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A Literature Review of the Control Challenges of Distributed Energy Resources Based on Microgrids (MGs): Past, Present and Future

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Abstract: Different types of distributed generation (DG) units based on renewable and non-renewable energy sources can create a local energy system in microgrids. The widespread penetration of distributed energy resources (DERs) has affected many power system issues, such as the control and operation of these networks. For the optimal operation of microgrids, optimal energy planning and management in the new space governing the distribution system requires extensive research and analysis. Getting acquainted with the latest research about the evaluation of the problems and challenges in the design of control systems plays an important role in providing a guidance map for researchers to find the recent challenges and propose new solutions. This paper tried to list the challenges of distributed generation sources for MG applications, opportunities, and solutions. These challenges are reported in hierarchical control strategies and power-sharing categories. Therefore, Model Predictive Control (MPC)-based approaches are reviewed for different recent control levels and power sharing strategies in a comprehensive and simple point of view. The performance comparison of MPC methods together and different allocated fitness functions and implementation algorithms are dedicated. Another hand, the potential of MPC methods to control inverters for increasing the reliability of the grid, which this feature could not be achieved by using conventional strategies, while has not been investigated by researchers widely, is introduced in a short review. Therefore, this paper shows an intersection guidance map for readers to facilitate future research works in these exciting and undiscovered fields.

Keywords: model predictive control; distributed generation sources; power sharing; reliability

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1. Introduction

Energy sources that use fossil fuels to generate electricity always have a devastating effect on the environment, so the attention of distribution network planners has been attracted to the use of renewable energy sources [1]. On the other hand, the existing advances in technologies related to the connection of renewable energy sources to the grid have caused the distributed generation resources connected to the grid to be considered more than before. These distributed generation resources, if installed in the right place and in the right size, can include many economic and technical benefits, such as reducing power losses, improving power quality, improving reliability, eliminating distribution density and causing economic benefits for the power grid [2].

The fundamental difficulty in integrating renewable energy sources is their intermittent nature and unpredictability. Intermittent power means that distributed renewable generations cannot produce power continuously and change dramatically in the short term. Uncertainty means that it is very difficult to predict renewable energy sources [3]. Therefore, this situation may cause changes in energy losses and an unexpected droop or increase in voltage. Increasing the influence of these resources along with the random nature of their output power has created many challenges in the operation of distribution networks [4].

The injected power by distributed generations changes size and direction of power flow in distribution networks. In recent years, the integration of distributed renewable generations in distribution systems has received much attention. With penetration of distributed generation in distribution networks, the concept of smart grids was formed [5].

Distributed energy sources are a key element in the formation of smart grids. The large distribution systems can be subdivided into a set of microgrids to build control and operational infrastructure capabilities in future distribution systems [6]. These sources are crucial in the development of microgrids. One approach to maximizing the potential benefits of distributed renewable generations and energy storage batteries is to optimize their allocation and sizing in a distribution system [7]. In this situation, the integration of energy storage devices such as energy storage batteries in distribution networks is one of the possible solutions to facilitate the penetration of high levels of distributed renewable generations in power system [8].

According to their applicability in microgrids, distributed generation sources are divided into two major types [9]:

- Traditional sources, which consist of rotating units in which the connection interface to the network consists of electric machines;
- Resources that inject power into the network by power electronic devices.

The control and operation of resources, in which the interface with the microgrid consists of power electronic devices, are different from the sources of energy generation in which electric machines act as an interface. Thus, the dynamic behavior and control of a microgrid with a traditional grid will be different [10]. The existence of distributed generation sources in the distribution network has an influence on the network's current and voltage, which can have a positive or negative impact on system performance [11]. Its positive aspects include increasing reliability, improving power quality, improving voltage profile and reducing losses. On the other hand, the most important problem created by installing distributed generation sources in distribution networks is increasing the level of the short circuit [12].

The task of the power grid is not only to supply electricity to consumers with the lowest number of blackouts. The quality of power delivered to consumers along with providing high reliability, generating power from clean sources and reducing costs at various levels are of great importance [13]. Therefore, the idea of a microgrid to generate electrical energy from various types of energy sources was proposed. A microgrid can be considered as a part of a power system that includes one or more distributed generation that will not lose its functionality if separated from the system [14]. A grid-connected device for power storage can also be classified as a DER system, often referred to as a distributed energy storage system (DESS) [15]. Using an interface, DER systems can be managed and synchronized within an intelligent network [16].

The microgrid can be disconnected from the centralized network and operate independently, which makes the network more flexible and helps reduce network disruptions [17]. Microgrids are increasingly being utilized to combine distributed energy sources, such as hybrid solar energy systems, greatly lowering carbon emissions [18]. The distributed power supply systems are small-scale power generation or storage technologies (usually in the range of 1 to 10,000 kilowatts) that are used as an alternative or upgrading a traditional power system. The following are the benefits of employing distributed generation sources [19]:

- Decentralization of the generation system and transmission to consumption centers using small-scale generation units with more appropriate technical conditions, which generally depends on the level of penetration in the network;
- On-site load energy supply reduces transmission and distribution losses, leads to capacity liberalization and reduces transmission capacity in the development planning phase.

Despite all the advantages of distributed generation, one of its possible negative effects on the distribution network is voltage level and protection coordination issues. The DGs develops a network protection system, and as a result, the operation and control of the network will be difficult. With connecting the DGs to the network, harmonics are created in the network and short-circuit impedance is reduced as well. In the rest of this paper, the features and challenges of distributed energy resources in microgrids are reviewed in Section 2, then the hierarchical control methods are discussed in Section 3. In Section 4, the power sharing control strategies are presented. Section 5 is related to the presented solution in the literature based on MPC control strategies. Section 6 first provides an overview of microgrid reliability, then provides predictive control approaches to increase microgrid reliability. Challenges and future perspectives are followed in Section 7; finally, the conclusion section is presented in Section 8.

