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Control of Microgrid – A Review

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Abstract The growing demand for energy and climate change, which has led to an increase in carbon dioxide in the atmosphere over the past few decades, are behind the progress made in renewable energy technologies. In addition, in most remote areas, solar photovoltaic, wind and diesel are generally the main sources of electricity. However, the integration of these distributed generations into the grid has had negative effects on the existing grid and its interconnected operation. One solution to this problem is the micro-grid concept that will make the existing grid suitable for increased integration of renewable energy sources. One of the factors limiting the use of renewable energy (solar, wind) is the variability of resources. Load fluctuations according to annual, seasonal or daily periods are not necessarily correlated with resources. A control and management system is necessary to improve the efficiency and quality of the energy. Several researchers have presented various control strategies for the microgrid under different conditions. This article presents a review of the most discussed control strategies in the literature.

Keywords Microgrid, configurations, regulations control, optimizations control and supervisory control

Introduction

In recent decades, the use of distributed energy resources (DERs) has increased due to economic, technical and environmental concerns. Micro-grids have emerged as a potential solution for the integration of DERs in distribution networks operating in grid-connected mode [1]. Photovoltaic (PV) generation, as a commonly used DER, is expected to contribute to the stability of the grid by providing high quality services, quickly correcting disturbances to eliminate the effect on the inverter and the grid, beyond the basic electricity supply [1][2].

One of the limiting factors in the use of renewable energies (solar, wind) is the variability of resources. Fluctuations in load over annual, seasonal or daily periods are not necessarily correlated with resources. For isolated regions, the solution to be retained is certainly the coupling of several energy sources [3]. The production can be higher than the energy demand. This excess production must be stored if the system has storage systems. Otherwise, the system will have to have a load shedding load or a device limiting or stopping the production of renewable energy. In general, non-storage systems use a load shedding load to maintain energy balance and frequency stability. Other applications require additional control systems to maintain voltage quality. All of these devices, such as shedding loads and control systems, increase the capital cost that may not be justified by the benefits of the hybrid system. Only an adequate control strategy can optimally integrate different components and thus make the system cost-effective [4].

Asynchronous generators, widely used in wind turbines, require a large amount of reactive power, especially during the excitation phase (start-up). If there are not enough sources of reactive power in the hybrid system while one or more wind turbines are starting at the same time, the sudden increase in reactive power consumption causes voltage dips and the system stalls. Other sources of disturbances that can cause voltage dips are short circuits [4]. These can cause the collapse of hybrid systems. Another disturbance can lead to overvoltage problems, which is caused by short circuits, stopping a large load or connecting a capacitor bank. A major disadvantage in a hybrid system connected in an isolated three-phase network is the voltage unbalance between the phases. An unbalanced three-phase electrical receiver or unbalanced single-phase receivers fed from the isolated three-phase network can lead to voltage unbalances. These unbalances cause parasitic braking torques and additional heat build-up in rotating AC machines.

In this article, a bibliographical study on microgrid will be made. In order to do so, we will first review the differents configurations of micro-grids by giving their advantages and disadvantages. Then the optimal control algorithms, control techniques and supervision methods will be listed.

1. Configurations

The components of a microgrid can be connected in several ways, depending on the topology of the power electronics proposed. One option is to connect the sources to the load and to the grid via an AC bus, using an inverter for each source. This will increase the reliability of the system, as each source can operate independently of the other sources [5]. However, the overall cost of the system becomes important. Another option is to connect the sources to a direct current (DC) bus. Then, an inverter will be used to power the AC loads and connect to the grid. Recently, DC microgrids have also started to attract attention for many reasons, such as reduced power conversion, lower losses and controllability. In particular, some generators and loads are inherently DC, such as solar photovoltaic (PV), batteries, electric vehicles (EVs), etc., where a DC microgrid would integrate them more naturally and improve system efficiency and reliability [6]. Siddique and Yadav have chosen to work with the DC bus configuration, illustrated in Figure 1, with a PV (GPV) generator, wind turbine, battery as a component and can operate in grid connected or grid disconnected mode [5]. As well as [6], consisting of GPV, an electrochemical battery, a fuel cell and the system can operate in grid connected or stand-alone mode.

