through modern and innovative schemes control, even when the HMG operates in different scenarios. It is important to note that the various electromagnetic
phenomena that HMGs encounter relate to the mode of operation of the HMG, the type of loads that make up the HMG, and the type of DGU. Finally, the types of control most used to face the challenges of poor-power quality in HMGs are described. For example, in [343], an exhaustive review of the elements of an HMG was presented, including the different RESs that constitute the HMG and the various types of control and operational strategies in an EMS. The authors apply the primary, secondary, and tertiary levels of the HMGs to contribute to the policies and regulations adopted by certain countries, their protection schemes, transactive markets, and load restoration in the HMGs. In [344], the issues faced by the DGUs that compose the HMGs in terms of hierarchical control strategies and power-sharing are listed, concluding that MPC-based approaches are mostly used in recent controls and distribution strategies of energy from an integral and simple point of view. In the review of [345], different ESSs are analyzed for integration into HMGs, as well as their working operations and characteristics; the controls of the EMS are also discussed. Reference [346] provides a review of techniques, issues, and future directions regarding the protection of HMGs based on various DGUs. In [347], a comprehensive review of distributed control methods for HMGs operating in islanded mode is presented. Finally, Table 16 shows a comparison of this review paper with other current reviews regarding HMGs, in which the main areas of research are addressed.

Table 16. Summary of power-quality challenges, optimization strategies, and control methodologies of an HMG.

<table>
<thead>
<tr>
<th>HMG Aspects</th>
<th>Topic Covered</th>
<th>Reference</th>
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7. Conclusions

This paper presents the main research areas regarding the topic of HMGs, knowing that these are the next steps in the realization of a decentralized EPS and a smart grid paradigm, which has many advantages over traditional electrical grids because of improved reliability and the elimination of multiple conversions, as well as the subject of ancillary services.

The paper offers a complete and general description of the different types of HMGs: AC–MG, DC–MG, and HMG, operating in islanded mode and grid-connected mode. In addition, their operation, structure, and construction are described. The medium- and large-scale pilot projects of HMGs installed in different parts of the world are detailed, which are being replaced by commercial projects driven by solid economic analysis and are causing the HMGs market to evolve rapidly with projects executed throughout the world.

The paper addresses the power-quality issue in HMGs in both modes of operation: islanded mode and grid-connected mode. First, different HMGs are analyzed for different scenarios by considering residential, industrial, and commercial loads. Similarly, the most important power-quality issues are described, such as voltage sags, harmonic distortion, and phase imbalance. However, there are also many practical issues, such as operational problems, coordination control, protection, stability, EMS, communication infrastructure, standards, and regulations, as well as electricity market trends cited in this paper that must be resolved to offer secure and reliable grids.

In this paper, we resoundingly conclude that the optimization techniques are related to the maximization of the output power of the generators at a particular moment, to the increase in the useful life of the ESSs and to the minimization of environmental impact and operating costs. To make this a reality, upgraded models have been used that employ various improved techniques to ensure optimum power flow and lower operating costs. In recent years, the pace of HMG design and topology research has been slow but constant. The modeling of existing equipment, as well as the development of new equipment and the application of improved techniques for optimal planning of RES and ESS, are important aspects of this area. Furthermore, the high integration of DC RES, non-linear loads, and PHEV in the HMG must be considered for optimizing the system for future needs.

Power-management schemes and control strategies are immensely important in the operation of HMGs and demand a thorough review. For example, the nonlinear control of a PC is of paramount importance and attracts the most attention from researchers regarding HMG integration. Additionally, recommendations about specific future directions of research in this field are presented.

Finally, there are still niches of opportunity in HMG issues, such as the protection of HMGs, which presents an important gap in research. In addition, in this area, it is necessary to continue exploring new techniques so as not to compromise power quality. Without a doubt, this study will serve as a basis for future research, comparative analysis, and further development of novel techniques regarding HMGs.

Authors Contributions: E.H.-M.: Conceptualization, methodology, investigation, writing—original draft preparation, writing—review and editing, project administration; M.M.-M.: Investigation, supervision and writing—original draft; J.D.M.-A.: Investigation and writing—original draft; R.I.-C.: Investigation; J.A.E.-S.: Investigation; O.R.-R.: Conceptualization and visualization; G.M.-R.: Conceptualization and visualization; E.M.-S.: Conceptualization and visualization. All authors have read and agreed to the published version of the manuscript.

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