2. Distributed Energy Resources in Microgrids

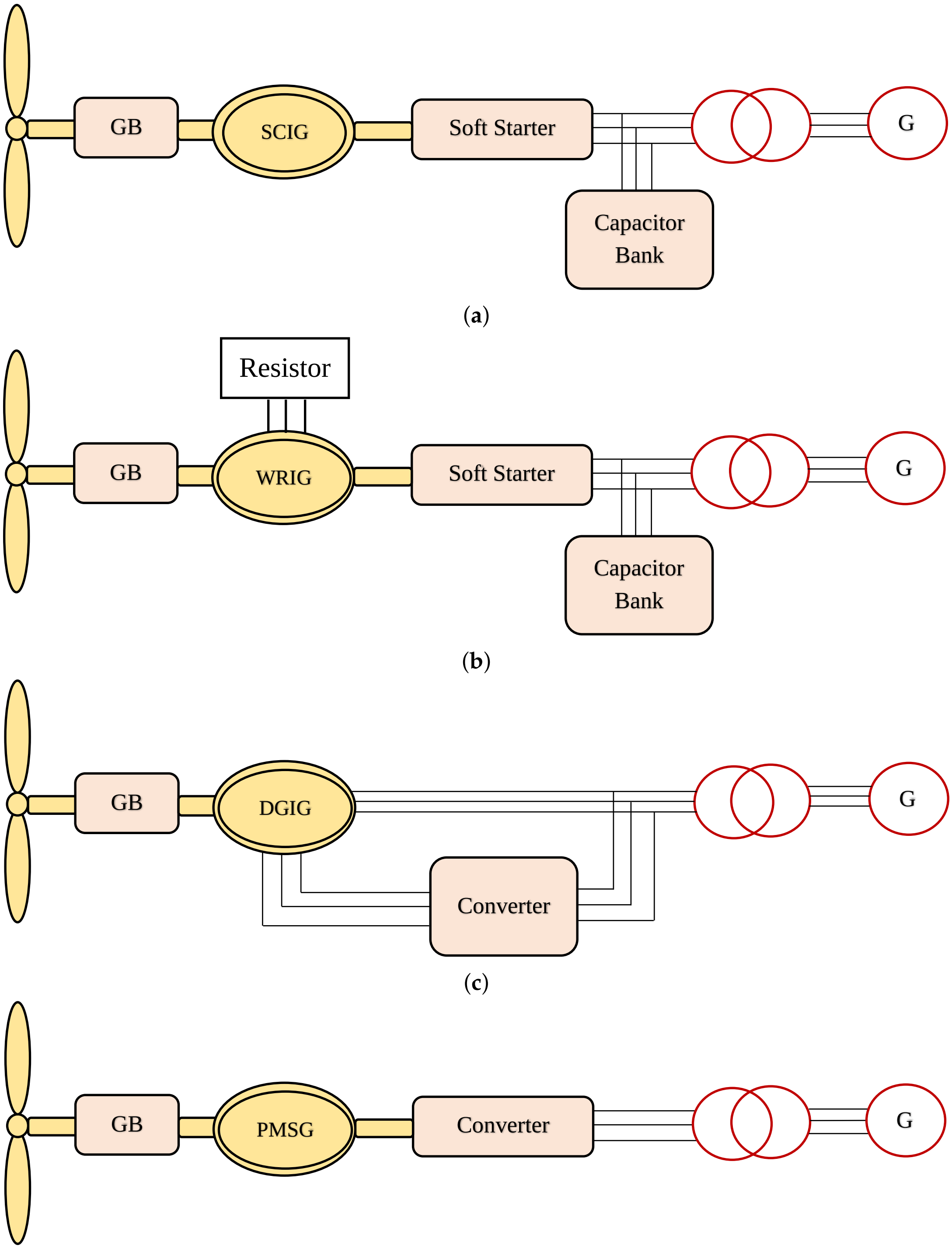
Any low-capacity energy generator of any type can be used in microgrids, which are divided into two main types [20]:

- Fossil fuel-based generators;
- Renewable energy-based generators.

Due to the small size of the network, diesel generators and gas microturbines are used in the microgrid, which are in the category of fossil fuel generators [21]. These units are of special importance in microgrids due to their high controllability in energy production, although they are considered as units for the production of environmental pollutants. The renewable generators, which are increasing their penetration in the power grids, are another type of generators that are of special importance due to their low or cheap fuel and their lack of environmental pollution. The most important of these units are wind turbines, solar cells and fuel cells [22]. Due to the unpredictability of the behavior of distributed generation sources, including wind turbines, solar cells and fuel cells, the frequency and power produced by these sources are variable and will not be able to connect directly to the main grid [23]. Therefore, in order to connect these sources to the power grid, power electronic converters with the ability to convert DC or AC voltage to desirable AC voltage will be required [24]. A power electronic converter can respond to rapid changes to control active and reactive powers and frequency control [25]. However, the use of DG units complicates the structure and poses challenges in the operation, control, stability, protection and security of power distribution networks [26]. Hence, new strategies have been proposed to connect these resources to the grid. According to these standards, whenever a fault occurs in the grid, the DG units are disconnected from the main grid and operate as an island [27]. However, in order to achieve the desired reliability and power quality, it is necessary to review these standards.

2.1. Wind Turbines

Nowadays, demand for renewable energy sources has increased significantly. Among renewable energies, wind energy is one of the most economical methods of generating electricity that does not pollute the environment. Wind generators are used in both stand-alone systems for powering remote loads and in grid-connected applications. The wind energy conversion system receives the wind energy from the wind turbine and converts it into electrical energy through a generator, which is available in two forms, fixed speed and variable speed. Due to the low energy production, stress in mechanical parts and low power quality, the fixed speed wind energy conversion systems have been replaced by variable speed energy conversion systems that reduce mechanical stress and aerodynamic noises. These systems can be controlled in such a way as to enable the turbine to operate at its maximum power factor under different wind conditions and receive maximum energy from the wind. Block diagrams of different types of wind turbines are shown in Figure 1 [28].



(**a**)

(**b**)

(**c**)

(**d**)

Figure 1. Block diagram of wind turbines. (**a**) Block diagram of squirrel cage induction generator. (**b**) Block diagram of wound rotor induction generator. (**c**) Block diagram of doubly-fed induction generator. (**d**) Block diagram of permanent magnetic synchronous generator.

2.2. Photovoltaic (PV) Generation Units

Photovoltaic systems for general and agricultural use operate in both connected and island operating modes. The advantage of moving systems is the ability to track the sun and increase the energy of the sun during the day. In grid-connected mode, the electrical energy from the photovoltaic system is injected into the main grid using the inverters while changing the shape and matching the voltage level and frequency of the electrical energy from the photovoltaic system. The use of photovoltaic power plants connected to the main grid in a centralized or decentralized manner (while amplifying the current energy in the distribution network), due to the injection of voltage and current, prevents the voltage drop of the distribution network. Block diagrams of photovoltaic solar cells are shown in Figure 2 [29,30].

