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# General Approach to Electrical Microgrids: Optimization, Efficiency, and Reliability

**Ma. Del Carmen Toledo-Pérez, Rodolfo Amalio Vargas-Méndez *, Abraham Claudio-Sánchez, Gloria Lilia Osorio-Gordillo, Luis Gerardo Vela-Valdés, Juan Ángel González-Flores and Omar Rodríguez-Benítez**

Tecnológico Nacional de México/CENIDET, Cuernavaca 62490, Morelos, Mexico; d19ce046@cenidet.tecnm.mx (M.D.C.T.-P.); abraham.cs@cenidet.tecnm.mx (A.C.-S.); gloria.og@cenidet.tecnm.mx (G.L.O.-G.); luis.vv@cenidet.tecnm.mx (L.G.V.-V.); d20ce017@cenidet.tecnm.mx (J.Á.G.-F.); d19ce044@cenidet.tecnm.mx (O.R.-B.)

* Correspondence: rodolfo.vm@cenidet.tecnm.mx

**Abstract:** In this article, a comprehensive review of electrical microgrids is presented, emphasizing their increasing importance in the context of renewable energy integration. Microgrids, capable of operating in both grid-connected and standalone modes, offer significant potential for providing energy solutions to rural and remote communities. However, the inclusion of diverse energy sources, energy storage systems (ESSs), and varying load demands introduces challenges in control and optimization. This review focuses on hybrid microgrids, analyzing their operational scenarios and exploring various optimization strategies and control approaches for efficient energy management. By synthesizing recent advancements and highlighting key trends, this article provides a detailed understanding of the current state and future directions in hybrid microgrid systems.

**Keywords:** microgrids; energy storage systems; energy management system; optimization; control; point of common coupling

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## 1. Introduction

There are various ways to generate energy, whether through conventional or unconventional energy sources. The concept of a microgrid (MG) emerges as a solution to address environmental degradation by harnessing energy generated from renewable energy sources (RESs), such as photovoltaic solar energy (PV) and wind energy. Microgrids are crucial in generating clean energy, emphasizing three key properties: reliability, sustainability, and economic efficiency [1].

These properties complement each other, providing a comprehensive solution for energy and environmental challenges. The high reliability of microgrids is achieved through a specific design. From a physical standpoint, they can operate autonomously and in isolation in case of disruptions to the primary grid, ensuring a continuous energy supply even during disasters or power outages. Additionally, component redundancy and self-diagnostic capabilities enhance the system's reliability. Sustainability is attained through integrating renewable energy sources [2], reducing reliance on fossil fuels, and lowering greenhouse gas emissions. The efficient design and management of microgrids also allow for the optimization of energy usage and energy resource utilization [3]. From an economic perspective, microgrids are designed to optimize energy generation, distribution, and consumption costs and efficiency. By leveraging renewable energy sources, long-term costs associated with the purchase of conventional energy are reduced, mitigating risks related to the volatility of oil and gas prices. Moreover, selling excess generated energy to the primary grid can generate additional income [4].

In summary, MGs represent a comprehensive solution to environmental depletion by harnessing RESs. Their reliability, sustainability, and economic efficiency make them a powerful tool for advancing towards a cleaner and more sustainable future in terms of energy and the environment.

In the literature, various classifications of microgrids can be found, with a fundamental categorization based on the operational scenario of the microgrid, dividing it into three main categories: grid-connected, islanded mode, and flexible mode. Each modality presents specific characteristics tailored to different needs and implementation conditions.

In the context of grid-connected MGs, the infrastructure is interconnected with the primary electrical grid, enabling bidirectional energy transfer. This configuration is instrumental in urban or industrial environments where reliability in electrical supply is essential.

On the other hand, isolated microgrids operate autonomously, disconnected from the primary grid. This approach is employed in remote areas or situations with limited access to the conventional electrical grid. The energy self-sufficiency of these microgrids makes them ideal for isolated communities or projects seeking energy independence.

An additional component is introduced in flexible mode: the Point of Common Coupling (PCC). In this scenario, the microgrid can operate connected to the primary grid and in an isolated mode, depending on specific conditions and requirements. The PCC acts as a transition point, allowing for flexibility to switch between operational modes based on demand and environmental conditions [5].

The choice of the appropriate configuration depends on specific goals, local conditions, and available infrastructure, highlighting the inherent versatility of MGs in the pursuit of a more efficient and sustainable electrical supply.

MGs can also be categorized based on their type of connection: either direct current (DC), alternating current (AC), or a combination of both, known as hybrids. Each category finds their preferred applications in various fields, as shown in [6]. For example, DC microgrids primarily power critical loads such as computer systems and hospital environments. AC microgrids supply power to loads connected and disconnected from the electrical grid, while hybrid microgrids (HMGs) are characterized by the interconnection of generation systems of different types, encompassing both renewable energy sources and conventional generation systems such as diesel generators. These systems also incorporate loads that can be directly connected or are typically linked to a storage system to ensure continuous supply, even in interference situations [7]. The main advantage of these hybrid systems lies in their ability to connect to the grid at any time, providing them with independence from renewable energy sources.

MGs can also be categorized based on their type of connection: either DC, AC, or a combination of both, known as hybrids. Each category finds preferred applications in various fields, as shown in Figure 1, which provides a detailed classification of microgrids based on their connection type. As depicted in the figure, DC microgrids are typically used for powering critical loads such as computer systems and hospital environments, where a stable and reliable supply is essential [8]. AC microgrids are designed to supply power to loads that are connected and disconnected from the main electrical grid, allowing for greater flexibility in grid interaction. On the other hand, hybrid microgrids (HMGs) are characterized by the integration of different generation systems, including both renewable energy sources and conventional generation methods like diesel generators. The figure highlights how these systems can incorporate loads that are either directly connected or typically linked to a storage system, ensuring a continuous power supply even during grid interruptions. The main advantage of hybrid systems, as shown in the figure, is their ability to connect to the grid at any time, offering greater energy independence by utilizing renewable energy sources while retaining the option of conventional power generation.