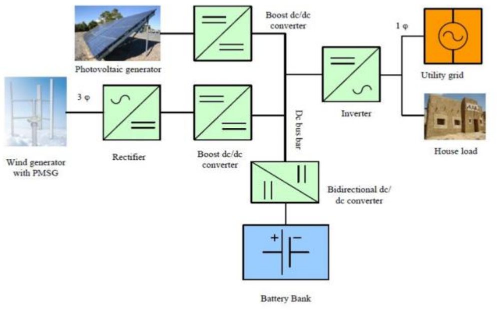

Figure 1: DC bus microgrid proposed by [5]

References [1][7] worked on a grid-connected PV system. In these articles, the PV generator is connected to the grid via a two-stage inverter (Figure 2). The same system is the subject of [8] but with asingle-stage inverter (Figure 3). Libo et al. see that with the two-stage inverter, two conversions are noted (DC-DC and DC-AC), which implies power losses [8]. A micro-grid composed of GPV, battery and a diesel generator is the object of the study of [9], the whole of which is connected to the AC bus. To meet the demand in an isolated area, [10] adds a wind turbine in the configuration proposed by [9] (Figure 4). [11] describes the power control strategies of a grid-connected photovoltaic and proton exchange membrane hybrid fuel cell distributed generation system with a battery as energy storage device. [12] works with a DC microgrid, consisting of GPV connected to the DC bus via a boost converter, a wind turbine with an AC-DC converter and a battery connected to the DC bus. [13] also adopts the same configuration except in its micro-grid, the battery is excluded.

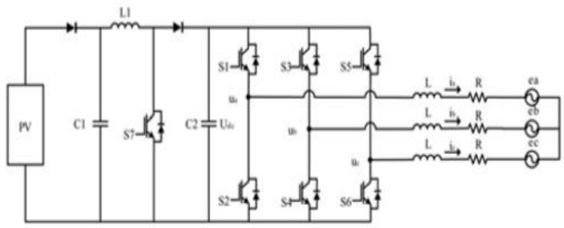

Figure 2: Grid-connected PV with two-stage inverter

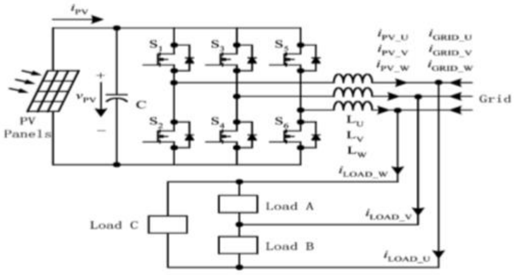

Figure 3: Grid-connected PV with a single-stage inverter

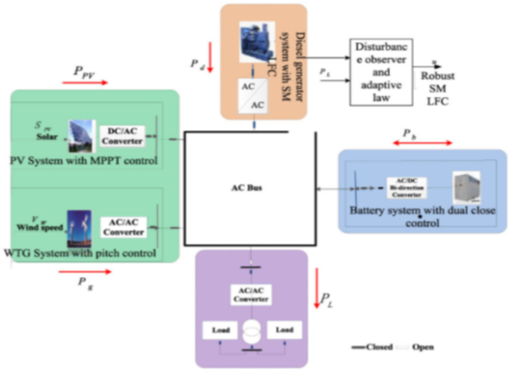

Figure 4: AC bus micro-grid proposed by [7]

[14] proposes a hybrid AC/DC microarray to limit multiple AC-DC-AC or DC-AC-DC conversions. In this microarray Liu and al. connect DC sources and loads to the DC bus while AC sources and loads to the AC bus and the energy transfer between the buses is provided by a bi-directional inverter. This configuration is shown inFigure 5. The system can have two modes of operation. In the grid connected mode, the inverter at the battery is not very important for the operation of the system because the energy is balanced by the power grid. But in stand-alone mode, the battery plays a very important role in both power balance and voltage stability. In reference [15] the same configuration is used. In the thesis [16], Boualam adopts the DC configuration of a system composed of GPV/Wind/Wind/Battery connected to the grid after having made a bibliographical study of the different configurations. [17], analyzes a micro-grid composed of GPV/Wind/Wind/Battery/Super capacitor, this system can operate either in grid-connected mode or in stand-alone mode. The author uses a hybrid AC/DC configuration because of its advantages.