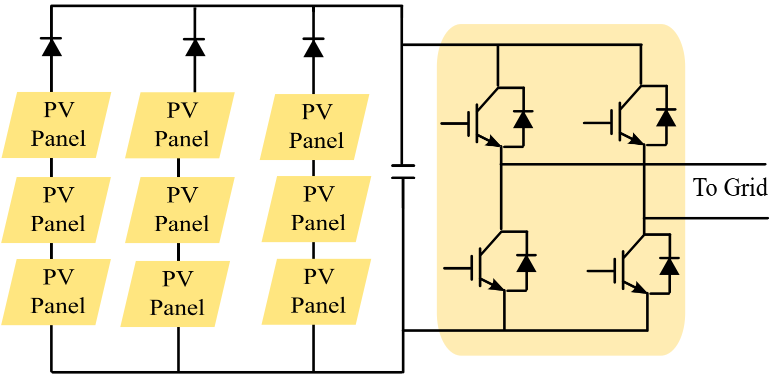


Figure 2. Basic diagram of photovoltaic solar cells.

2.3. Microturbines

Microturbines are small turbines that generate electricity using wind, water or various fuels, such as natural gas. Microturbines have more advantages than other small-scale technologies, some of which are fewer moving parts, compact size, light weight, higher efficiency, lower emission, lower power costs and use of wasted fuel [31].

2.4. Fuel Cells

Among the distributed energy sources, fuel cells have been highly regarded due to their high efficiency. In a fuel cell, the method of generating electricity is from the chemical reaction of hydrogen fuel and air oxygen. One of the characteristics of the fuel cell is its slow dynamics due to the chemical process [32].

2.5. Diesel Generators

A diesel generator is a combination of a diesel engine, a generator and various accessories such as chassis, control systems, emergency circuit breakers, heat generating system, automatic start system, etc. that are used to generate electricity. Diesel generators have lower initial costs, easier maintenance and shorter turning times than small turbines. The production capacity of a diesel generator depends only on the amount of fuel. The relationship between fuel content and diesel generator output power can be modeled as a linear relationship [33].

2.6. Batteries

Rechargeable batteries belong to the group of electrochemical cells that store electrical energy. These types of cells are called secondary cells, because electrochemical reactions occur reversibly in them. Rechargeable batteries exist in a range of sizes and kinds, ranging from small button batteries to grid-connected megawatt batteries. Lead-acid, nickel-cadmium, nickel-metal, lithium-ion and lithium-ion-polymer are some of the most popular chemical compounds used in rechargeable batteries. Rechargeable batteries are less expensive than other disposable batteries and have less environmental impact. Some rechargeable batteries are produced and supplied in the same sizes as other batteries, except that they can be charged and reused. In grid energy storage applications, rechargeable batteries are used to balance the grid load when they want to inject electrical energy into the grid for use at peak times. New power grids, such as solar power, also use rechargeable batteries to store energy during the day and consume it at night [34,35].

2.7. Challenges and Limitations of Distributed Generation Resources

With penetration of distributed generation sources in the microgrid, the dynamics of the system are affected [36]. In this case, the analysis of the connection of distributed generation resources to the network becomes complicated, especially when it is necessary to analyze the types of distributed generation sources in the distribution network, which usually passes power in one direction [37]. Researchers and operators of microgrids face these challenges when distributed generation resources are widely used. Some of these challenges are [38,39]:

- Reverse power flow: Connecting distributed generation sources to the distribution network can cause power flow in the reverse direction, which causes faults in the detection of protection systems;
- Reactive power: Many types of distributed generation sources use asynchronous generators that cannot inject reactive power into the grid;
- System frequency: Deviation from the nominal frequency of the system occurs with an imbalance between production and consumption. Increasing distributed generation resources affect system frequency and complicate the control process;
- Voltage levels: Distributed generation sources change the voltage level of feeders due to changes in the direction of the load distribution.
- Protection: The structure of most distribution networks is radial. This causes the load to be distributed unilaterally and the corresponding protection systems to be designed accordingly;
- Harmonic injection into the grid by distributed generation sources that are connected to the grid by an inverter. Short-circuit faults increase with respect to the location of distributed generation sources;

3. Hierarchical Control of Microgrid

Hierarchical control of microgrids has been proposed in several studies. The overall microgrid control structures are in three levels that each have specific objectives, and different methods for their operation have been proposed and controller of each level must be calculated and designed. Figure 3 shows the hierarchical control of the microgrid [40,41].

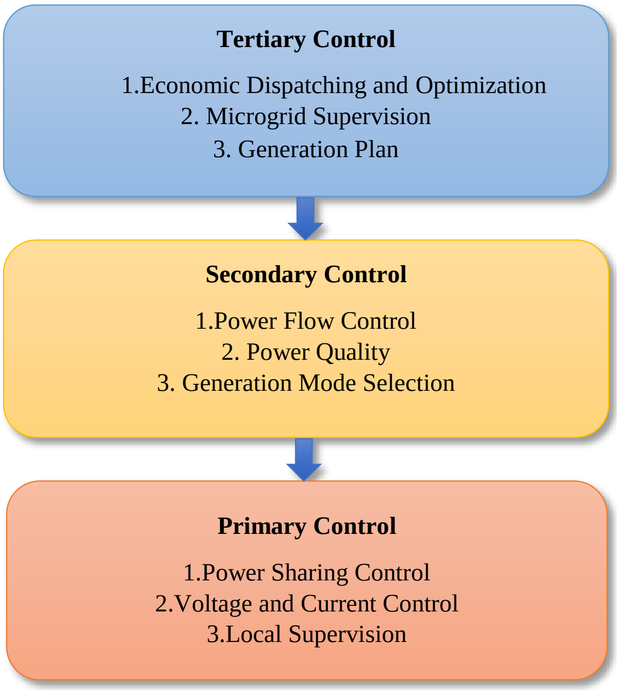


Figure 3. The hierarchical control strategy.