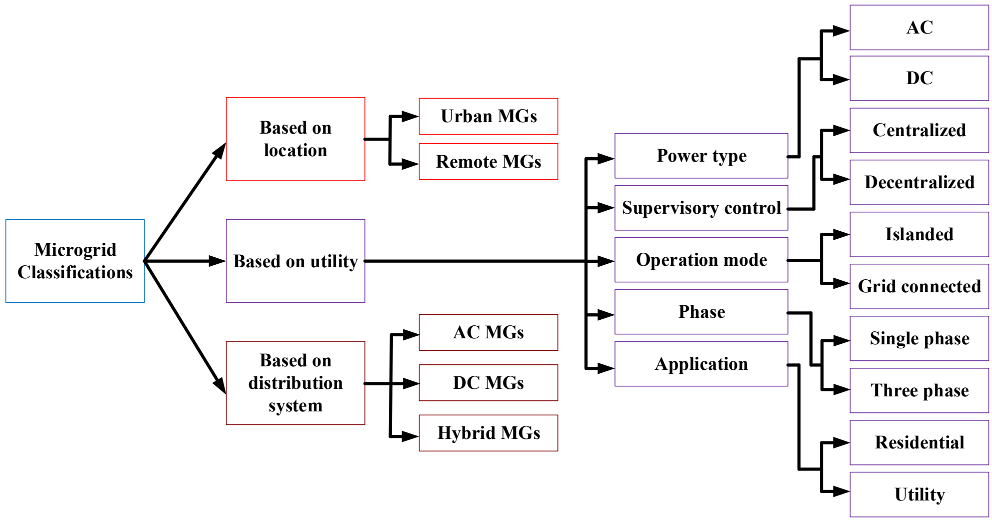


**Figure 1.** MG classifications.

The objective of this paper is to present a comprehensive review of electrical microgrids, emphasizing their growing role in integrating renewable energy, as microgrids can operate in both grid-connected and islanded modes. This review is very helpful for a comprehensive understanding of hybrid microgrids, examining their operational scenarios and exploring optimization strategies and control approaches for efficient energy management. The contribution of this paper is to synthesize recent advancements and key trends while providing a detailed understanding of the current state and future directions of hybrid microgrid systems.

This research paper has been organized as follows: Section 2 provides an overview of DC-MGs. Section 3 presents a review of AC-MGs. Section 4 offers an analysis of hybrid-MGs and the characteristics that need to be considered for their adaptation to a specific application, depending on the required features. Section 5 presents the impact of energy variability and system costs on microgrid configurations.

Power converters need to operate effectively to ensure a proper connection between various RESs and ESSs in an electrical microgrid [9].

One way to classify the different converters used is shown in Figure 2.

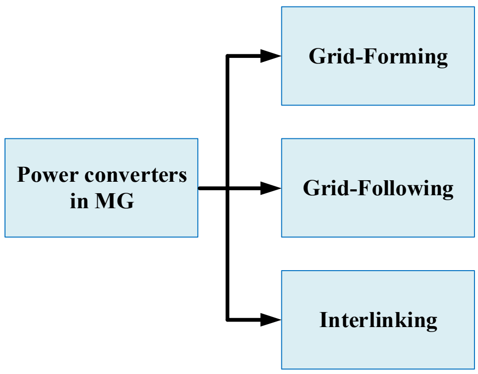


**Figure 2.** Power converters in MGs.

Forming: Primarily, power converters are linked to storage units and are responsible for maintaining voltage and frequency levels in the AC grid [10,11].

Following: These converters are associated with non-dispatchable distributed generation sources, as they continuously monitor the voltage and frequency of the grid and supply both active and reactive power to achieve a unity power factor [12].

Interlinking: Interconnection power converters (IPCs) are used to establish the connection between the DC and AC parts to create an AC/DC-MG. The interconnection part is bidirectional, allowing for the transfer of surplus power between the electrical grid and the MG [13].

Now that various power converters in microgrids have been discussed, we shift our attention to the description and classification of microgrids themselves. Each presents distinctive characteristics, from direct current-based microgrids to alternating current-powered ones and those that combine both technologies in hybrid microgrids; these characteristics are shown in Table 1.

**Table 1.** Types of microgrids.

| Type of Microgrid | Operational Current | Features |
|---|---|---|
| DC Microgrid | Direct current | Exclusive for DC; ideal for DC electronic and renewable loads; requires inverters to integrate with AC. |
| DC-coupled Hybrid Microgrid | DC with AC sources | Combines DC with AC power sources via converters; flexible in the use of power supplies and power supply. |
| AC Microgrid | Altern current | AC operation; most common in micro-grids and is compatible with many conventional power sources. |
| Hybrid Microgrid coupled to AC | AC with DC sources | Uses AC and DC power sources; employs AC-DC inverters to integrate DC components into AC grids. |
| Hybrid AC-DC Microgrid | Simultaneous AC and DC | Combines both types of current to support mixed loads and improve the flexibility and stability of the system. |

## 2. DC Microgrids

Generally, renewable energy sources require conversion to direct current within the MG to directly power loads. Additionally, most electronic devices can be powered directly by a direct current [14–16].

DC microgrids offer several advantages over their AC counterparts, detailed as follows:

- Reduction in conversion stages;
- Decrease in losses;
- Greater simplicity in control.

However, fascinating aspects within the field of DC microgrids remain as areas of research opportunity, notably highlighting control and energy management. Compared to AC microgrids, DC microgrids do not face issues such as synchronization, harmonics, reactive power control, and frequency control. Nevertheless, distributed generators in the DC bus, such as PV systems, wind systems, loads, and battery-based energy storage systems (BESSs), have introduced complexities in voltage control and energy distribution [17].

To ensure the safe operation of DC microgrids, various control techniques have been proposed, including the following [18]:

When planning a DC microgrid, it is essential to consider various aspects, including economic impact, ecological considerations, and system stability and reliability. Figure 3 illustrates the planning process for DC microgrids.

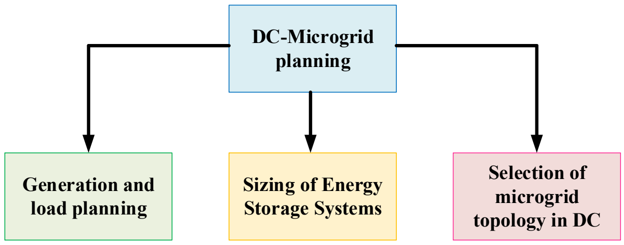


**Figure 3.** Planning process of the DC microgrid [14].

In the architectural context, a DC-MG comprises distributed energy resources (DERs), which can come from both renewable and non-renewable energy sources. It includes ESSs, power converters, and loads interconnected through one or more direct current buses. Figure 4 provides a visual example of this configuration. However, various elements such as power converters (AC/DC and DC/AC) are still necessary because several sources and loads cannot be directly connected to the direct current bus. Under normal operating conditions, two microgrid networks (AC and DC) are interconnected through the PCC. At the same time, loads are supplied by both local sources and distributed generation units based on renewable energy sources and, if necessary, from the primary grid.