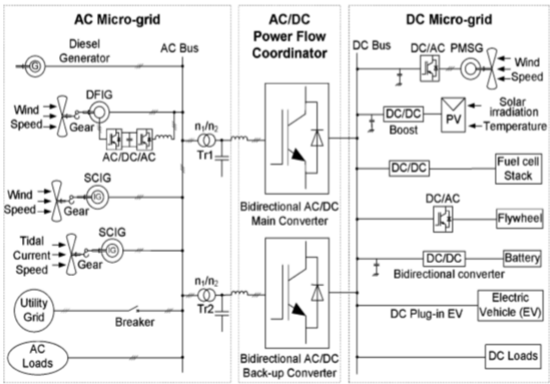

Figure 5: Hybrid AC/DC micro-grid proposed by [8]

Table 1: Advantages and disadvantages of a micro-grid proposed in [4]

Micro-grid	Advantages	Disadvantages
DC	▪ Possibility of direct use of production sources ; ▪ Low losses; ▪ Few equipments; ▪ Ease of extension ; ▪ Optimal diesel unit sizing, i.e. to operate at nominal power during the battery charging process up to a state of charge of 75-85 %.	▪ Requires the addition of an inverter or an increase in the power of the inverter in case of high demand ▪ High cost of DC switchgear and protection equipment. ▪ Loss of availability for AC in case of inverter failure ▪ The efficiency of the entire system is low.
AC	▪ Possibility to increase the AC voltage with a passive component (transformer) ▪ Equipment cheaper than direct current and easily available ▪ Possibility to use frequency as a means of adjustment	▪ Multiple power losses due to multiple converters ; ▪ Use of several converters (high cost of equipment) ; ▪ Use of several converters (high cost of equipment)
AC/DC	▪ Good yield ▪ Possibility to directly connect the AC load ▪ Less stress on the inverter ▪ Ability to supply loads from a large AC source ▪ Possibility of autonomous or parallel operation of the diesel generator and the inverter ▪ Possibility to reduce the nominal power of the diesel generator and the inverter without affecting the system's ability to supply peak loads.	▪ Decrease in fuel consumption efficiency ▪ Realization of this relatively complicated system due to parallel operation

2. Optimization commands

Power electronics is the key to improving PV panel efficiency and system stability in grid-connected PV systems. One of the tasks of power electronics converters is to continuously adapt the system so that it can draw maximum power from renewable generators, regardless of weather or load conditions. For this purpose, many MPPT methods are developed such as perturbation and observation (P&O), incremental conductance (Ind.Cond), Fuzzy Logic (FL), Artificial Neural Network (ANN) etc. The P&O method is the most widely used in the literature because of its simplicity of implementation, but it is less accurate [9]. In addition, when sunshine changes rapidly, the P&O method would probably not be able to track the maximum power point (MPP)[10]. The Ind.Cond method performs well in rapidly changing sunlight conditions. However, the high complexity of the method requires high sampling accuracy and fast testing speed, which increases the total system cost[9][10]. TheFigure 6summarizes the operation of the two algorithms. Thus, for an optimal operation, the objective of these two algorithms is to converge towards the point defined by:

- $\frac{dP_{pv}}{dV_{pv}} = 0$, For the P&O algorithm on the curve *Ppv(Vpv)* ;
- $\frac{\Delta i_{pv}}{\Delta V_{pv}} = \frac{-i_{pv}}{V_{pv}}$, For the Inc. Cond algorithm on the curve*Ipv(Vpv).*

The original P&O and Inc. Cond algorithms are constrained by the amplitude of the injected perturbations, which condition the importance of the oscillations around the PPM as well as the convergence time. To solve this problem, several algorithms based on the variation of the increment step are proposed in the literature [6][9][11][20]. Indeed, these solutions allow a faster convergence towards the PPM and reduce the oscillations around this point. Ramesh and al. proposed the improved incremental conductance (I-Inc) and a comparison was made with conventional methods (P&O, Inc.Cond) (Figure 7)