3.1. Microgrid Primary Control

The main controller is in charge of ensuring the reliability of the microgrid system as well as increasing the performance and stability of each converter's local voltage control system. This control level also regulates the reference voltage required for the internal voltage and current loops so that the distribution of active and reactive powers between the distributed generation sources is done optimally. The most common method for the primary controller is droop control, which aims to compensate for the mismatch between the generated power and demand. Based on this requirement, the droop control generates a reference voltage signal for the source and then the internal control loop (voltage and current) ensures that the actual voltage is equal to its reference value. In reality, in grid-connected mode, the primary controller of a microgrid regulates the active and reactive powers of each DG unit, as well as the voltage and frequency in island mode [42–44]. Various approaches to primary control have been proposed, especially for the inverter voltage source interface of distributed energy sources [45]. Most of these approaches use an inner/outer control loop based on the PI controller [46]. In [47], an intelligent load strategy based on a three-phase-single-phase AC-DC converter is proposed as a virtual synchronous machine to reduce frequency fluctuations in the island microgrid. This approach can also carry out grid support operations. By increasing the sources of distributed generation in a microgrid, the inertia of the system decreases, In case of load changes or generation loss, the primary frequency controller faces the problem of high-frequency change rate. A new way to increase system inertia is to use solid-state transformers as virtual synchronous machines in island operation mode. The solid state transformers can play an effective role in improving the island microgrid frequency [48]. Several studies have evaluated the role of electric vehicles in regulating the primary frequency of microgrids; with the penetration of electric vehicles in microgrids, the load profile will change significantly. The authors in [49] illustrated that the high penetration of electric vehicles can have a significant effect on reducing the primary frequency fluctuations in microgrids. In [50], an adaptive droop controller for optimal power distribution in the DC microgrid is presented. The problem of economic distribution of microgrids has been proposed by distributed hierarchical control. The droop controller receives the reference values from the economic regulator and provides the desired output power while maintaining system stability. The conventional droop control method is a decentralized method that is mostly used to control parallel-connected converters in the DC microgrid. One of the disadvantages of the conventional droop control method is incorrect power sharing and voltage deviation in the DC bus [51]. The small signal stability in a hybrid microgrid has been analyzed by considering changes in renewable energy sources. Due to the fact that the wind speed fluctuates, the active output power of the DGs will change significantly, and as a result, power sharing will also change. A suitable power sharing strategy is provided to manage the fluctuations of energy sources that regulate the voltage and frequency of each DG [52].

3.2. Microgrid Secondary Control

A centralized control strategy is proposed for distributed multipurpose inverters that allows the detection of adverse current components. It also allows the inverter to monitor and measure the desired values through the Internet protocol [53]. With the increase of renewable energy sources and due to its oscillating nature, the separation of secondary and tertiary control levels has negative effects on the overall efficiency of the microgrid. An optimal and robust control strategy for the secondary control level and the distributed MPC approach are proposed to solve the optimization problem [54]. The secondary controller, also known as a microgrid energy management system, is used to ensure the reliability, economics and safety operation of microgrids in both grid-connected and island modes. This level of control is important when the microgrid with the presence of distributed energy sources enters the island mode. This level of control can include a synchronization control loop. It also intervenes when the primary control is not able to return the frequency to the desired values and returns the system frequency values to the reference values [55]. In general, the secondary controller will be responsible for recovering the frequency deviation and voltage range. Furthermore, this control level provides network connection conditions for the microgrid when synchronizing. Many control systems have been proposed for this level of control, which may be grouped into three categories: distributed, centralized and decentralized [56]. The microgrid controllers in the centralized method are based on the same internal loop controllers. In this method, there is a central microgrid controller called MGCC (Microgrid Cenral Control), which allows each DG to communicate with the distribution management system. This type of control is used for small microgrids that are manually controlled. In fact, the definition of centralized and decentralized control for secondary control is based on the status of the MGCC [57]. In centralized control, the frequency and voltage amplitude of DGs are compared with the reference values received from the main grid (in grid-connected mode) [58]. The advantage of this control structure is that due to the fact that the message transmission path is one-way, the telecommunication system does not suffer from high traffic, but the disadvantage of this method is the existence of a central controller, which if it malfunctions can cause the system to also be affected. In order to connect the microgrid to the main grid, the voltage and frequency of the network must be measured [59]. These values are used as a secondary control reference. Furthermore, the phase angle between the microgrid and the main grid must be synchronized using the synchronization control loop. The consensus-based secondary frequency control is provided for islanded microgrids under weak communication conditions. In this research, to reduce the effects of weak communication conditions, a new approach with time-varying control gain is proposed [60]. A distributed secondary control approach is proposed to distribute power and voltage restoration in island mode, which, unlike other secondary controller methods, is based on the idea of feedback, and only by knowing the voltage of each bus, can the secondary controller be designed for each DG [61]. The authors of [62] proposed a method for island mode of inverter-based microgrids. The proposed method is able to predict system dynamics at high and low frequencies. The wireless power sharing approach is proposed for DGs and converts the output impedance of the inverter to the pure impedance by adjusting the virtual impedance. Table 1 summarizes the advantages and disadvantages of control strategies.

Table 1. Advantages and disadvantages of control strategies.

Control Structure	Control Approach	Advantages	Disadvantages	Application	Ref
Primary Control	Adaptive droop control	Reduction of rotational current between parallel inverters	Resistances between converter terminals must be specified	DC/DC converter	[50]
	Conventional droop	Simple and easy to implement, quick response	Unsuitable power sharing and stability	DC system	[51]
	Dynamic droop control	Suitable power sharing and stability	Slow response, complex to implement	AC system	[52]
Secondary Control	Centralized control	System controllability	Occurs in the current sharing bus, the output voltage will drop	Cluster of MGs	[53]
	Distributed control	Suitable for short transmission lines, accurate load sharing	Unsuitable for long transmission lines, security	DC/DC converter	[54]

3.3. Microgrid Tertiary Control

The purpose of this control layer is to manage the microgrid power flow in the grid-connected mode by adjusting the voltage and frequency, which is done by the secondary controller. By measuring the P/Q ratio at the Point of Common Coupling (PCC), the active and reactive powers of the grid can be compared with the desired reference values. This level of control is the last level and the slowest in terms of response. In fact, tertiary control consists of the optimal operation of the microgrid in the economic and technical sectors.

