International Journal of Emerging Scientific Research 3 (2021) 1 – 12

International Journal of Emerging Scientific Research (IJESR)

Journal homepage: www.sciengtexopen.org/index.php/ijesr

Microgrid, Its Control and Stability: The State of The Art

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ARTICLE INFO

Article history:
Received 25 March 2021

Received in revised form
11 June 2021

Accepted 17 June 2021

Available online
10 July 2021

Keywords:
Control strategies
Microgrid
Power stability

ABSTRACT

Some of the challenges facing the power industries globally include power quality and stability, diminishing fossil fuel, climate change amongst others. The use of distributed generators however is growing at a steady pace to address these challenges. When interconnected and integrated with storage devices and controllable load, these generators operate together in a grid, which has its own incidental stability and control issues. The focus of this paper, therefore, is on the review and discussion of the different control approaches and the hierarchical control on microgrid, the current practice in literature with respect to stability and the control techniques deployed for microgrid control; the weakness and strength of the different control strategies was discussed in this work and some of the areas that require further research are highlighted.

1. Introduction

The power industries are today facing series of challenges which include power stability and quality, increasing cost of energy, climate change and diminishing fossil fuel. All these are in addition to emission of carbon which pollutes the environment and so on [1]. For the above problems to be solved and to make our environment to be friendly there is need to adopt renewable energy source concept which is a fast-growing energy system in the world today. Countries and industries all over the world are strategizing ways of reducing greenhouse emissions from their operations [2]. Distributed generators (DGs) consist of renewable energy (RE) sources which include geothermal, wind turbines, photovoltaic and hydro plants. These are cleaner and they also reduce greenhouse gas emissions, as well as provide remedy for global warming problem. In decentralized distributed generation of electricity, the micro-sources (MS) are located close to the point of consumption.

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https://doi.org/10.37121/ijesr.v3.145

Microgrid is a small entity in a power system [2]. It is when distributed generators such as wind turbine, fuel cells, micro-turbines, photovoltaic (PV), small hydro plant and so on, are interconnected and integrated with energy storage devices, which include batteries, super-capacitors and flywheels with electrical loads, operating within electrical boundaries. It can function as a stand-alone system or with respect to the main grid [3] or ability of managing DGs in a more decentralized manner [2]. Microgrid can operate in a transition mode, which is, switching from grid connected to off-grid connected mode. It can operate either in grid-connected or standalone mode (islanded mode) [4]-[5]. For any of the operation modes, different operational requirements and highly sensitive control strategies are required. The major advantage of a microgrid is that it operates autonomously whenever there is power failure from the main grid due to fault or maintenance, which results in the consumer still enjoying power. Moreover, if there are voltage and frequency instabilities on the main grid, the microgrid can disengaged from the main grid and operate as a stand-alone grid so as to supply quality power to the consumers. Microgrid not only provides uninterrupted power supply, but also provides quality power [2]; it can supply power in direct current (DC), alternating current (AC) or high frequency AC grid. It can operate as a single-phase or three- phase power network which can be connected to low, medium and high voltage distribution networks.

The DGs can be classified into two groups based on interface mode, such as inverter interfaced DGs and non-inverter interfaced DGs or DGs directly connected to the microgrid. Examples of DGs with inverter interface are PV, batteries, fuel cell, flywheel, super capacitors, synchronous generators and so on. Voltage source inverters are the major type of inverters which are used to connect inverter-based DGs to the main grid [6]. While DGs that can be directly connected to the microgrid are induction generators, diesel generators, small hydro plant units, asynchronous generator and so on. For a DC source, a DC/AC inverter interface is needed for an AC power network system or wind farm operating with doubly-fed induction generator (DFIG), synchronous generators may need AC-DC-AC inversion either for grid connected or islanded mode with energy storage devices integrated into the network [2].

An inverter interface of a microgrid makes microgrid control more flexible [7]. However, the flexibility of microgrid control has led to the increase in the operating mode [6], this makes the behavioral characteristics of a microgrid different from the conventional grid [3]. Therefore, the conventional grid stability classification and analysis are different from the stability classification of a microgrid system [3]. Stability in any conventional power system, can be defined as achieving asymptotic synchronization of the frequency of all power generating units in the network, with the angle differences not exceeding 90^0 at constant generated voltages [8].

