Survey of load frequency control strategies in a Microgrid

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Abstract

Microgrids (MGs) represent a set of interconnected power generation sources, storage devices, and loads. The most solicited sources are renewable energy sources (RESs) because they help fight against global warming. However, the intermittency of the photovoltaic (PV) and wind (WTG) sources that are the most used will increase the power imbalance that generates the frequency variations since the inertia in the MGs is low. Thus, control strategies are increasingly used to ensure automatically a frequency balance. Therefore, in this paper, after presenting the microgrid and its components understandably, we have used recent papers to illustrate and discuss the most important frequency control strategies within a microgrid, and also some perspectives for future research to better exploit microgrids are presented.

1. INTRODUCTION

Nowadays, with the world’s population of more than eight billion people, and an ever-increasing development of enterprises, industries, and residences, growing electricity demand is observed on the world scale. To satisfy this demand, conventional production methods are no longer adequate and go against the current standards that require a reduction of greenhouse gas emissions (GHG) [1–3]. This GHG is responsible for global warming, and therefore new rules have been established. Thus, for the production of electricity, it is recommended to combine renewable energy sources (RESs) and conventional production techniques [4].

From the point of view of the use of RESs, especially solar photovoltaic (PV) and wind turbine (WTG), which are the most widely used as depicted in Fig. 1, and have become less expensive, an acceleration of their massive integration is observed at large and small scales. At a small scale, RESs integration is done through the microgrid (MG) as presented in Fig. 2, which represents an interconnection of distributed generators (DG), storage devices, and loads. However, in contrast to synchronous generators (SG), these RESs do not have large inertia [5] to be able to satisfy the frequency stability problem in the microgrid. On the other hand, since in an electrical system, it is necessary to ensure the balance between demand and consumption [6], considering the relationship between active power and grid frequency [7], the power imbalance also affects the frequency of the grid, which can lead to losses of some equipment and even the collapse of the grid. Moreover, this frequency instability problem is even higher in microgrids due to uncontrollable loads and fluctuations of renewable sources that are intermittent due to the variation of solar irradiation and wind speed.

Solving the frequency deviation problem in a microgrid can be done in several aspects. First, we have the noted load shedding [8], which is not very desirable, then comes the use of storage devices, virtual inertia [9], and also the intervention of controllable sources like diesel generators and many others used to improve the frequency stability. The control of these devices is done by some control strategies that we present in more detail in this work, with emphasis on recent references.
Indeed, in the literature, several works highlight the controllers to improve the stability of the frequency in MGs. The most common and widely used control strategies are proportional-integral (PI), and Proportional Integer and Derivative (PID) controllers [10–19], which is a very popular controllers in industries due to their simplicity of implementation and low cost. However, this controller is not very effective when the parameters are not judiciously chosen and also when the system undergoes large variations. On the other hand, we have the Model Predictive Controller (MPC) [20–28], which despite the complex calculation, anticipates the future state of the set point. The Sliding Mode Control (SMC) [29–33], ensures a smooth transition. Intelligent strategies such as fuzzy logic (FL) [29, 34–41], artificial neural network (ANN) [34, 42, 43], and Artificial Neuro-Fuzzy Inference System (ANFIS) [44–46] are also widely used except that they are highly dependent on data that must be stored to promote their training. Faced with multiple uncertainties in MGs, the H-Infinity controller coupled with µ-synthesis and µ-analysis [47–49] also allows for improved stability of the frequency. The metaheuristic algorithms [50–58] are also very often observed when we want to optimize some parameter. Thus, the genetic algorithm (GA), the particle swarm optimization (PSO), the grey wolf optimization (GWO), and many others are used in the literature, and the notion of the objective function is also discussed in this work. With the evolution of technologies, especially with the presence of the Internet of Think (IoT), the idea of demand response (DR) [59–62] is addressed to ensure frequency balance in microgrids as well, which we have also presented in this work.

In the rest of this paper, structuring is established to facilitate the understanding of the readers. First, detailed generalities on MGs are presented in section 2, with an emphasis on the constitutive elements of the MG, and tables for more understanding. In section 3, different control strategies used in the literature to overcome the frequency deviation problem are presented with their structural scheme and recent references. The modelization of frequency control is presented in section 4, and some of the most common controller positions found in the literature are illustrated. Section 5 presents the future perspectives to be considered for the deployment of microgrids and finally, section 6 concludes this work.