Technically, if there is an error or unplanned islanding in the microgrid, the third-party control tries to absorb the active power from the grid, so that if the main grid is not available, the frequency will be reduced. It is noteworthy that depending on the allocation of active and reactive powers values, the distribution of active and reactive powers can be from the microgrid to the main grid or vice versa [63]. Table 2 evaluates the performance modes of microgrids [64].

Table 2. Comparison of microgrid performance modes [64].

Parameters	Sensitivity to Load Fluctuations	The Complexity of Control	Objective of Control	Control Strategy
Grid-Connected Mode	Low sensitivity due to better performance as a fixed source	Easy	PQ	P-Q Control
Island Mode	High sensitivity to load fluctuation due to low inertia	Complex	VF	V-F Control

4. Power Sharing Theory

In order to investigate the distribution of active and reactive powers by distributed generation sources and power distribution equations, the equivalent circuit of a distributed generation source is considered according to Figure 4. In this equivalent circuit, the distributed generation source is modeled with an alternating voltage source that is connected to the ac bus via a Z-impedance supply line and supplies the load. The power transferred from the distributed generation source to the ac bus is as follows:

$$S = P + jQ \tag{1}$$

$$S = \bar{E}I^{*} = E\angle\left[\frac{E}{Z}\angle(\theta-\delta) - \frac{V}{Z}\angle\theta\right] = \frac{E^{2}}{Z}\angle\theta - \frac{EV}{Z}\angle(\theta+\delta) \tag{2}$$

$$P = \frac{E^{2}}{Z}Cos\theta - \frac{EV}{Z}Cos(\theta+\delta) = \frac{(E^{2} - EVCos\delta)Cos\theta}{Z} + \frac{EVsin\theta sin\delta}{Z} \tag{3}$$

$$Q = \frac{E^{2}}{Z}Sin\theta - \frac{EV}{Z}Sin(\theta+\delta) = \frac{(E^{2} - EVCos\delta)Sin\theta}{Z} - \frac{EVsin\theta sin\delta}{Z} \tag{4}$$

In which S, P and Q are apparent power, active and reactive powers transmitted to the load, respectively, E and V are inverter output voltage amplitude and AC bus and δ, Z and θ are load angle, line impedance amplitude and phase, respectively. Table 3 shows the general equations of droop and power sharing based on different impedance angles according to Equations (1)–(4).

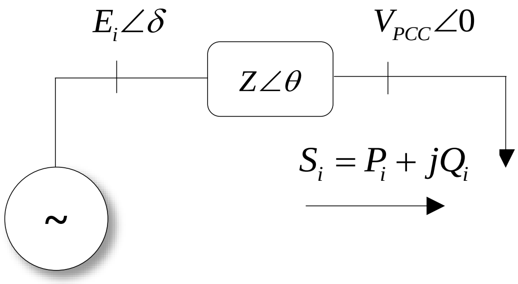


Figure 4. Single line diagram of power system [65].

According to the equations of active and reactive powers distribution (3) and (4), the line impedance is proportional with the inverse power distribution, i.e., $P \propto \frac{1}{Z}, Q \propto \frac{1}{Z}$. This means that in the high line impedance, the amount of power transmitted to the load will be lower [66]:

$$P = \frac{(E^{2} - EVCos\delta)Cos\theta}{Z} + \frac{EVsin\theta sin\delta}{Z} \tag{5}$$

$$Q = \frac{(E^2 - EVCos\delta)Sin\theta}{Z} - \frac{EVsin\theta sin\delta}{Z} \quad (6)$$

Therefore, the output power of each unit can be controlled by controlling the line impedance.

Table 3. Power sharing and droop equations [65].

Line Impedance Type	Line Impedance Angle	Power Equation	Droop Equation
L	$\theta_i = 90^\circ$	$P_i = \frac{E_i V_{PCC} Sin\delta_i}{X_i}$ $Q_i = \frac{E_i^2 - E_i V_{PCC} Cos\delta_i}{X_i}$	$f_i^* = f_0 - k_{pi}P_i$ $E_i^* = E_0 - k_{qi}Q_i$
RL	$0^\circ < \theta_i < 90^\circ$	$P_i = \frac{E_i^2 Cos\theta_i - E_i V_{PCC} Cos(\theta_i + \delta_i)}{Z_i}$ $Q_i = \frac{E_i^2 Sin\theta_i - E_i V_{PCC} Cos(\theta_i + \delta_i)}{Z_i}$	$f_i^* = f_0 - k_{pi}P_i + k_{qi}Q_i$ $E_i^* = E_0 - k_{pi}P_i - k_{qi}Q_i$
R	$\theta_i = 0^\circ$	$P_i = \frac{E_i^2 - E_i V_{PCC} Cos\delta_i}{R_i}$ $Q_i = -\frac{E_i V_{PCC} Sin\delta_i}{R_i}$	$f_i^* = f_0 + k_{qi}Q_i$ $E_i^* = E_0 - k_{pi}P_i$
RC	$90^\circ < \theta_i < 0^\circ$	$P_i = \frac{E_i^2 Cos\theta_i - E_i V_{PCC} Cos(\theta_i + \delta_i)}{Z_i}$ $Q_i = \frac{E_i^2 Sin\theta_i - E_i V_{PCC} Sin(\theta_i + \delta_i)}{Z_i}$	$f_i^* = f_0 + k_{pi}P_i + k_{qi}Q_i$ $E_i^* = E_0 - k_{pi}P_i + k_{qi}Q_i$
C	$\theta_i = -90^\circ$	$P_i = -\frac{E_i V_{PCC} Sin\delta_i}{X_i}$ $Q_i = -\frac{E_i^2 - E_i V_{PCC} Cos\delta_i}{X_i}$	$f_i^* = f_0 + k_{pi}P_i$ $E_i^* = E_0 + k_{qi}Q_i$

Control Strategies for Power Sharing

One of the most important and challenging issues in the control of island microgrids is the control of power sharing among distributed generation sources, so that each unit must feed the load in proportion to its nominal value. The main purpose of power sharing is to increase the network capacity to meet power demand. Power sharing among distributed generation units is one of the most important challenges; lack of power sharing among them leads to unequal load sharing, which may damage the load and often leads to instability. Various methods have been proposed to control the power sharing in microgrids, one of the most famous of which is the droop control method. The droop control method is a decentralized control method that uses local control signals such as frequency and voltage to control power sharing in microgrids. In the droop control method, active and reactive powers, frequency and voltage amplitude of distributed generation sources are the control variables that are used to share power [67,68].