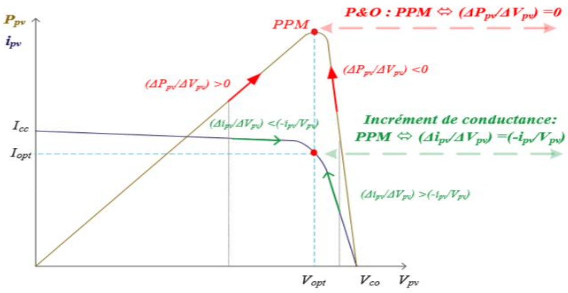

Figure 6: Principle and similarities of operation of P&O and Inc. Cond MPPT algorithms [11]

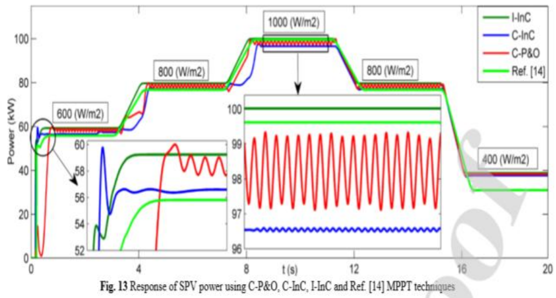

Figure 7: Response of GPV power using P&O, Inc. Cond and ref [20] MPPT techniques

According to [12] an important advantage of fuzzy logic is the fact that this method does not require any knowledge of the parameters of the PV plant. In this way, the same algorithm for finding the maximum power point can be applied to several PV plants without additional parameterization. But according to Beltran [13], the fuzzy logic-based MPPT control is less efficient compared to the classical slurry control in a wind turbine system. In fact, the realization of maximum power point tracking by a fuzzy supervisor is close to a realization of the P&O method, but the difference is that the fuzzy supervisor can adapt the value of the step increase or decrease of the control variable according to the system response. The RNA control has shown a very fast response time, high stability and high reliability. It has the potential to improve the frequency and voltage stability of an AC micro-array, improve power quality and ensure fast response from one mode to another [6]. Libo et al present a modified MPPT Ind. Con method applied to a single-stage inverter for a grid-connected PV system [9]. The control objective of this method is to balance the input and output current of the DC link capacitor and maintain its voltage to follow the PPM to maximize energy capture. The P&O algorithm is used to acquire the maximum output of the GPV in [5][7][8] [14]. Reddy and Babu adopt fuzzy logic and simulation on Matlab/simulink shows that the controller allows the hybrid system to operate at or close to a unit power factor [15]. The Ind.Cond algorithm is adopted by [16] to track the point of maximum power and the simulation results show a good power tracking by keeping the voltage almost constant. For the wind turbine part a sliding mode control has been used and the simulation results show an optimal output, the DC bus voltage is kept constant and the reactive power injected into the grid is set to zero in order to reach the unit power factor condition. The network currents have a sinusoidal waveform with a constant network frequency value equal to 50 Hz. Boualam also used the sliding mode in his thesis to optimize the wind generation and the results show that the GSAP speed, power factor, speed ratio and current follow their optimal references respectively after an acceptable response time of about 0.25 seconds. For the tracking of the GPV PPM, the Fuzzy Logic based P&O algorithm is used. This method proposed by Boualam has been compared with the conventional P&O algorithm and the results show that the proposed controller is more efficient in terms of dynamic performance under different conditions (load variation, partial shading) [17].