2. General information on microgrids

In this part, some information about microgrids has been presented. Thus, the definition, operating mode, components, and different types of a microgrid are presented. Also, hierarchical control of microgrids has been presented with a brief description of all levels of control.

2.1. Definition

Facing the problems of environmental degradation, industrial production must be less polluting. However, in the field of electricity, with the growing population and the increasing demand, it is important to rethink the mode of electrical production to both satisfy the demand and meet the environmental conditions. Thus, to help improve the reliability, efficiency, and sustainability of electrical power systems, the concept of microgrids is being developed by the CERTS (Consortium for Electric Reliability Technology Solutions) [65]. More essentially, as with the evolution of mobile network generations (1G, 2G, 3G, 4G, 5G), a
microgrid can be defined as a new generation of electricity, on a reduced scale, intelligent (because of the use of communications links and control system) and environmentally friendly (because of less emission of CO₂).

2.2. Operation mode

Microgrids have two main modes of operation, namely the island mode and the grid-connected mode [66, 67] [68].

- Grid-connected mode

When we talk about a grid-connected microgrid, we see the parallel operation of the microgrid and the conventional grid, interconnected by a static transfer switch (STS) at the point of common connection (PCC). In connected mode, the frequency and voltage of the microgrid are supplied by the main grid. Also, the user of the MG can sell the surplus of its production on the main grid, but this is done through a set of agreements between the user and the main grid operator.

- Islanded mode

This model is very interesting for isolated sites such as some villages and islands that do not have access to the conventional power grid. In the same way, in case of a failure on the main grid, the microgrid disconnects from the main grid to operate in islanded mode. Conversely, when the failure is on the microgrid side, islanding is recommended to avoid creating a breakdown of the main grid. It is essential to properly size and control the islanded microgrid because it is very vulnerable to frequency and voltage instability due to the variation of loads and renewable energy sources such as solar and wind power.

For a grid-connected microgrid, it is possible to switch from connected to islanded mode and vice versa. However, the disconnection and connection of the microgrid with the main grid can be intentional (smooth transition especially in case of maintenance) or accidental (fault). Thus, for both, it is important to ensure a good smooth transition to ensure the frequency and voltage stability of the microgrid as well as its security.

2.3. Components of a Microgrid

As defined above, microgrids involve distributed generators (DGs), storage devices, loads, and also a management system called a microgrid control center (MGCC) which ensures the control of the whole microgrid through the communication of all devices.

- Sources

Within a microgrid, we distinguish several types of sources. The most used are renewable energy sources, which allow fighting against global warming, and environmental pollution and which also help to reduce the cost of electricity consumption. Thus, among the most used sources, we distinguish fuel cells (FC),
photovoltaic systems (PV), wind turbine generators (WTG), and microturbines (MT). Other sources such as diesel engine generators (DEG), combined heat and power (CHP), and electrical vehicles (EV) are also encountered.

- Energy storage devices

The storage devices are used to help the MG to be stable. Thus, in case of overproduction, the surplus is stored in the storage devices, which is returned when the system is under production. We have several types of storage devices such as batteries (BESS), inertial flywheel (FESS), Superconducting magnetic energy storage (SMES), electric vehicle (EV) which is often used as energy storage, and many others as presented in Table 1.

<table>
<thead>
<tr>
<th>Type of energy</th>
<th>Energy storage category</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical</strong></td>
<td>Biomass storage</td>
<td>[71−73]</td>
</tr>
<tr>
<td></td>
<td>Hydrogen storage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel cell (FC)</td>
<td></td>
</tr>
<tr>
<td><strong>electrical and</strong></td>
<td>Supercapacitor</td>
<td>[74−78]</td>
</tr>
<tr>
<td><strong>electrochemical</strong></td>
<td>Superconducting magnetic energy storage (SMES)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Batteries (BESS) like Lead Acid, Lithium Ion, Zinc Air, Vanadium, and so on</td>
<td></td>
</tr>
<tr>
<td><strong>Mechanical</strong></td>
<td>Compressed air</td>
<td>[79, 80]</td>
</tr>
<tr>
<td></td>
<td>Flywheels</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pumped storage</td>
<td></td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td>Sensible heat storage</td>
<td>[81, 82]</td>
</tr>
<tr>
<td></td>
<td>Latent heat storage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermochemical storage</td>
<td></td>
</tr>
</tbody>
</table>