In microgrids with a large amount of reactance to resistance ratio (X/R), due to the relationship between active power and frequency, as well as the relationship between reactive power and voltage, the conventional droop control method is used. However, in low voltage microgrids, due to the small ratio of reactance to line resistance, there is a resistance connection between the inverters, and therefore, the active power depends on the voltage and the reactive power depends on the frequency. In island microgrids with inverter-based distributed generation sources, mismatching the impedance of the supply lines leads to a voltage difference between the inverter terminals, which can cause a rotational current between inverters and over-current in the distributed generation sources. In order to solve the challenges in microgrids, including the dependence of active and reactive powers on low voltage microgrids by the distributed generation sources in the microgrids, as well as the rotational current between these sources, various methods, such as the virtual power method, voltage method and virtual frequency and virtual impedance methods, are proposed. Figure 5 shows the challenges and proposed solutions [69–78].

A network-based power sharing strategy under unknown impedance is presented [79–81]. This improved strategy can provide acceptable power sharing while keeping the steady-state frequency constant. In addition, it improves microgrid dynamic performance and power sharing errors under unknown impedance. Network-based active power sharing strategies have been proposed in previous research [82–84]. However, there are two main drawbacks: (1) Due to the presence of voltage and frequency droop loops, the frequency droop cannot be eliminated. (2) Communication delays under the uncertainties parameters increase system sensitivity. In microgrids, the virtual impedance method was used to eliminate the dependence of active and reactive powers between power supplies that were connected directly to the PCC in microgrids through resistance lines [85,86]. Virtual impedance has been proposed to stabilize the line impedance of distributed generation sources to improve the power sharing performance by droop control method [87], which can be placed in the inverter output without a physical connection. By implementing virtual impedance in the controller of the distributed generation unit, the line-equivalent impedance can be divided into two parts: physical impedance and virtual impedance. When virtual impedance is considered, the distributed output source can be considered as a voltage droop source controlled by the droop method in series with the virtual impedance [88]. Table 4 shows the challenges of active power sharing for different types of control strategies.

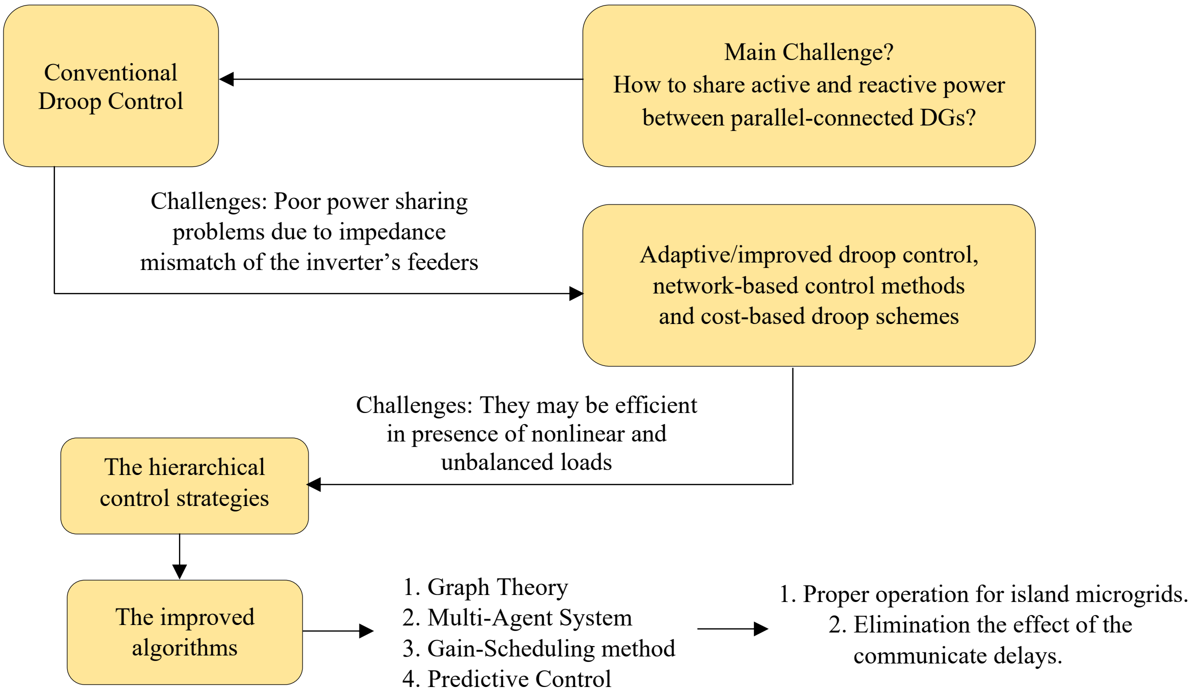


Figure 5. Challenges and proposed solutions.

Table 4. Active power sharing strategies.

Methods	Challenges	Ref.
Under an inductive/resistive feeder impedance condition	1. Sensitivity to communication delays. 2. Failure of recovery of frequency drop in the presence of complex control loop.	[69–78]
Under an unknown impedance condition	1. No proportional active power sharing. 2. Not considering total cost of generation.	[79–81]
Proportional active power sharing strategies	1. Sensitivity to communication delays. 2. Not suitable for complex MG.	[82–84]

Virtual impedance is used for various purposes, such as independent control of active and reactive powers, the realization of proper power sharing, increasing power transmission capacity, etc. [89]. Therefore, if the virtual impedance is properly designed and controlled, it can have a significant impact on improving the performance of control methods by reducing the dependence of power distribution on line impedance. In order to facilitate the use of the conventional droop control method in microgrids and to solve the problem of line impedance mismatch, a virtual and physical impedance interface inductor is considered to reduce the dependence of active and reactive power sharing as well as to stabilize the output impedance [90,91].

5. Control Approaches Based on MPC

The basic idea of model predictive control or Receding Horizon Control (RHC) was introduced in the 1960s and then in the 1970s in industrial control applications, especially in the chemical industry. Then, this control approach entered the academic and research space and was welcomed by researchers. Various papers have described and compared the types of predictive controllers well. MPC is an intuitive method for systems that have constraints. This fact demonstrates why predictive controllers are so popular among other controller types. In general, the predictive controller sends the appropriate control signal to the converter by minimizing the cost function that provides the proper behavior of the system. For each sampling time, MPC calculates a series of control signals that minimize the cost function, with this description that the first signal is applied to the converter [92]. Table 5 shows some cost functions for power electronics applications.