3. Regulations

Wen and Fazeli proposes a method for regulating the voltage drop noted in the electrical network. This method uses voltage compensation calculation (VCC) which forces the GPV to produce less power during faults. Concerning the current of the PI regulators are used. The DSC-PLL allows the synchronization of the system. A regulation block of the reactive power injected during faults is also included in the method. This method allows the system to operate in symmetrical and asymmetrical faults, to limit the current by 2 pu during a three-phase fault, 1.5 pu for unbalanced faults, to provide a good quality sinusoidal voltage and current for all faults and also to eliminate the need to switch between MPPT and non-MPPT mode [1]. Reference [14] has proposed a new algorithm based on the voltage sensitivity method to reduce unbalanced voltage. The inverse of the Jacobian matrix is used to calculate the coefficient of sensitivity. Autonomous micro-grids composed of renewable energy sources are the most used in isolated areas. This during the intermittency of renewable energy sources can cause a wide frequency fluctuation. Many methods have been developed to limit the fluctuation of this frequency. A new method of frequency control based on dual slip mode (SM) controllers is proposed in[7].The MG control is used to separately design the stall angle controller for the wind turbine and the load frequency controller for the diesel generator to improve the response speed and robustness of the micro array. The method proposed by [7] using the disturbance observer can smooth the frequency variation with the rated power limit of the diesel generator. However, it cannot cover the penetration of large-scale wind power that exceeds the power limit of the diesel generator. If the production of renewable energy sources is greater than the rated power of the diesel generator, an alternative method such as load shedding must be used to maintain stable system operation in the event of a large drop in wind speed. Compared to the typical architecture of an AC microgrid, DC microgrids have many advantages: they require fewer power converters, higher system efficiency, and an easier interface between the renewable energy sources and the DC system, there is no need to control frequency, phase, or reactive power. On the other hand, consumer electronics such as LED lighting, computers, pagers, telephones, etc. can be more easily powered by DC power, so the DC micro grid will be the main power supply system for future green homes and buildings. In a DC microgrid, the key point of energy management is to maintain the balance between power sources, utilities, storage devices and DC loads at all times, which means controlling voltage stability is the important thing in a DC microgrid [18]. Na et al. propose a strategy that allows renewable generators to operate in either MPPT or constant voltage mode [18], as well as [8] with PI controllers. [6] used the RNA to stabilize the DC bus voltage and to ensure power sharing of the corresponding microarray. Evaluation of the system performance shows that the bus voltage can be regulated to the desired value and that the output power of the converters can be regulated quickly when there are changes in reference or load. A fractional-order PID controller is used in [17] to keep the DC bus voltage within a certain reference value regardless of changing operating conditions. Simulation results show the advantage of using fractional order PID controllers in terms of fast response and no overshoot. In grid-connected mode an inverter is used together with a PID controller to regulate the compound voltage. For load-frequency control in islanded micro-grids, Amir and al. proposed an intelligent Terminal Sliding Mode Control (TSMC) based on Artificial Bee Colony (ABC) optimization algorithm [23]. To control the voltage in a DC bus configuration, the authors in [24] use direct lyapunov method. In article [19], Mojtaba says that when the microgrid is connected to the power grid, the DC bus voltage is regulated by the inverter and the AC bus voltage by the power grid. Just as when the microgrid is operating in stand-alone mode, it is the renewable generators and the storage system that regulate the DC bus voltage, whereas the AC bus voltage and frequency are regulated by the frequency-voltage controller of the inverter.

4. Supervisions

In light of the above, the combination of several renewable energy sources to form a hybrid energy system is a reliable and efficient solution for many remote regions. However, the fundamental challenge in the operation of these hybrid systems is the management of the power delivered to the load. Since the power output of renewable sources is intermittent and dependent on many uncontrollable conditions, an effective management system is needed to make decisions for better energy utilization. An optimal power management strategy must result in an efficient, reliable and cost-effective system. The main objective of energy management is to be able to meet peak load demand at all times. Devices for converting primary energy from renewable sources are generally not compatible with conventional constant frequency alternative networks. For example, photovoltaic panels are sources of direct current, micro gas turbines associated with a synchronous machine rotate at high speed and supply high frequency currents. Electronic power converters are therefore necessary to adapt them to three-phase interconnection networks. In this context, a sophisticated control device is required to drive the static converters and supervise the operation of the various elements carrying out the energy conversions up to the electrical networks [4].

Local supervision of the various components of the generator is necessary. This communicating local supervision is based on reference powers, because for a micro-grid, all the storage units are close. This proximity of production, consumption and storage allows an easy installation of a communication bus. Local supervisions can therefore be designed by receiving the instructions given by a central supervision via the communication bus. Their optimal exploitation is thus made possible by taking into account information on their operation.

Another more global type of control allows the monitoring of some or all components [4] (Figure 8). This monitoring system is usually automatic. Specific functions may include controlling the starting and stopping of diesel generators, adjusting their operating points, battery power management and power distribution for different types of loads.