- Loads

The loads are the end-of-the-line equipment of an electrical system because the product is made to feed the electrical devices which can be grouped in industrial, commercial, and residential structures. It is important to know that the end users who are the customers can also be small producers and sell the surplus of their energy to the main grid or neighboring microgrids. In this case, they are called prosumers [83].
In the literature, to ensure better stability control in microgrids, dynamic models are used because of their simplicity. Thus, for each device mentioned above, dynamic models can be represented by transfer functions as shown in reference [29].

2.4. Types of microgrids

We distinguish three main types of microgrids: AC microgrids, DC microgrids, and hybrid microgrids. For these microgrids, depending on the place of deployment and the type of loads (AC or DC), a set of advantages, and above all, it should be noted that the notion of cost must be taken into account when setting up a microgrid. Some advantages and disadvantages of the different MG structures are presented in Table 2.

- **AC microgrids (AC MG)**

The AC microgrid represents the very first microgrid structure. It consists of an AC bus as shown in Fig. 3, where the different distributed generators (DG) and loads are interconnected. However, the DC sources (PV, battery...) need DC/AC converters to facilitate their connection. Similarly, DC loads (TV, electric car...) need AC/DC conversion to be powered without deterioration. This microgrid structure is easily connected with the classical networks which are mostly AC systems.

- **DC microgrids (DC MG)**

Contrary to the AC MG, the DC MG has a DC connection bus where the AC sources (wind turbine, inertial flyer...) need the help of AC/DC converters, as well as DC/AC converters for the AC loads (washing machine, refrigerator...). However, the connection with the main grid is not obvious because it also requires power electronics. Figure 4 gives a schematic of a DC microgrid.

- **Hybrid microgrids**

Because of some of the disadvantages of AC and DC microgrids, the hybrid microgrid is set up with its advantages presented in Table 2 to overcome these problems. Indeed, a hybrid microgrid illustrated in Fig. 5 is a set of AC and DC sub-microgrids connected through a bidirectional converter. In addition to the easy connection of AC and DC sources as well as AC and DC loads, hybrid microgrids also allow for limiting the number of converters to be used, which is more economical in terms of cost. However, this structure complicates the control of the microgrid as well as the energy management [65].
Table 2

<table>
<thead>
<tr>
<th>Type of Microgrid</th>
<th>Benefits</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC microgrid</td>
<td>Adapted for existing AC loads</td>
<td>Reactive power flow</td>
</tr>
<tr>
<td></td>
<td>Easy connection with the conventional grid</td>
<td>Frequency control is required</td>
</tr>
<tr>
<td>DC microgrid</td>
<td>Fewer converters required</td>
<td>Requires additional investment for connection to the network</td>
</tr>
<tr>
<td></td>
<td>No reactive power</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Adapted for more DC loads</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency control is not required</td>
<td></td>
</tr>
<tr>
<td>Hybrid AC-DC microgrid</td>
<td>Easy connection with the conventional grid</td>
<td>Complex control</td>
</tr>
<tr>
<td></td>
<td>Easy connection of AC and DC loads and sources</td>
<td>Complex energy management</td>
</tr>
<tr>
<td></td>
<td>Favorable extension</td>
<td>Complex maintenance</td>
</tr>
<tr>
<td></td>
<td>Favorable cost</td>
<td></td>
</tr>
</tbody>
</table>

### 2.5. Hierarchical control of the Microgrid

The hierarchical structure is the structure established to ensure good control of the microgrid. Indeed, within a microgrid, it is important to maintain stable frequency, voltage, and power sharing and also to ensure a gain in terms of cost. Thus, the hierarchical structure is constituted of three levels of control to ensure the above objectives [42, 84].

- **The first level of control: primary control**

This control has the fastest response time (a few seconds), takes care of the management and distribution of the active and reactive power of the network, and also allows the stabilization of the microgrid frequency and voltage.

- **The second level of control: secondary control**

This level of control allows to compensate for the voltage and frequency deviations caused by the primary control and also allows the management and control of each component of the microgrid. The communication of the microgrid components is ensured by a communication network.