Table 5. Example of cost functions for power electronic applications.

Strategy	Cost Function	Ref
FCS-MPC	$g = \lvert i_{\alpha}^{*}(k+1) - i_{\alpha}^{p}(k+1)\rvert + \lvert i_{\beta}^{*}(k+1) - i_{\beta}^{p}(k+1)\rvert + \lambda n_{sw}$	[93]
CSC-AFE	$g = (q)^2 + \lambda(\hat{i}_L - i_L^{*})^2$	[94]
VSC-AFE	$g = \lvert \hat{i}_k - i_k^{*}\rvert$	[95]
Motor drive	$g = (T - T^{*})^2 + \lambda(\hat{\phi} - \phi^{*})^2$	[96]
MPDPC	$g = \lvert P^{*} - P^{k+1}\rvert^2 + \lvert Q^{*} - Q^{k+1}\rvert^2$	[97]

In recent years, widespread research has been done on microgrid control systems. In small-scale microgrids, the most important issue is to attain reliable performance, balancing supply and demand, while in other structures, optimal performance is required. Several types of research have been performed using the hysteresis band control method to energy management due to the simplicity of the structure and its implementation. On the other hand, predictive controllers have found a wide range of applications in the field of power electronics and drives, also minimizing the cost function by solving optimization problems while considering technical constraints [98].

The predictive controller is very suitable for electronic power converters and drives due to its fast dynamic response. Some of the features that make predictive control a suitable method to microgrids are as follows [99]:

- It is equipped with a feedback system that enables it to cope with uncertainty and disturbances;
- It may take into account prediction for both consumption and production;
- Its basic principles are based on the futuristic behavior of the system that rely on the demand and production of renewable energy;
- The multivariate structure of the predictive controller can manage the performance of microgrid units in a coordinated manner since coordination between diverse sources of renewable energy or energy storage systems in a microgrid is particularly challenging;
- When a disconnection or failure of one of the generation units occurs in a microgrid, the predictive controller can adapt to the current situation and provide safe operation for the entire system.

In modern industrial control, the model predictive control method is used for many industrial applications. These methods can be divided into two categories: 1. Finite control set MPC (FCS-MPC), which uses the advantage of limiting the number of switching possibilities to optimize the problem; 2. Continuous control set MPC (CCS-MPC), which requires a modulator to generate switching pulses according to the control system settings [100].

As we know, in a converter, the switches can only be switched on and off in two states, and their combination creates a limited number of different states. Using this inherent feature, the converter switching model can be easily presented and the prediction can be summarized only in the limited situations mentioned. The main elements of this control schemes are the mathematical model of the system and the predefined cost function. One of the most important advantages of FCS-MPC is its simplicity. The operation of this controller is that first, the system variables are measured or estimated, then the system model is extracted and discretized according to the controlled variable, which can be current, voltage and power. By discretizing the system model and knowing the value of current variables, controlled variables can be predicted in future times [101]. Table 6 provides a general classification of MPC approaches.

Table 6. General classification of the MPC approaches.

Microgrid Based on MPC	
Predictive model	Dynamic of converters and RLC circuits, topology features, forecast, dynamic of DGs, ESSs, local demand
Control scheme	Centralized Decentralized Distributed/hierarchical
Objectives in cost function	Converter outputs: voltage, current, active power reactive power, circulating currents, Compensation of frequency and voltage
Control parameters	Voltage, frequency, active/reactive power
Solving algorithm	Exhaustive search (FCS-MPC, CCS-MPC) Specific toolbox and solver

All predictive control strategies are based on solving an optimization problem so that it can select the appropriate control signal and apply to power electronic converter. Cost functions also define the appropriate behavior for the system. Thus, cost functions can be complex depending on what type of variable is considered.

5.1. MPC-Based Primary Control

In [102], the FCS-MPC approach is proposed as the primary control layer to control the output power of each DGs (grid-connected mode) and the voltage regulate in PCC (in island mode). In the grid-connected mode, the Direct Power Model Predictive Control approach (DPMPC) is applied to manage the power sharing between each DG and the grid, and in island mode, Voltage Model Predictive Control (VMPC) approach is provided as a droop control and secondary to adjust the output voltage of DGs. In [103], a research on the design of predictive controller based on discrete time model for voltage control in island microgrids is presented. In this research, several distributed generation units are connected in parallel to build a microgrid. The purpose of the controller design is to control the mains voltage on different loads. The design of this controller is done using a discrete-time function that provides extensive microgrid tracking function; the controller is for a single-phase microgrid design. The performance of this controller has been tested in various ways. This controller offers acceptable performance in microgrids against the dynamics of different loads and shows better tracking performance.

In the reference [104], a study on the method of controlling multiple photovoltaic systems in a DC microgrid using a predictive controller is presented. Direct current microgrid sys- tems are beneficial due to higher efficiency, reliability and easier connection of renewable energy sources compared to AC microgrid systems. The finite set of predictive control models is a robust control technique that predicts the future behavior of the system in a number of arbitrary sampling steps over the time horizon, based on a set of possible control operators [105]. The proposed predictive controller for DC microgrids includes maximum power point tracking and bidirectional DC-DC converter control to evacuate the battery power storage system. Using predictive controller features with the ability to add design constraints, the proposed system ensures maximum output power from the PV system due to the battery SoC. The controller increases the speed of the control loop because it increases the prediction and correction of the error before the switching signal is applied to the DC-DC converters. In [106], a MPC-based VSG control structure is proposed for the primary controller for voltage control and power sharing, i.e., firstly this predictive controller is applied to the inner loop, which provides a faster dynamic response as well as increased bandwidth and stability; then, a VSG has been proposed to proper power sharing in an outer loop, and a comprehensive comparison between the proposed control structure and the conventional structures is presented in Table 7.

Table 7. Comparison of control strategies.