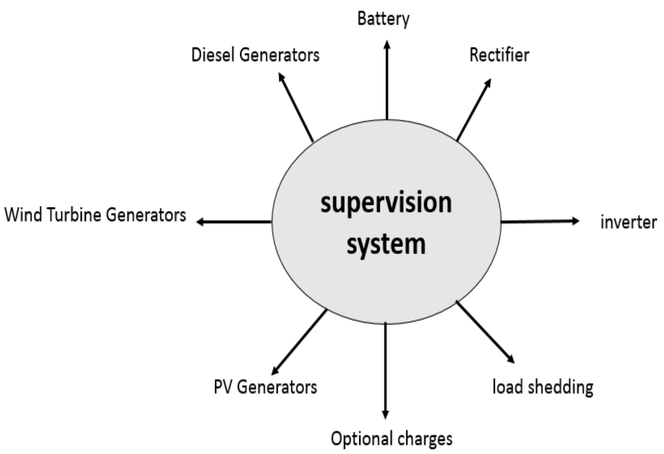

Figure 8: Supervision system

The reference [18] uses droop control based on DC bus voltage detection to perform power management in the DC microarray. The power balance of the DC microgrid under variable load power conditions is guaranteed by the proposed control method. The practical feasibility and effectiveness of the proposed control strategies have been verified by simulation. The intermittency of renewable sources and load variability cause disturbances in the power flow pushing [5] adopted the fuzzy logic based controller. In the work of [8], a management algorithm has been proposed. This algorithm allows to coordinate all the converters of the hybrid microgrid and the simulation results show that the hybrid microgrid can operate stably in grid-coupled or isolated mode. [17] develops a supervision algorithm based on the state of charge of the battery, the flowchart of which is shown in Figure 9. The supervision system of [3] is almost similar to that of [17], because all these supervision methods are based on deterministic rules and take into account all the operating scenarios of their studied systems.

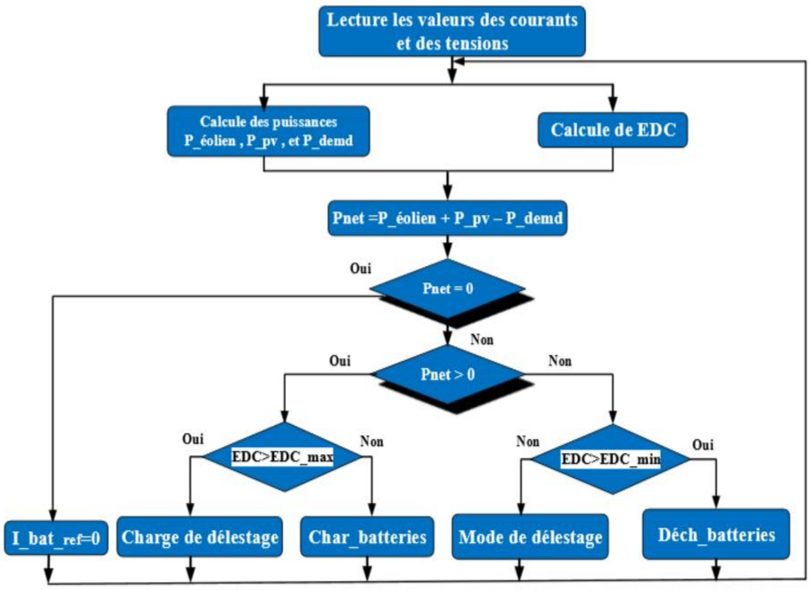

Figure 9: Flowchart of the Hybrid System Power Management Algorithm [17]