- **The third level of control: tertiary control**

This level manages the flow of power and energy between the different microgrids and the main grid. It also facilitates the cost by taking into account the economic forecast data of the energy market and the
weather data.

The following Fig. 6 shows the commands provided by each control level as well as the action time for each level and the communication links with the power market.

3. Control strategies

In the literature, we distinguish several control techniques. Among others, we can note the techniques called classical or conventional such as the PI/PID, the sliding mode, and linear quadratic. Similarly, we distinguish other more advanced (intelligent) techniques such as fuzzy logic, based on neural networks, and many others. After a description of each control strategy with illustrative papers, some comparisons between all of them are given in Table 3.

3.1. Conventional PI/PID controllers and their derivatives

PID (Proportional-Integral-Derivative) controllers as shown in Fig. 7 are the most popular controllers in the industry due to their easy implementation and low cost. Other variants of the PID controller such as cascading models and fractional models have been developed to make them more efficient and robust. However, since the pure derivative action of the PID controller is not physically realizable because its transfer function gives a denominator degree lower than the numerator degree, the causality problem arises, and thus, the addition of a filter \((n)\) is requested to suppress the pure derivative action and introduce the notion of \(\text{PID}_n\) depicted in Fig. 8 and applied in references [10, 13–15]. Based on this controller, several researchers have stabilized the variation of frequency and voltage in microgrids [11, 16, 17, 85–88]. In the literature, several methods are used to determine the parameters of this controller such as the Ziegler-Nichols method [89–91], Cochen-Coon, Chien, and many others [92]. Also, the meta-heuristic algorithms developed below are increasingly used to assist in finding the best parameters.

- Cascading models

Cascading models are formed by more than one step of control. Thus, we can have PI-PD, PD-(1 + PI), (1 + PD)-PID, and many others. These controllers have the advantage of overcoming the disadvantage of simple controllers. Since the number of control nodes is higher with these controllers, an improvement in the system performance is expected [93]. For this reason, a PD-(1 + PI)-controller is used in [94] to ensure the frequency deviation stability in a microgrid. The parameters of this controller are optimized by a metaheuristic algorithm. In [95], a (1 + PD)-PID controller (as shown in Fig. 9) is used to ensure the frequency response of multi-area systems.

- Fractional model

With the fractional model, the presence of new parameters that allow better flexibility in the controller design is observed. Indeed, non-integer or fractional calculus is a branch of mathematics that studies the possibility of extending derivatives and integrals to non-integral orders. In [96], a comparison in terms of
response time, error, and overshoot is made to evaluate the frequency deviation in an MG using PID, FPID(Fuzzy-PID), FOPID, and FOFPID(Fractional Order-Fuzzy-PID) controllers and the FOFPID allows obtaining more interesting results for the control of the frequency deviation. A TID (Tilt-Integral-Derivative) based on INFO (weighted mean of vectors) is used in [18] to ensure frequency stability and tie-line power in an MG with two areas, and the result is best than the results we PID based on TLBO(teaching learning-based optimization) is used and also when TID based on IPA(interpretative phenomenological analysis) is used. Performance analysis of a FOPID-(1 + PI) is presented in [19] to ensure frequency deviation control and the GOA (Grasshopper optimization algorithm) which is used to optimize the controller parameters is found to be better than the PSO (Particle swarm optimization), GA (Genetic algorithm), and GSA (Gravitational search algorithm) algorithms. A study of the classical FO, Fuzzy logic integrated FO, cascaded and double stage FO controllers, used in the literature for FO-based frequency control is presented in [12] and they are very beneficial for the researchers in this field. A hybrid fuzzy proportional derivative-tilt integral derivative (FPD-TID) controller optimized by a chaotic crow search algorithm (SSCA) is proposed in [97] to ensure frequency control in an MG. Here the advantages of FPD and TID controllers are implemented. Moreover, as we can see in Fig. 10, the first stage represents the FPD model, and the second stage is the TID controller model.