In a microgrid network, there are three major problems that can be addressed. These are frequency instability, voltage instability and equal power sharing among DGs. Power sharing is when the local controller shares power among each distributed generator according to their capacity. Droop control can be used to solve the problem of active power sharing in large power system with inverter-based grid. But, if the network is more resistive, the droop control will not be effective for such a network [9]. Frequency instability is when the power system is unable to maintain steady frequency under power variation condition. It is the imbalance between powers generated and the electrical load including power losses. Then voltage instability is when the power system is unable to maintain steady voltage on all bus-bars after subjected to disturbance. It is the imbalance between the voltage on each bus-bar and the voltage generated [9]. In a microgrid operating in islanded mode, there should be balance of active and reactive powers generated to the active and reactive powers consumed. That is, controlling the voltage and frequency in microgrid operating in islanded mode is very important which must be put into consideration when studying microgrid stability. Whereas in the grid-connected mode, managing the energy of the microgrid system is of utmost importance [2].

Microgrid can be in multi-system network, that is, the cluster of microgrids with large number of DGs integrated together. The multi-microgrid (MMG) reaches power balance by the interaction and cooperation among all the DGs [10]. The interconnection of microgrids is a strategy of expanding and producing a large-scale power generation and integration of distributed renewable energies. It allows two or more microgrids to exchange power with one another so as to facilitate their interaction and operation. Microgrid can be connected together by back-to-back converter or by connecting static switches between the adjacent microgrids [11]. However, multi-microgrid can be grouped as AC MMGs, DC MMGs and AC/DC hybrid MMGs [12]. The control architecture of a multi-microgrid system consists of three levels of control, which are the: distributed management system (DMS); central autonomous management controller (CAMC); and microgrid central controller (MGCC).

The motivating factors for this review work on microgrid control and stability are supported by the operation, the architecture, mode of connection, and some related issues on microgrid control. Many aspects of microgrid have been researched on in the past, ranging from architecture, frequency and voltage stability using different control strategies such as conventional control, intelligent control, droop control, and optimization approach [13]. Fig. 1 shows a general view of a microgrid system [14].

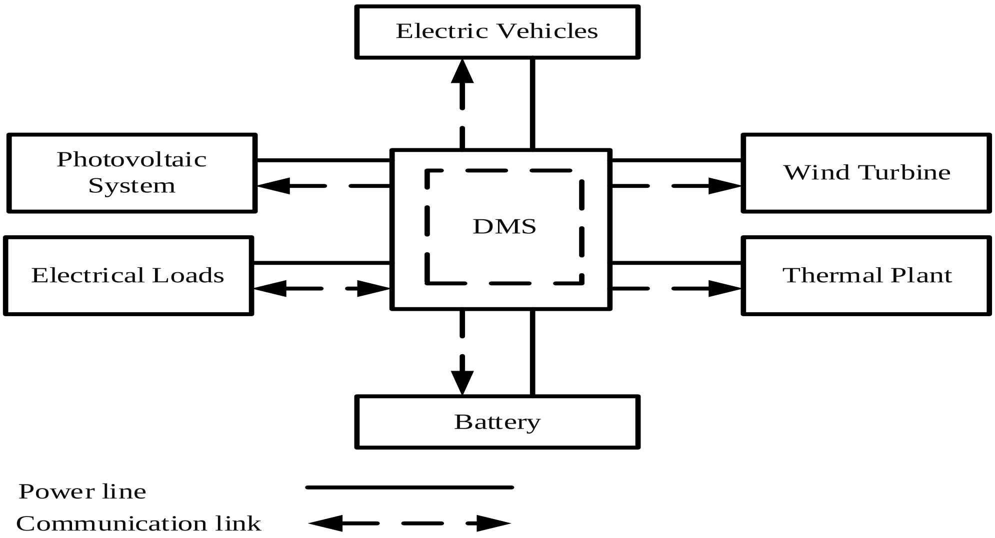

Fig. 1 A General View of a Microgrid System [14].

2. Microgrid Stability

The traditional power system stability problems can be grouped into three categories, namely rotor angle, voltage and frequency instabilities. The rotor angle instability is when the generators that are connected to the network are out of synchronism after they have been subjected to disturbances. The ability to balance the electromagnetic torque of the generator rotor and the mechanical torque is called rotor angle stability. Frequency instability is when there is a variation in frequency whenever there is a disturbance in the power system, while voltage instability is when there is mismatch of voltage across all bus-bars and the generated voltage.