Table 2: Summary of some approaches used in the literature

Réf	Configuration	Optimization	Supervision	Remarks
[5]	Bus DC	P&O	fuzzy logic	The authors work on a system composed of GPV/Wind/Battery.
[14]	Bus AC	P&O	Algorithm	In this article, the microarray is composed of GPV/Battery/Diesel. The authors use this algorithm to correct the voltage unbalance noted in isolated micro-grids. This approach is based on demand management.
[7]	Bus AC	P&O	sliding mode charge frequency controller (SM CFC)	Wang and al. propose a new frequency control strategy based on dual sliding mode controllers for microarrays isolated with renewable sources.
[18]	Bus DC	Algorithm	-	The authors work on a micro-grid composed of GPV/Wind/Battery. To optimize and maintain the DC bus voltage, the authors use an algorithm that allows the system to operate in different modes.
[8]	Bus Hybrid AC/DC	Dual sliding mode	Algorithm	Liu and al. proposes a management algorithm. This algorithm allows to coordinate all the converters of the hybrid microgrid and the simulation results show that the hybrid microgrid can operate stably in grid-coupled or isolated mode.
[20]	Bus AC		Hierarchical coordination	This strategy is composed of an autonomous operating mode, connected to the network, and transitions between these two modes. Test results show that when the micro-network is applied with relay protection and load shedding, the system loses 37 kW of load, while with the hierarchical protection system, the

				system is restored to a stable state and does not lose any load.
[17]	Bus DC	Sliding mode and P&O mode based on FL	Algorithm	In this thesis Benlahbib proposes a supervision algorithm that allows to manage the energy flow produced by renewable generators. The sliding mode control is used to optimize the production of wind turbines. Concerning the continuation of the maximum production of the GPV, the P&O algorithm with the Fuzzy controller is used.
[16]	Bus DC	Inc. Cond and Sliding mode	-	The Ind.Cond algorithm is adopted by the authors to track the point of maximum power and the simulation results show a good power tracking by keeping the voltage almost constant. For the wind turbine part a sliding mode control was used and the simulation results show an optimal output, the DC bus voltage is kept constant and the reactive power injected into the grid is set to zero in order to reach the unit power factor condition.
[23]	Bus DC	-	Algorithm	In this paper, the authors propose an modified dragonfly algorithm with bat search algorithm based PI to minimizing the real and reactive power variations of the system. The stability of the system is maintained effectively by the proposed controller by the settling time and overshoot. By using the proposed methodology, the power flow management of the smart grid system is controlled based on the source side and load side parameters variations.
[24]	-	I-Inc FWPGM	Fuzzy logic-based adaptive control	The renewable solar and wind are achieved using the proposed I-Inc MPPT algorithm and FWPGM, respectively. From the obtained results I-Inc proves to have higher tracking efficacy with maximum efficacy of 99.90%, faster MPP tracking speed and aimost negligible divergence from MPP under changing solar insolation levels.
[27]	Bus hybrid AC/DC	-	Dynamic programming approch	The proposed PV/Battery system yielded $1.336 million of average annual savings, reduced the system overall COE from 13.7¢/kWh to 8.8¢/kWh during the first year and from 14.4¢/kWh to 10¢/kWh during the 10th year.
[28]	Bus AC	-	Algorithm	In this paper, as a method for incorporating renewable energy sources into a distributed generation network, a high-frequency single phase AC microgrid is proposed.

[29]	Bus hybrid AC/DC	-	ANFIS	The authors introduce a replacement advent for power flow control of interconnected AC/DC micro grids in hybrid micro grids connected to grids. It also supports implementing an Adaptive Neuro Fuzzy Inference Ssystem (ANFIS) controlled modified Unified Inter-Phase Power Controller (UIPC).

Conclusion

In this chapter, the bibliographical research on hybrid microarrays has allowed to list the different types of configurations, optimal controls, regulation techniques and supervision algorithms. Concerning configurations, the AC/DC hybrid configuration is more interesting. The P&O controller is a controller that is used a lot in the literature, but it is based on the least performing controllers. On the other hand, the fuzzy logic command is a high-performance command and does not require knowledge of the GPV parameters. That is, the same algorithm for finding the maximum power point can be applied to several PV installations without additional parameterization. The microgrid can have two modes of operation, one mode connected to the national power grid and one stand-alone mode. In the stand-alone mode the AC bus voltage and frequency is imposed by the grid and it is up to the microgrid inverter to adapt these quantities. About the autonomous operation, the voltage of the DC bus is imposed by the battery voltage. So the converters of the energy sources have the primary role of maximizing the production but also to adapt their outputs in relation to the bus sizes. For the sharing of the power delivered by the sources, a supervision algorithm is necessary. Many algorithms have been developed in the literature for power management in a micro-grid. These depend on the objectives set by the designer and the most used is the algorithm based on the battery state of charge.

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