3.2. Sliding Mode Control (SMC)

The sliding mode is a nonlinear control method using a flexible structure [98]. Because of its simple construction, it is widely used in industrial applications [31]. Also, several variants exist in the literature such as fractional, terminal, and many other models. Thus, an intelligent control based on the ABC (artificial bee colony) algorithm is used by a TSMC (terminal sliding mode control) type controller [32] to ensure frequency stability in an islanded MG with variable sources and loads. These performances compared to the PID controller are remarkable through the maximum overshoot, the steady-state error, the maximum settling time, and the objective function value. In [33], fractional computation is used for a sliding mode controller to ensure the quality of the load frequency in an MG. This controller, still called fractional order sliding mode control (FOSMC), uses a hybrid SCA-HS (Sine Cosine algorithm- harmony search) algorithm to optimize the controller coefficients, and also, hardware-in-the-loop (HIL) experiments are used to reassure the reliability of the controller. Also, structures such as model-free SMC controllers are encountered in the literature, and thus in [30], a model-free is combined with the classical P, PI, PD and PID controllers to set up the intelligent iP, iPI, iPD and iPID controllers. This type of model is presented as shown in the Fig. 11.

3.3. Model Predictive Control (MPC)

This control strategy allows us to calculate in advance the setpoint signals [20]. With MPC, the control is more accurate and also, and this technique includes the nonlinearity of the system. More complex models like MMPC (Multi-Model Predictive Control) [22–25] are used for systems with a high number of operating conditions. The load voltage is regulated in [26] by an MPC-based control, as well as the frequency control is established by an MG. An MG with load variation and DG source is presented in [27]. The frequency control is performed at two levels. The first level is performed by a diesel generator and the
second level is performed by the storage system controlled by an MPC-based controller. The predictive control system (MPC) is used in a multi-area interconnected power system for frequency deviation maintenance in [28]. In [21] the gradient optimization technique is used to determine the optimal parameters of an MPC controller for a frequency-enhanced power system. Figure 12 shows the structure of an MPC with the setpoints, the input error, and the output control signal.

3.4. H-infinite (H-∞) control

The H-infinite method (H-∞), is a relevant control method for multivariable systems and is based on mathematical modeling. Its main role is to find an optimal controller to ensure the stability and performance of a system in the presence of modeling uncertainties and external disturbances. Thus, the controller found from this method is optimal provided that the mathematical modeling is reasonable for the system to control. Moreover, due to the difficulties in satisfying robust performance and having robust stability, the H-∞ is the technique that comes nearest to satisfying these constraints. Note that this strategy is often supported by a sensitivity and robustness analysis ensured by a method known by the name of µ-analyses, and a complementary method called µ-synthesis. The model of this method is presented in Fig. 13.

The H-infinity method is proposed in [47] for robust and optimal control of the parameters of a synchronous virtual generator (VSG), which allows controlling and stabilizes the frequency of an MG. In [49], a virtual inertia controller based on H-∞ is proposed to efficiently and robustly regulate the frequency in an MG. In [48] the H- and µ-synthesis control strategies are used to provide secondary frequency control in a microgrid. The results obtained on an MG test platform justify the robustness of the proposed strategy.

3.5. Fuzzy logic control (FLC)

Fuzzy logic control, classified as non-linear control, is an intelligent control strategy that requires experience and knowledge of the system to be controlled and applied to complex systems whose mathematical formulation is not clearly defined. This control strategy with its various fields of application is one of the tools used to solve the optimization problem and is also often used to adjust the parameters of a classical controller like the PID.

A fuzzy logic controller is used in [34] to provide voltage-frequency control, as well as inertia control in an MG based on the virtual synchronous generator (VSG). In [35], the authors propose a fuzzy logic combination to optimize the parameters of a PI controller to overcome the production-demand problem in an AC MG. In addition, a PSO algorithm is used to try to address the membership function problems encountered by fuzzy logic. A conventional integral controller based on fuzzy logic and a SMEC storage device is used [36] to ensure frequency control in an isolated microgrid. Thus, several other papers deal with this problem of frequency control based on fuzzy logic control such as [29, 37–41]. However, if bad rules are assigned to the fuzzy logic, this controller will provide poor performance. Figure 14 illustrates the fuzzy logic control structure, and Fig. 15 illustrates the self-turning of the PID controller by the fuzzy controller.
3.6. Artificial Neural Network (ANN)