Control Type	Advantages	Ref
DMPC	It has the benefits of MPC. Compatibility of constraints and good optimization performance. Flexibility distribution framework. There is also fault tolerance, connection and execution in the network.	[102]
MPC	Ensures maximum output power from the PV system. The controller increases the speed of the control loop. Increases error prediction and correction before the switching signal is applied to DC/DC converters.	[103]
MPC	Has the ability to predict the future behavior of the system. The proposed technique is able to cope with the limitations that often occur in practice. The predictive controller uses current system measurement, current system dynamics, target process variables and future event calculations that are rarely considered in other control techniques. This control uses the proposed cost function, which ensures high tracking performance of the microgrid system.	[104]
Droop	Frequency return under optimal active power control. The voltage restoration and power sharing reactive simultaneously. Select a critical path for voltage restoration or accurate reactive power sharing with AC side voltage limitation.	[105]
Droop	The voltage controller is fully centralized at the initial level and no digital communication is required. The design method is scalable. The controller ensures the stability of the overall microgrid system. The stable performance of the microgrid system is in accordance with IEEE standards. The controller provides control power according to load changes and microgrid structure.	[106]

5.2. MPC-Based Secondary Control

In [107], a unified model predictive voltage and current control (UMPVIC) strategy is presented for both grid-connected mode and island mode, which can be flexibly applied in the primary control layer for proper load sharing and in the tertiary layer for power flow. A fuzzy control algorithm is proposed to reduce the voltage and frequency deviations caused by the primary droop layer. This fuzzy controller can optimize secondary layer coefficients to improve voltage quality. The dynamic response of converters is much faster than the frequency load. Usually, the droop control method is used to share the active and reactive powers of microgrids. The disadvantages of this method are the deviation of voltage and frequency from its nominal value in the steady state. A distributed secondary controller based on the prediction model with a state space approach is proposed to return the voltage and frequency of the microgrids. Therefore, a secondary controller is provided to eliminate voltage and frequency deviations, and the performance of the proposed method is evaluated by evaluating it under a feeder impedance that is inconsistent with balanced and unbalanced linear load conditions [108]. A distributed model predictive control strategy based on voltage observer for multiple energy storage systems is proposed. In order to reduce the effects of communication delay on the voltage observer, an improved distributed predictive control algorithm is proposed. This proposed scheme strengthens the delayed system. A small-signal dynamic model with a predictive controller is used to analyze the dynamic performance [109].

6. Fault Tolerant of Microgrids

Assessing the reliability of the distribution system is one of the most important studies for power system operators and planners. Existing distribution networks are designed to be powered on one side, but with the presence of distributed energy resources, it is possible to transfer power from both sides. In other words, power may be transferred from the distribution network to the transmission network. For this reason, conventional risk management methods will not be used to calculate the reliability of this type of network, and researchers are looking for new solutions to calculate the reliability of this type of network. Reliability is predicted based on expected performance; in other words, performance without failure. Increasing the use of power generation units using renewable energy in microgrids has led to attention to the reliability of these systems. Since such distributed generation sources have a lot of uncertainty, necessary measures should be considered to provide sustainable power to the consumer [110,111].

Recently, the predictive control method of the model has found increasing interest among researchers in the field of reliability. In [112], a combined method of dynamic planning based on predictive control is presented. In [113], a predictive-based approach is proposed for the management of grid-connected photovoltaic power generation. In [114], a microgrid scheduling method based on MPC is proposed to increase the flexibility of distribution networks. A robust MPC-based two-layer model has been developed considering the worst case scenario for microgrids. It is shown that the proposed solution can ensure the reliability and feasibility of microgrids in the presence of uncertainties. A microgrid power management framework that is connected to the grid via a transformer and contains a local consumer, a wind turbine and an energy storage system is provided to minimize costs based on optimal battery planning. The model predictive control approach has been used to improve power, cost and production in the presence of uncertainties [115]. In [116], a predictive control algorithm is proposed to solve the problem of economic optimization in the presence of distributed generation sources.

7. Challenges and Future Perspectives

Among different types of microgrids, DC microgrids have problems in the field of power quality and one of the important obstacles to the development of this type of microgrids is limited DC loads. Therefore, with the development of technologies, it is expected that DC loads will be more compatible. On the other hand, due to the high cost of energy storage systems in AC microgrids, such advances in technology can make these systems more cost-effective. Since the issue of power quality and grid stability are the most important issues in the field of microgrids, with the widespread penetration of renewable energy sources in microgrids, more efforts should be made in this area [117].

An integrated distributed planning model can provide an effective solution for balancing the efficiency and allocation of costs of DERs. Among the items that can play an important role include [118]:

- Improving connection cost estimates can develop an integrated planning model for energy resources to make photovoltaic system equipment installation more efficient;

- Estimating and predicting more accurate, robust economic distribution of distributed generation resources can help reduce the risk of recovering potential future costs due to uncertainty in the future development of distributed generation resources.

Accurate forecasts of distributed energy sources are of particular importance in the long-term planning of distribution and transmission. In both over and under forecasting, the transmission line in turn can have special consequences for the system. In other words, if this forecast is done too much, the reliability and flexibility of the system will be affected. In case of under forecasting, unnecessary generation distribution resources can be added.

The two forecast methodologies for future distributed energy sources are shown in Table 8. Top-down approaches provide a significant improvement in data and methodological complexity. Time series, econometric and bass diffusion models are among the top-down models that have been employed to anticipate DER adoption. Time-series models extrapolate historical, cyclic data to future outcomes. Econometric models are statistical models that are used to explain observable data and can be expressed in a variety of ways. The most often utilized strategy for forecasting DER adoption is the use of bass diffusion models.

Table 8. Methods used for DER forecasting [118].

	Top-Down			**Bottom-Up**
	Time Series	**Econometric**	**Bass Diffusion**	
Prospective	Simple, easy to estimate and validate	High familiarity and use in other domains	Easy to specify	Modeling unique attributes of consumers
Consequence	Lack of expression of technical restrictions	Prediction aggregate adoption than feeder level is better	Sensitive to transient market effects	Requires computational investment resources

8. Conclusions

Microgrids are a modern concept for the future of energy systems that have made it possible to use renewable energy and require electrical and control structures and equipment for optimal performance. One of the most important and fundamental issues in microgrids are how to control distributed generation sources to supply local load. Since most distributed generation sources are connected to the grid by electronic power converters, appropriate methods must be used to control electronic power converters to ensure the microgrid's economic performance. The purpose of this research is to review what has been done so far about energy source-based microgrids in the literature. Hierarchical control structures are expressed and its control method is evaluated. The MPC play an important role in microgrid performance and system reliability. Therefore, a review of MPC-based control structures and following that a comparison between its control strategies are performed.

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