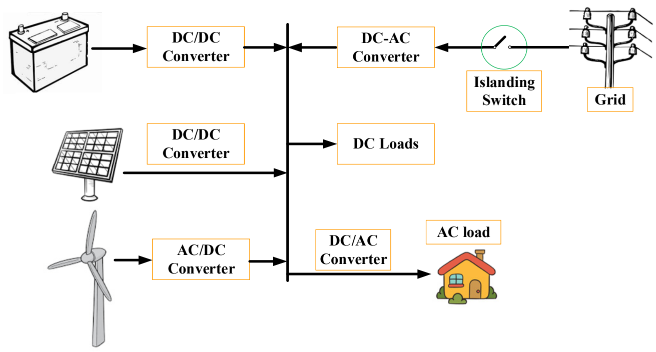


**Figure 4.** General structure of a DC microgrid [19].

Once the general structure of DC microgrids has been presented, it is crucial to highlight some essential characteristics. Table 2 shows the most significant aspects of the architecture of a DC microgrid, and one of these critical aspects is the control type. It is important to note that the control strategy varies for each case study due to the diversity of employed DERs. In this context, the connected load type also plays a crucial role by directly influencing the choice of appropriate control. In some scenarios, it is necessary to keep the loads powered without interruption, while in other cases, load shedding can be applied.

Additionally, several authors emphasize the implementation of Maximum Power Point Tracking (MPPT) control, especially applied to photovoltaic systems, which allows for maximizing the use of generated energy [20]. The various control strategies used in microgrid studies often interconnect systems to facilitate information exchange. This approach enhances overall energy management and contributes to achieving the established objectives.

In summary, implementing adaptive and context-specific control strategies, system interconnection, and a focus on MPPT control are essential elements to ensure optimal performance of direct-current microgrids. These approaches provide effective energy management, ensuring electrical supply continuity and maximizing energy efficiency in various operational scenarios.

**Table 2.** Characteristics of DC microgrids.

| Ref. | Operating Scenario | System Capabilities (kW) | Type of Load | Control | Remarks |
| --- | --- | --- | --- | --- | --- |
| [21] | Grid-connected | PV<br>WT<br>BESS | Customers (2 kW) | Droop | They use a hierarchical control to correct voltage variations. |
| [22] | *** | PV<br>BESS | *** | Multi-agents | Local controls (LCs) are used, and they exchange information with neighboring controls. |
| [14] | Grid-connected | PV<br>WT<br>BESS | Resistive motors | *** | Various centralized, decentralized, and distributed control strategies are presented. |
| [23] | Grid-connected | PV (12 kW)<br>BESS ion litio (6.5 kWh/ 710 VCD/3 A) | Essential criticisms (9 kW) | SCADA | The EMS in this work is designed to minimize the energy consumption from the main grid, and it also operates with the Maximum Power Point Tracking (MPPT) of the photovoltaic panels. |
| [24] | Autonomous | PV<br>WT<br>BESS<br>Acid lead | AC loads (lamps) | Rapid Control Prototype (RPC) | They employ a real-time control system to operationally and experimentally validate the resources of the microgrid. |
| [25] | Grid-connected | *** | Variants | Finite State Machine | A second output voltage tracking controller with performance recovery was implemented. |
| [26] | Autonomous | PV (9 kW)<br>WT (5 kVA)<br>BESS<br>(60 Ah/12 V)<br>SC (16 V) | Critical loads on CD (4 kW)<br>Critical loads in AC (1.5 kW) | Real-time laboratory | The dispatchable generator plays a crucial role in isolated scenarios from the electrical grid. |
| [27] | Autonomous | PV<br>Diesel generator (6 kW)<br>BESS<br>(10 Ah/36 V) | CD loads | Model Predictive Control | It performs real-time measurements for the optimal dispatch of energy, ensuring the distribution of the energy flow. |
| [28] | Grid-connected | PV (150 kW)<br>BESS<br>(200 Ah/336 V)<br>VE<br>(40 kW) | LED lights (20 kW)<br>Air conditioning (30 kW) | Jerarchic | An EMS is proposed where the prioritization is given to minimizing battery wear, along with a strategy based on minimizing operating costs. |
| [29] | Grid-connected | FC<br>PV<br>BESS | Commercial building | *** | EMS is based on a Particle Swarm Algorithm (SSA) due to its advantages in convergence and computational simplicity. |

*** represents that there is no information reported.

## 3. AC Microgrids

In AC microgrids, it is necessary to coordinate four main components: control, which encompasses elements of active power, reactive power, harmonics, and unbalance [30]. In contrast, in DC microgrids, only one component must be controlled: DC power. This simplification in the control system of DC microgrids makes them less complex than AC ones. Additionally, power quality emerges as the primary challenge in AC microgrids in contrast to DC microgrids.

The architecture of the AC microgrid is presented in Figure 5.

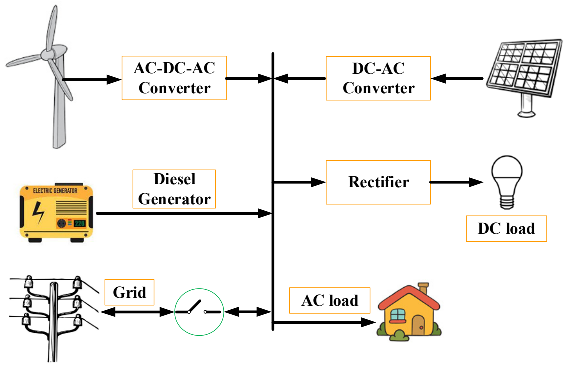


**Figure 5.** AC microgrid architecture.

The main advantage of an AC microgrid lies in its ability to quickly step up for long-distance energy distribution and then step down again near the load using a high-efficiency transformer [31]. Because of the periodic zero-crossings of voltage, protection schemes for AC circuits experience improvements as the fault current arc is extinguished by breaker switching at the zero-crossing. Voltage stability can be achieved by controlling reactive power independently of absolute power.

In the grid-connected mode, if the main grid experiences abnormal or faulty conditions, the AC-MG isolates itself to safeguard the load within the microgrid. This way, disturbances in the primary grid will not affect the AC load of the MG-AC. Most loads in the current system are AC loads that can be directly connected to the AC microgrid without the need for any conversion [32].

The MG-AC presents various potential advantages and establishes a new model for future applications in the electrical system, which are detailed below:

- In situations of uncertainty or transients in the grid, the soft isolation capacity of the AC-MG facilitates less distortion of loads within the microgrid operation;
- The average performance of the electrical grid is optimized;
- During peak load demand, the AC-MG protects against grid faults by regulating load demand;
- A significant improvement in environmental conditions is made possible by using low- or zero-emission-power generators;
- The system enhances overall efficiency by enabling multiple energy sources and reducing heat generation;
- Production costs and electricity availability decrease for users;
- It facilitates the improvement of energy quality and reliability during the application of microgrids based on sensitive loads.