To improve and tune the performance of classical controllers, ANNs are used. As the name suggests, ANNs are artificial intelligence inspired by the behavior of the human brain. Thus, a similarity between ANN and the human brain is shown in Fig. 16, where dendrites represent inputs \((x)\), axons represent outputs, soma represent neurons (somatic point and decision function), and synapses represent weights \((w)\). Several learning modes exist for ANNs, but the most popular learning mode is error correction learning, which compares the output of the ANN with the desired output to produce a difference called error, that can be used to directly adjust the weights \((w)\) of the ANN. At each iteration, the goal is to minimize this error signal. Thus, ANNs require input data which are very often the error signals and generate an output estimate without having any priority knowledge of model building. Note that, to better train the neural networks and bring them to an efficient operation, a well-supplied database is beneficial. Figure 17 presents a structure of an ANN controller.

The ANN approach is applied in [42] in combination with the Genetic Algorithm (GA) to determine the parameters of a PI controller, to control the frequency in an island microgrid. In [43] an adaptive proportional integral (API) controller is replaced by an adaptive neural network (NN) controller to reduce the error signal and cover the frequency fluctuations. The comparisons made in this work allow us to notice that the oscillations are damped as well as the response time. This same approach is also used in [34].

3.7. Artificial Neuro-Fuzzy Inference System (ANFIS)

This strategy combines the performance of ANN in process learning and the ability of fuzzy logic in processing uncertain information. The structure of this technique is presented in Fig. 18. In the paper [46], the authors improve the sliding controller and have proposed an ANFIS. Comparisons with other intelligent control techniques such as ANN and FL are presented for a multi-area system consisting of a thermal power plant and a hydroelectric power plant. In [44], ANFIs is proposed to ensure good frequency control in 100% renewable AC microgrid while ensuring good power sharing among DG units. In [45], the load frequency control of an islanded microgrid consisting of PV, microturbine, and a diesel generator is based on ANFIS. This improves the dynamic response and stabilization time compared to a PID controller and a fuzzy controller.

3.8. Meta heuristic-based control

To ensure better system stabilization, the controller parameters must be optimized. Indeed, a controller is only efficient if these parameters are optimized. If not, it risks deteriorating the system further. The diagram describing the principle of optimization by taking into account the fitness function and optimization algorithms to ensure the reliability of the controllers is represented as we can see in Fig. 19.

- Fitness function
In the literature, the fitness functions in the context of frequency control, minimize the deviation of the frequency that represents an error to optimize the control of the frequency. We distinguish several types of the objective function (often noted J) [11], [103], [104], [29], such as ISE (integral-squared error), ITSE (integral-time-multiplied-squared error), IAE (integral-absolute error), ITES (integral-time-multiplied-absolute error), and ISTSE (integral of squared time multiplied by error squared) whose characteristic equations are respectively presented by equations (1), (2), (3), (4), and (5) where $\xi$ represents the error.

- **ISE**: integral of squared error
  \[
  ISE = \int \xi^2 \, dt
  \]

- **ITSE**: integral of time multiplied by a squared error
  \[
  ITSE = \int t\xi^2 \, dt
  \]

- **IAE**: integral of absolute error
  \[
  IAE = \int |\xi| \, dt
  \]

- **ITAE**: integral of time multiplied by absolute error
  \[
  ITAE = \int t|\xi| \, dt
  \]

- **ISTSE**: integral of squared time multiplied by error squared
  \[
  ISTSE = \int t^2\xi^2 \, dt
  \]

- **Optimization algorithms**

There is a multitude of optimization algorithms. From the simplest to the most complex, with computation times quite high for some and low for others. In the literature, we distinguish several
categories of algorithms. Some are based on the intelligent behavior of animals and insects in search of food like the ant colony optimization algorithm (ACO) [51], the gray wolf optimization (GWO) [52], the particle swarm optimization (PSO) [53, 54], the firefly algorithm (FFA) [55] and many others. Another category of the algorithm is based on genetic evolution like the genetic algorithm (GA) [56]. We also have algorithms based on physical phenomena such as the sine cosine algorithm (SCA) [57]. For more details, a review is presented in [58] and [50] where many algorithms and their flowcharts are presented.

### 3.9. Demand Response (DR)

DR is a control strategy that focuses on loads and is based on advanced communication and measurement systems. Most of the time, equipment that can reduce or increase their consumption is solicited (thermostatic loads such as air conditioners, water heaters, refrigerators, and many others). DR allows a system to automatically control the frequency deviation [59]. Thus, in [60], the DR strategy is applied to a three-zone system to control the frequency deviation. Here, to optimize the parameters of the DR control and for an automatic generation control (AGC), a GA is used. In [61] an IBDR (incentive-based demand response) program is used to support the storage device to solve the frequency variation problem. Furthermore, by projecting the Irish power system in 2030, the authors in [62] proposed a DR control on the cooling system of shopping malls. This study improves the frequency quality, characterized by a Fast Frequency Response (FFR), and also reduces the production cost. Figure 20 despite some examples of architecture of a demand response for a residential consumer.
<table>
<thead>
<tr>
<th>Control strategy</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>Low cost of calculation</td>
<td>Do not resist complex disturbances</td>
<td>[11]-[17], [85]-[88]</td>
</tr>
<tr>
<td></td>
<td>Easy to implement</td>
<td>Do not resist harmonic disturbances</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High dynamic response</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cascading PID</td>
<td>More robust than PID</td>
<td>More parameters to optimize</td>
<td>[93], [94], [95]</td>
</tr>
<tr>
<td>Fractional order controller</td>
<td>Robust performance</td>
<td>Parameters difficult to tune</td>
<td>[12], [18], [19], [96], [97]</td>
</tr>
<tr>
<td></td>
<td>More flexible</td>
<td>High simulation time</td>
<td></td>
</tr>
<tr>
<td>SMC</td>
<td>smooth transitions</td>
<td>Cannot provide good transient and steady-state performance simultaneously</td>
<td>[29–33]</td>
</tr>
<tr>
<td></td>
<td>follows the system behavior</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unaffected by some uncertainties</td>
<td>serious chattering problem</td>
<td></td>
</tr>
<tr>
<td>MPC</td>
<td>Minimizes the commutation frequency of the inverters</td>
<td>Involves a lot of calculation</td>
<td>[20–28]</td>
</tr>
<tr>
<td></td>
<td>Takes into account the nonlinearity of the system</td>
<td>Sensitive for future prediction</td>
<td></td>
</tr>
<tr>
<td>H-Infini</td>
<td>Great performance</td>
<td>Exact accuracy of the state space difficult</td>
<td>[47–49]</td>
</tr>
<tr>
<td></td>
<td>Easy to implement in real applications</td>
<td>Slow dynamics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Takes into account uncertainties</td>
<td>Requires careful modeling</td>
<td></td>
</tr>
<tr>
<td>FLC</td>
<td>Fast response time</td>
<td>Depends on membership functions (requires good rules)</td>
<td>[29, 34–41]</td>
</tr>
<tr>
<td></td>
<td>Easy to design</td>
<td>Slow control</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Resistant to parametric variations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANN</td>
<td>Large processing capacity</td>
<td>Requires extensive training data</td>
<td>[34, 42, 43]</td>
</tr>
<tr>
<td></td>
<td>Parallel learning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANFIS</td>
<td>do not require precise mathematics</td>
<td>Depends on the training data</td>
<td>[44–46]</td>
</tr>
<tr>
<td>Based on metaheuristics</td>
<td>The main advantage is the optimization of controller parameters to make them even more reliable and efficient</td>
<td>it is difficult to determine the number of parameters to fix at the beginning of the algorithm</td>
<td>[42], [50–58]</td>
</tr>
<tr>
<td>Control strategy</td>
<td>Advantages</td>
<td>Disadvantages</td>
<td>References</td>
</tr>
<tr>
<td>------------------</td>
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<td>------------</td>
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<tr>
<td>DR</td>
<td>Very practical for multi-area systems</td>
<td>It is still difficult for operators to access customer loads</td>
<td>[59–62]</td>
</tr>
<tr>
<td></td>
<td>Helps the customer to reduce his bill</td>
<td>IoT is not yet widely deployed to facilitate this technique</td>
<td></td>
</tr>
</tbody>
</table>

4. Frequency control modelization

To stabilize the frequency in a microgrid, several structures can be encountered. These structures depend on the experience of the constructor, the cost of the project, the objectives of the installation of this MG, and the devices available to the MG. Thus, some researchers prefer to place the controller directly at the output of the frequency deviation [106]. A sketch of the structure of this approach is presented in Fig. 22.