However, despite these advantages, some disadvantages of the AC-MG system are highlighted [33].

The increase in the number of integrated renewable energy sources entails the following drawbacks:

- Increased costs and net metering for microgrid integration;
- Requires the involvement of expert energy engineers and well-equipped engineering techniques;
- It is necessary to follow or develop interconnection standards to maintain coherence;

- Control and protection are major issues for harnessing the network formation and tracking mode.

Resynchronization/restoration of the AC-MG is considered a significant challenge due to the following reasons:

- Synchronization difficulties after islanded operation in terms of stability;
- Appearance of voltage angles and phase mismatch during resynchronization from network formation to tracking mode;
- Errors in voltage setpoints increase by circulating current between the microgrid and the main grid, thereby increasing oscillations in active and reactive power;
- In islanded operation mode, to track changes in load frequency, the MG must regulate operating power, causing frequency error generation issues affecting system voltage and phases;
- Impedance-related factors, such as line and distributed generation (DG), also affect the control and distribution of reactive power during grid-connected and isolated modes, respectively.

Global control encompasses the primary, secondary, and tertiary levels of an AC-MG system. The primary loop regulates the microgrid system's impedance, voltage, and current parameters. Similarly, the secondary loop is employed to regulate voltage and frequency. Tertiary control is used to regulate the active and reactive power of the system, thereby facilitating optimal power exchange with the grid. Table 3 shows the most relevant works of AC microgrid.

**Table 3.** Reported work of AC-MG.

| Ref. | Location | Component Systems | Power Ranges (kW) | Remarks |
|---|---|---|---|---|
| [34] | Greek Island | PV<br>WT<br>BESS | 12<br>50<br>85 | Development of a large number of reliable forecasting algorithms is applied to a remote island along with an innovative storage system. |
| [35] | Hachinohe | PV<br>WT<br>Diesel generator | 100<br>50<br>510 | The main objective was to optimize the operation and control of the system, assess costs and benefits, and evaluate the potential for emissions reduction. |
| [36] | Senegal | PV<br>BESS | 10<br>80 | Reducing loss rates in local networks resulting from the use of renewable energy in a grid-connected environment. |
| [37] | Porto | PV<br>WT | 150<br>50 | Supplies a time-variable load, and the numerical results verify the applicability and accuracy of the developed technique for estimating the load and filter currents. |
| [38] | Japan | PV<br>WT<br>BESS | 200<br>100<br>450 | Joint estimation of an advanced filter to estimate the current of the AC microgrid and unknown loads from the measurement of the AC bus voltage. |

## 4. Hybrid MGs

These microgrids maintain the inherent advantages of both AC and DC power systems, comprehensively encompassing power distribution and transmission [39].

The classification of an HMG-AC/DC structure depends on how sources and loads are connected to the system, as well as the configuration of AC and DC buses. These microgrids can be categorized as AC-coupled, DC-coupled, and AC/DC-coupled [40].

In AC-coupled HMGs, various DG sources and energy storage systems (ESSs) are connected to the standard AC bus through their interconnection converters. On the other hand, in DC-coupled HMGs, the DG and ESS are connected to the common DC bus, using an interconnection converter (IPC) to link the DC and AC buses. Regarding AC/DC-coupled HMGs, DERs, and the ESS are connected to both DC and AC buses, which are interconnected through an IPC [41].

### *4.1. AC-Coupled Hybrid Microgrid*

In an AC-coupled HMG, as shown in Figure 6, various RESs and ESSs are connected to the common AC bus through their interconnection converters.

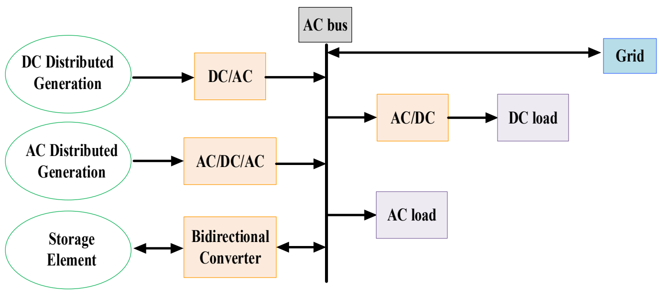


**Figure 6.** AC-coupled hybrid MG [42].

Energy storage systems require bidirectional converters to provide energy flow capability [43]. In this structure, both AC and DC loads are also connected to the common bus (with or without power electronic converters). This structure is commonly used when the dominant generation sources in the microgrid produce AC voltages at the network level directly (as is the case with a diesel generator) or indirectly through interconnection power converters [42].

The predominant configuration currently is the AC-coupled microgrid, thanks to its simple design, energy control, and management scheme. Most AC/DC hybrid microgrids are connected to alternating current [44].

In some AC-coupled microgrids, instead of using interface converters for each distributed generation source or energy storage source, various energy conversion steps can be replaced by multi-port converters that combine different energy sources into a single power converter [45]. As a result, the entire system can be considered a single power processing stage with multiple interface ports. In these systems, input energy sources are typically connected to a high-frequency AC link, and isolation transformers and AC/DC interface converters connect generation to the load/grid [40,46].

### *4.2. DC-Coupled Hybrid Microgrid*

In this microgrid, the distributed generation units and energy storage systems (ESSs) are connected to the common DC bus, and an interconnecting power converter (IPC) is used to link the DC and AC buses, as shown in Figure 7. This design is employed when the direct current energy sources are the primary power generators in the microgrid [47].

It is essential to highlight that, in this configuration, all DERs and ESSs are connected to the DC bus. In this type of microgrid, variable-frequency AC loads, such as variable-speed motors, can be connected to the DC bus through a DC/AC converter (to avoid additional AC/DC conversion when connecting them to the AC bus).

IPCs facilitate bidirectional power flow between the AC and DC buses in this system. Depending on the DC and AC bus requirements, IPCs are expected to be used in parallel with higher power capacity and reliability.

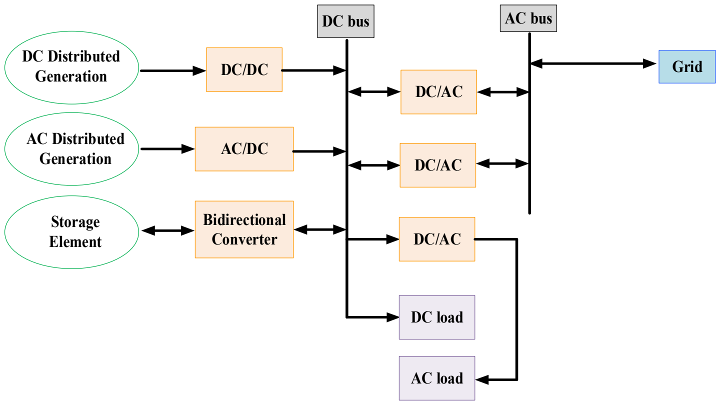


**Figure 7.** Coupled HMG [48].

A simple structure characterizes the DC-coupled microgrid and does not require synchronization when integrating different DERs. However, controlling and managing the power of parallel IPCs and synchronizing their output voltage (either among themselves or with the grid in grid-connected mode) can pose some challenges. Additionally, DC and AC voltage control and subsystem power management are necessary for a DC-coupled system. In some DC-coupled hybrid microgrids, the ESS is directly connected to the DC bus without converters [48].

### *4.3. AC-DC Coupled Hybrid Microgrid*

Figure 8 shows the representative architecture of a hybrid microgrid that combines distributed generation sources, energy storage elements, and different types of electrical loads. The microgrid integrates two main buses, a direct current (DC) bus and an alternating current (AC) bus, which allow for the connection of sources and loads of different natures. The distributed generation sources can be either DC or AC, while the storage elements are connected through bidirectional converters that facilitate energy management. Furthermore, the microgrid is designed to interact with the primary power grid, enabling the import or export of energy based on the system's needs. This configuration enables efficient and flexible operation, maximizing the utilization of renewable energy sources and ensuring the continuity of power supply to connected loads.

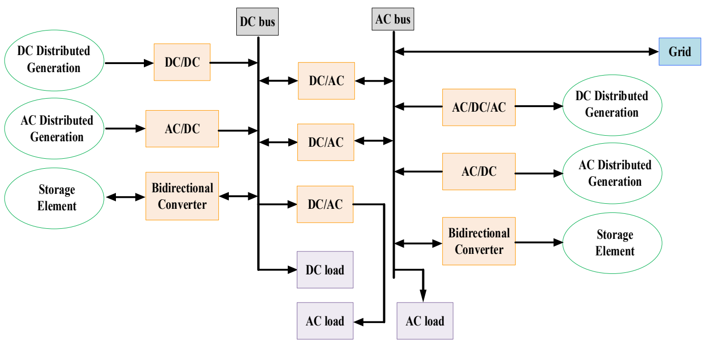


**Figure 8.** AC/DC-coupled hybrid MG [41].

Generally, this structure is considered when the primary energy sources include DC and AC. This design enhances overall efficiency and reduces system costs by minimizing the number of energy converters when connecting sources and loads to AC and DC buses with minimized energy conversion requirements. Considering these benefits, hybrid microgrids coupled to alternating current/direct current are emerging as the most promising structures [49].

Although hybrid microgrids coupled to alternating current/direct current are promising, they require thorough study and research, especially regarding energy and power management. The control of such a system must consider both voltage (and frequency) control on direct current and alternating current buses, as well as power balance within direct current and alternating current subsystems, which will be further discussed later.

Once the characteristics above are presented, a table incorporating various hybrid microgrids is included, as shown in Table 4. This table can be a valuable tool for visualizing and comparing key aspects, such as the generation systems and power ranges used. This visualization can provide a clear and concise view of the diversity of configurations in such systems.

**Table 4.** Reported works of HMGs.

| Ref. | Location | Component Systems | Power Ranges (kW) | Features |
| --- | --- | --- | --- | --- |
| [50] | Hachinohe in Japan | PV<br>Diesel Generator<br>WT<br>BESS | 2 de 50<br>3 de 170<br>2 de 2<br>100 | Provides electricity to four schools and an office. The energy control and management system ensure a balance between generation and consumption through a weekly plan, updated every three minutes, and regulates the energy flow at the interconnection points. |
| [51] | Bronsbergen in Netherland | PV<br>BESS | 315<br>*** | Two battery banks, acting as a central energy storage system, are connected at the common coupling point. |
| [52] | Kythnos in Greece | PV<br>BESS<br>Diesel generator | 10<br>53/h<br>5 | The residential service is powered by three battery inverters in parallel using the frequency droop control method, in which the grid frequency is used as the communication signal. |
| [53] | Aichi in Japan | FC carbonate<br>FC solid oxid | 300<br>25 | The matching between supply and demand power, as well as voltage control, are managed by the battery converter. In addition, optimization techniques (genetic algorithm for day-ahead generation planning) are used. |
| [54] | Cesi in Italy | PV<br>Diesel generator | 350<br>*** | It features a central control scheme, using optimization techniques, which regulates the set points of each source. |
| [55] | Kahua in the USA | PV<br>WT<br>BESS<br>FC | 10<br>7.5<br>85/h<br>5 | The electricity generated by the wind turbine and solar array is used to power an electrolyser that produces hydrogen, which is stored without further compression. If electricity is needed, the hydrogen is supplied to a fuel cell to generate electricity. |

*** represents that there is no information reported.

Hybrid microgrids (HMGs) have emerged as an efficient solution to integrate diverse renewable energy sources, storage systems, and loads in various operational configurations. However, their implementation and operation present technical and administrative challenges that must be addressed to ensure their functionality and reliability.

The main challenges are power quality protection, bidirectional power flow management, transitions between operational modes, and islanding detection. Additionally, challenges arise in balancing energy demand and generation, coordinating subnetworks, compensating for reactive power, meeting communication infrastructure requirements, and complying with regulatory policies. Figure 9 illustrates these issues in a structured manner, highlighting the complexity and the multiple areas of focus required for the effective development and operation of hybrid microgrids in a modern energy environment.