Another approach is to place the controller after the first control provided by the energy storage devices that have a fast reaction time. Here, one controller can be used for all the controllable devices as sketched in Fig. 23 and as presented in the paper [48], where one controller is used to control both the diesel generator (DEG), the microturbine (MT), and the fuel cell (FC). In another case, each device has a controller as in [18], sketched in Fig. 24 (N = number of devices). Uncontrollable sources in an MG system can be wind generators and photovoltaic systems. Controllable sources are often fuel cells, diesel generators, thermal power plants, gas power plants, and hydropower plants.

The power system represented by \( \frac{1}{2Hs + D} \) comes from the relationship between the frequency and the power [107, 108] as represented in the Eq. (6) which is the temporal derivative of the frequency for an electrical system and whose transfer function leads to the Eq. (7) and the block diagram representation is shown in Fig. 21 with \( D \) representing the load oscillation, \( H \) representing the inertia of the system, \( \Delta P_s \) the small-signal variation of the sum of the supplied power, and \( \Delta P_{load} \) the small-signal variation of the power consumed by the load.

\[
\frac{d\Delta f}{dt} = \frac{1}{2H}(\Delta P_s - \Delta P_{load}) - \frac{D}{2H}\Delta f
\]

6

\[
\Delta f(s) = \frac{1}{2Hs + D}(\Delta P_s - \Delta P_{load})
\]

7

5. Prospects of future works

Microgrids are becoming more and more popular because of the advantages they offer in terms of meeting the electricity demand, but also and above all because of the need to reduce global warming,
from which our planet is now suffering. However, the control of the frequency, although relevant, is not enough to guarantee the proper functioning and the best deployment of MGs. A thorough analysis of the protection of the MG and especially of its elements are of paramount importance to avoid the risks of fire. Moreover, being in the digital age, the communications within the microgrid must be analyzed and updated because of the different communication techniques and especially the great development of the IoT (Internet of Things). These technologies will help to ensure reliability and flexibility to the microgrid while helping to meet the power balance through DR (demand response) and DMS (demand management system) which require advanced and also secure communication techniques. Speaking of security here refers to cyber security within the microgrid.

6. Conclusion

This paper presents a detailed study of microgrids, taking into account their elements, as well as a review of the control strategies used for frequency stability in a microgrid. Starting from the simplest to the most complex strategies, descriptions and discussions about different control strategies are made with illustrative diagrams and recent papers. Also, a discussion on the strategies of demand response is presented, thus revealing one of the future visions of the world with the evolution of communication techniques in this field. Since microgrids represent a set of interconnected devices exchanging information and power, future perspectives taking into consideration the scientific evolutions are presented to broaden the study, ensure protection, secure communication, and thus promote the efficient deployment of microgrids.

Declarations

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures
Modern renewable energy generation by source, World

Figure 1

Modern renewable production [63]
Figure 2

Schematic diagram of a microgrid [64]
Figure 3

Schematic of AC microgrids
Figure 4

Schematic of DC microgrids
Figure 5

Schematic of Hybrid AC-DC microgrids
Figure 6

Microgrid controller—time frame and action domain [83]

![Diagram showing microgrid control](image)

Figure 7

PID controller

![PID controller diagram](image)
Figure 8

PIDn Controller

Figure 9

Cascading (1+PD)-PID controller
Figure 10

Transfer function model of the hybrid FPD-TID [97]

Figure 11

Model-free control structure [99]

Figure 12

MPC Controller
Figure 13
H-infinity Controller

Figure 14
Fuzzy logic structure

Figure 15
The structure of self-tuning fuzzy PID controller [100]
Figure 16

ANN model from the brain [101]

Figure 17

ANN Controller
Figure 18

Adaptive Neuro-Fuzzy Inference System Block Diagram [102]

Figure 19

Principe d'optimisation par meta heuristique
Figure 20

Illustration of home energy management system (HEMS) architecture [105]

\[
\Delta P_{load} \quad \Delta P_s \quad \Sigma \quad \frac{1}{2Hs + D} \quad \Delta f
\]

Figure 21

Block diagram representation of the power system
Figure 22
The control structure for frequency deviation with an example in reference

Figure 23
Structure of a controller for all controllable devices with an example in reference
Figure 24

Structure of each controllable device with one controller with an example in reference