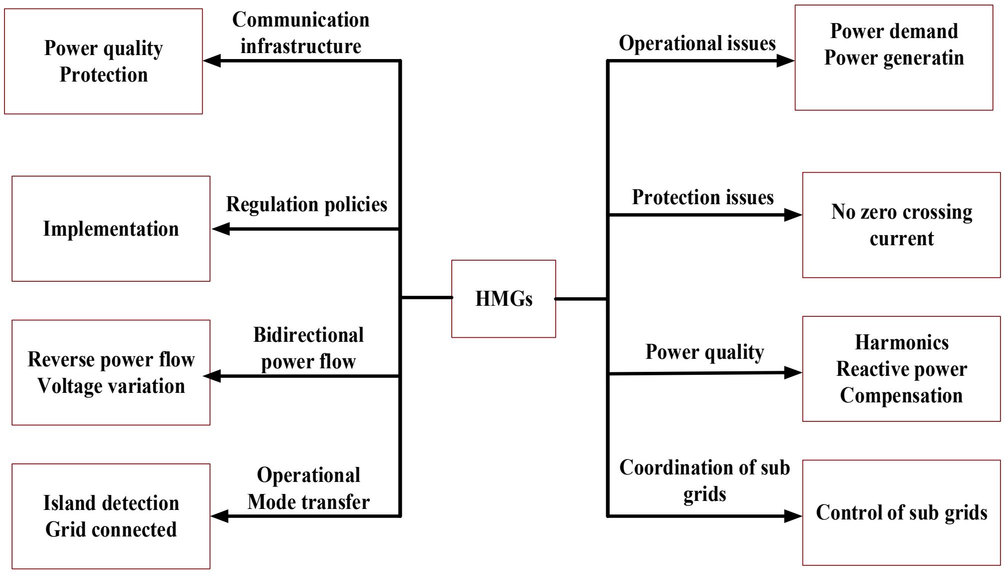


**Figure 9.** Challenges of hybrid microgrids [56].

Hybrid microgrids, by integrating renewable and intermittent energy sources like solar and wind with conventional systems, create complexities in managing the variability of generation. This requires advanced control mechanisms to maintain stability and ensure reliable operation. Moreover, the high costs of investment and maintenance, coupled with the complexity of their infrastructure, present significant financial hurdles. Interaction with the main grid adds to these challenges, particularly in terms of synchronization and managing energy flow control. Additionally, the reliance on storage systems, such as batteries, to ensure a continuous supply poses limitations due to their capacity, lifespan, and high cost.

Operationally, hybrid microgrids face challenges related to bidirectional energy flow, which is crucial for network stability. A robust optimization model is needed to handle the operation of these complex systems efficiently. Challenges with energy quality also emerge, particularly due to voltage fluctuations, harmonic distortions, over voltages, and frequency deviations. The variable production from distributed generators further complicates the energy flow, causing reverse power flow issues. These problems underscore the importance of addressing energy quality in microgrids, which is often categorized into harmonics, reactive power compensation, and standardization of technical and commercial protocols. To mitigate these issues, filtering techniques and other solutions must be applied to maintain a clean and stable energy system. Furthermore, the hybrid nature of these systems is influenced by regulatory complexities, cybersecurity risks, the need for a specialized workforce, and social acceptance, all of which must be managed for successful implementation. Despite these challenges, hybrid microgrids offer significant potential for enhancing energy resilience, reducing dependency on conventional power sources, and advancing towards sustainable, decentralized energy systems.

Some of the operational challenges arise when implementing bidirectional energy flow, which is crucial to ensure network stability. Additionally, there is a need to develop a robust optimization model for the operation of microgrids [57,58].

Challenges related to energy quality are directly linked to voltage fluctuations, harmonic distortion, over voltages, and frequency deviations. Furthermore, the variable production of distributed generators poses a reverse power flow issue. Energy quality in the system is the most critical problem in terms of operation and is categorized into harmonics, reactive power compensation, and standardization of technical and commercial protocols [59]. Therefore, to address this issue, some filtering techniques must be applied to achieve a pollution-free system.

Communication poses a significant challenge in achieving a reliable and efficient system, impacting its design, including topology, operating mode, hybrid network control system coordination, protection schemes, system control requirements, and energy management.

The literature addresses the challenges associated with hybrid microgrids through advanced optimization and control methods, enabling the efficient management of the complex and dynamic systems that characterize these networks. Optimization is primarily employed to tackle issues related to generation variability, interaction with the primary grid, and energy storage system management. Mathematical optimization models determine optimal operational strategies, considering renewable energy availability, load demand, and grid conditions. These models help minimize operational costs and enhance energy efficiency while ensuring the microgrid's stability.

On the other hand, advanced control techniques are utilized to address critical issues such as bidirectional power flow, power quality, and the integration of multiple generation sources [60]. Intelligent control strategies, such as predictive control and distributed control algorithms, can dynamically adjust the microgrid's operational parameters, responding in real time to renewable generation and demand fluctuations. These control systems ensure grid stability by enabling renewable and conventional energy systems to work complementary. Additionally, reactive power control and harmonic compensation techniques are applied to improve power quality, reduce distortions, and ensure a clean and stable supply.

Regarding operational challenges, such as variability in energy generation, the literature proposes using real-time optimization algorithms to manage the integration of intermittent renewable sources with conventional systems, minimizing reliance on diesel generators and maximizing the use of available renewable energy. Furthermore, multi-objective optimization models balance multiple variables: cost minimization, energy efficiency maximization, and system stability maintenance.

These optimization and control approaches enhance the performance of hybrid microgrids and provide long-term solutions to the reliability and sustainability issues associated with these systems [61]. Continued energy optimization and advanced control research are expected to play a key role in overcoming hybrid microgrids' technical and economic challenges, enabling their effective integration into the future of decentralized and sustainable power networks.

A critical element for the efficient operation of these AC/DC hybrid microgrids is formulating a control strategy and power management scheme, both essential to ensuring autonomous operation [62]. In this context, it is crucial to recognize that "energy management" and "power management" take on distinct meanings, considering various control tasks and temporal variability.

Long-term energy management algorithms aim to optimize the overall energy production to meet demand efficiently. These algorithms address the complex monitoring of a system composed of electrical, thermal, and mechanical components, emphasizing factors such as fuel costs, capital costs, maintenance costs, mission profiles, and lifespan during the decision-making process, as shown in Figure 10.

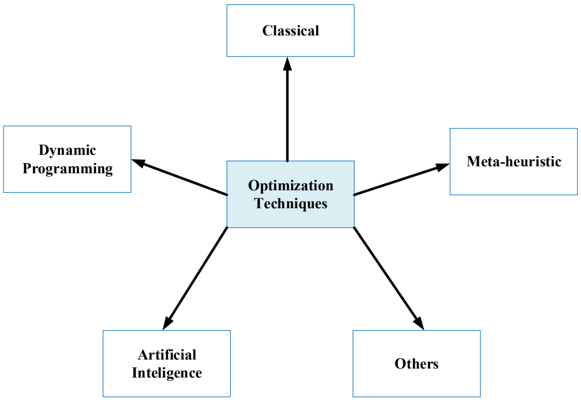


**Figure 10.** Classification of optimization techniques [61].

Optimization of a problem refers to finding the maximum and minimum of an objective function by systematically evaluating the function using systematically selected inputs within a permissible set.

The best options for building or managing a variety of complex systems involve using heuristic optimization algorithms for multi-objective optimization problems [62]. These algorithms include search methods based on experimental arrays to solve complex problems within continuous limits.

Table 5 presents the optimization methods commonly used for controlling and optimizing microgrids. These methods vary in terms of their approach, advantages, and specific applications within the microgrid context [63–65].

The optimization methods outlined in the table are critical for addressing the complex challenges of microgrid operation and control, particularly in hybrid systems that integrate intermittent renewable and conventional energy sources. Each approach presents distinct advantages and limitations, making its selection dependent on the microgrid's specific characteristics and the objectives to be achieved, as shown in the Appendix A.

For instance, linear and non-linear programming methods effectively solve problems with explicit constraints, such as minimizing operational costs and load scheduling. However, these approaches may be insufficient for highly dynamic or non-linear systems, such as those involving variable renewable generation. In such cases, stochastic optimization or MPC can provide an advantage by effectively managing energy source uncertainties.

Conversely, GA and PSO are highly effective for complex problems involving multiple variables and constraints. These methods excel at exploring a wide range of solutions, enabling them to identify optimal configurations in non-linear and high-uncertainty scenarios. These methodologies are particularly valuable in designing and optimizing hybrid microgrids, where the integration of various energy sources—such as solar, wind, and diesel generators—must be managed efficiently.

Among these methods, PSO has emerged as one of the most relevant and widely used techniques in the literature for microgrid optimization, owing to several key advantages. First, its ability to handle non-linear and complex problems efficiently makes it particularly suitable for hybrid microgrids that combine intermittent renewable sources with conventional systems. Unlike other optimization methods, PSO demonstrates a remarkable capacity for global exploration of the solution space, avoiding entrapment in local optima—an essential feature when addressing challenges such as renewable generation variability or infrastructure constraints.

Moreover, PSO does not require detailed mathematical formulations of constraints, simplifying its implementation in systems with multiple interdependent variables. This flexibility and ease of implementation, combined with its ability to deliver high-quality solutions within relatively short timeframes, have contributed to its widespread adoption in studies and practical applications. The literature shows that PSO is employed not only for optimizing generation and storage distribution but also for energy flow control and hybrid network planning, further reinforcing its relevance and applicability in microgrid optimization.

**Table 5.** Optimization method.

| Optimization Method | Approach | Advantages | Disadvantages | Common Applications |
|---|---|---|---|---|
| Optimization based on Linear Programming (LP) and Non-Linear Programming (NLP) | Use mathematical models to re-solve linear or linear optimization problems. non-linear in real time. | Computational efficiency for well-defined problems with clear constraints. | Not suitable for extremely complex problems or problems with high uncertainty. | Optimization of operating costs, generation and load planning in microgrids. |
| Model-based Predictive Control (MPC) | It uses a dynamic model of the system to predict and optimize the future actions of the microgrid. | Enables real-time optimization and handling of stability constraints. | It requires accurate modeling and can be computationally intensive. | Energy flow control, optimization of generation and storage distribution. |
| Genetic Algorithms (GA) | It uses evolutionary processes to find optimal solutions, adapting parameters as progress is made. | Flexibility to solve non-linear and multi-constrained problems. | Slow convergence and sensitivity to parameter selection. | Design of micro-grid configuration, integration of renewable and conventional sources. |
| Stochastic Optimization | Probabilistic models to optimize systems under uncertainty, ideal for renewable sources. | Effective in managing uncertainties, such as variability in renewable production. | It requires adequate uncertainty and can be computationally intensive. | Integration of intermittent renewable energies; optimization of storage. |
| Artificial Neuronal Networks (ANN) | Use of neural network models for prediction and decision making in complex systems. | Ability to learn and adapt to complex patterns in non-linear data. | It requires large amounts of data to train and is difficult to interpret. | Demand and generation forecasting, real-time optimization, adaptive control. |
| Particle Swarm Optimization (PSO) | Based on the simulation of the collective behavior of particles (agents) seeking optimal solutions. | Effective in finding solutions to complex and non-linear problems, fast in convergence. | Requires proper parameter setting to avoid suboptimal solutions. | Optimization of generation distribution, power flow control, design of hybrid microgrids. |

## 5. Impact of Energy Variability and System Costs on Microgrid Configurations

Energy variability is primarily associated with the intermittency of the renewable sources integrated into microgrids, such as solar and wind, which, along with implementation and operational costs, are key factors in determining the viability of microgrids in different contexts. These variables affect the technical design of microgrids and their long-term economic profitability.

Table 6 presents the main microgrid configurations, their technological components, and the approximate costs per installed kW. This analysis helps to understand how different design approaches and employed technologies address the challenges of energy variability and costs, optimizing system performance across various scenarios.

**Table 6.** Economic evaluation of microgrid configurations.

| Ref. | MG Configuration | Main Components | Approximate Cost (USD/kW) | Features |
|---|---|---|---|---|
| [66] | AC Microgrid with PV | PV systems, inverters, storage system | 1500–3500 | Costs highly dependent on the size of the MG and the quality of the PV systems. |
| [67] | Hybrid Microgrid (AC/DC) | PV systems, wind turbine, batteries, AC/DC converters | 2500–5000 | Combination of AC and DC systems, more flexibility, but also more complexity in integration and control. |
| [68] | Microgrid with FC | Fuel cell, batteries, converters, back-up grid | 3500–6000 | High initial investment due to fuel cells but offers higher reliability in constant generation. |
| [69] | Microgrid PV-WT-Diesel | Diesel generator, PV systems, wind turbine, storage system | 2000–4000 | Often used in remote areas; operating costs depend on the price of fuel and the proportion of renewables used. |
| [70] | Industrial Microgrid | Combined generation (CHP), storage, grid integration | 2000–5000 | Configuration designed for industrial environments, with increased capacity and redundancy to ensure continuous supply. |
| [71] | Residential Microgrid | PV systems, storage system whit batteries | 1500–3000 | Low capacity, designed to meet the specific demands of small households or communities. |

It is important to highlight that the costs presented in the previous table can vary significantly due to factors such as geographic location, which affects the availability of renewable resources; the quality and durability of the components used; tax incentive policies and subsidies in each region; and local energy prices, which have a direct impact on the economic feasibility of microgrids. These elements must be carefully analyzed when planning and implementing such a system.

Detailed studies of the renewable resources available at the selected location and the prioritization of high-quality components with a good cost–benefit ratio are recommended to mitigate cost variations. Additionally, the implementation of advanced control strategies can improve efficiency and ensure the microgrid's long-term economic viability.

## 6. Discussion

This review highlights the key role of hybrid microgrids in integrating renewable energies. While control and optimization strategies have been developed to manage diverse sources and variable demands, challenges remain regarding stability and efficiency in the face of renewable energy variability. Hybrid microgrids present unique characteristics, including combining renewable energy sources like solar and wind with conventional systems such as diesel generators. This integration offers greater flexibility and autonomy but also introduces significant challenges, such as the intermittent nature of renewable generation, which can lead to fluctuations in power supply and complicate energy distribution. Additionally, the management of ESSs is critical for ensuring a continuous and reliable energy supply, yet limitations in storage capacity and cost, along with the finite lifespan of these systems, remain substantial obstacles. Furthermore, the interaction between microgrids and the primary grid still requires advancements in synchronization and bidirectional energy flow control, especially in hybrid systems where seamless integration is essential. Interoperability between microgrids and the primary grid also remains a challenge, requiring further development of standards and regulations to ensure smooth operation. Although studies have proposed promising approaches, validating these models in real-world environments is needed to ensure their practical feasibility. Future work should focus on more robust control algorithms, such as predictive control and advanced optimization techniques, and economic strategies to address cost barriers and expand the adoption of hybrid microgrids.

## 7. Conclusions

This study focused on researching the various operational scenarios of electrical microgrids, conducting a comprehensive analysis of their dimensions. Different DER options that can be integrated into these microgrids were thoroughly examined. Special attention was given to the topology of hybrid microgrids, explicitly focusing on optimization strategies.

After a thorough evaluation, it has been concluded that the PSO algorithm stands out as one of the best options for addressing optimization challenges in hybrid scenarios. This method presents broad advantages and is versatile for minimizing operational costs and maximizing specific aspects in particular cases. The implementation of PSO is distinguished by its simplicity and user-friendly nature, which are particularly beneficial in microgrids.

It is important to note that PSO requires easily accessible input data from the microgrid, such as the operation costs of generation systems, capacities, and consumption/demand profiles. However, other optimization methodologies were explored in this work, and their selection will depend on the specific application, operational scenario, and diversity of systems involved. Additionally, various control mechanisms used for information exchange among DERs were investigated, contributing to better energy management in the overall microgrid.

The comprehensive exploration of optimization strategies and control modalities is crucial in the energy management of microgrids. This approach facilitates more efficient operation, allowing microgrids to operate in an improved manner.

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## Abbreviations

| | |
|---|---|
| ESS | Energy Storage System |
| MG | Microgrid |
| RES | Renewable Energy Source |
| PV | Photovoltaic Solar |

| | |
|---|---|
| PCC | Point of Common Coupling |
| DC | Direct Current |
| AC | Alternating Current |
| HMG | Hybrid Microgrid |
| IPC | Interconnection Power Converter |
| MPPT | Maximum Power Point Tracking |
| MPC | Model Predictive Control |
| GA | Genetic Algorithms |
| LP | Linear Programming |
| NLP | Non-Linear Programming |
| ANN | Artificial Neuronal Network |
| PSO | Particle Swarm Optimization |
| FC | Fuel Cell |

## Appendix A

**Table A1.** Operation scenarios and optimization methods.

| Ref. | Operating Scenarios | Optimization Method | Type of Control | Function Objective | Elements and Power Range Power |
|---|---|---|---|---|---|
| [72] | Isolated | Mixed Integer Linear Programming (MILP) | Centralized | Net project cost | L (66.3 kW), PV (60 kW), BESS (464 kWh), GENSET = (58 kW) |
| [73] | Grid-connected | Fuzzy Decision-Making Method | *** | Operational costs | L (20 kW), PV (7 kW), WT (5 kW), BESS (100 kWh), PF (4 kW) |
| [74] | Isolated | Chaotic Crow Search Algorithm (CCSA) | Coefficient diagram method (CDM) | Frequency stability | L (15 MW), PV (6 MW), WT (8 MW), BESS (4 MW/h). |
| [75] | Grid-connected | Improved Hybrid Optimization by Genetic Algorithms (iHOGA) | LF = load following CC = cycle charging | Maximizing the service life of the elements | L (50 kW), PV (31.9 kW), PF (1.9 kW), BESS (89.520 kW/h) |
| [76] | Isolated | Gauss–Seidel (Coordinate Descent) | Intelligent load control | Minimizing the size of the energy system | L (450 kW), PV (1000), PVS (120 kW) |
| [77] | Isolated | MOPSO | Centralized | Minimization of energy costs | L (84.7 kW), PV (61 kW), HG (11 kW) |
| [78] | Grid-connected | Non-linear Programming | *** | Minimize daily operating costs | L (80 kW), PV (100 kW), FC (50 kW), |
| [79] | Grid-connected | PSO | P&O | Minimizing response time to disturbances | L (60 kW), PV (40 kW), WT (50 kW) |
| [80] | Grid-connected | Gift-based Algorithm (RB-EMS) | *** | *** | L (400 kW), PV (235 kW), WT (200 kW), BESS (750 kWh), PEV (60 kWh) |
| [81] | Isolated | Mixed Integer Linear Programming (MILP) | Centralized | Minimizing operating costs | L (3500 kW), PV (4000 kW), BESS (1200 kWh) |

**Table A1.** *Cont.*

| Ref. | Operating Scenarios | Optimization Method | Type of Control | Function Objective | Elements and Power Range Power |
|---|---|---|---|---|---|
| [82] | Isolated | Mixed Integer Quadratic Programming (MIQP) | Distributed Explicit Model Predictive Control (DeMPC) | Reduce FC starts and stops | L, PV (57.6 kW), FC (1200 W), EA (5 kW) |
| [83] | Isolated | Construction of the Pyramids of Giza (GPC) | *** | Minimizing the net annual cost | L(43 kW), PV, WT, BESS, BG |
| [84] | Isolated | Particle Swarm Optimization (PSO) | *** | Minimizing the net annual cost | L (2.3 kWh), PV (2.65 kW), WT (2.01 kW), BESS (14.86 kW), GD (3.6 kW) |
| [85] | Grid-connected | Modified Particle Swarm Optimization (MPSO) | Hierarchical Control | Minimize system costs | L (650 kW), PV (500 kW), BESS (30 kW), GD1 (200 kW), GD2 (200 kW), MT (65 kW) |
| [86] | Isolated | PSO | *** | Minimize installation costs and running costs | L, PV, WT, BESS, GD. |

*** represents that there is no information reported.

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