In the traditional power system, the dynamic behavioral characteristic of the synchronous generator plays a vital role in the stability study of power system [15]. Since the source of power supply to microgrid is through DGs, therefore, the dynamic characteristics of the DGs will determine the dynamic behavior of the system. The DGs in a microgrid are supposed to operate in a stable state in terms of protection, operation and control. Frequency and voltage stabilities within the electrical boundaries of the microgrid need to be investigated [16]. The dynamic stability of microgrid process is more complicated than the traditional grid. Microgrid stability can be classified according to the operational mode, time frame, type of faults and physical characteristics of the instability. The operational mode can be grouped into grid-connected stability and islanded stability as shown in Fig. 2 [6].

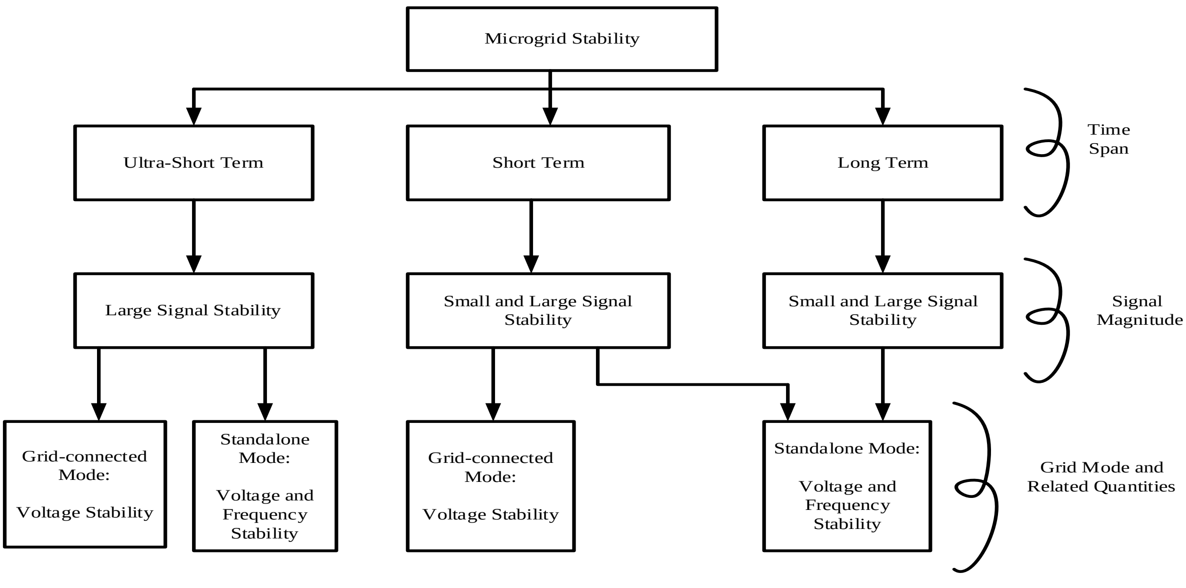

Fig. 2 Classification of Microgrid Stability [6].

2.1. Ultra-Short-Term Microgrid Stability

Ultra-short disturbance in microgrid stability occurs in the system within few milliseconds which can be cause by sudden load variation, starting of heavy electric machines, and this type of disturbance can case threat to the inverter safety. It can be further classified into large signal disturbance, grid-connected and islanded mode. In grid-connected network, the output frequency and voltage are controlled mainly by the main grid. Therefore, stability investigation for DGs and small microgrid may not be necessary. The capacity of a microgrid compared to a utility grid is very small. Therefore, the frequency variation in a microgrid cannot affect the frequency of a utility grid. Frequency stability is not considered in microgrid operating in grid-connected mode [6]. In islanded mode, frequency and voltage stability are investigated because it is like a stand-alone system.

2.2. Short-Term Microgrid Stability

Microgrid stability in terms of short-term disturbance can be grouped into small and large signal stability as a signal magnitude, and this type of stability problem mainly occurs in grid-connected and islanded mode. In grid-connected, only the voltage stability can be analyzed whereas in islanded mode both the voltage and frequency stabilities can be investigated. The stability of a microgrid in islanded mode depends on the structure of the microgrid, the capacities of the DGs, the electrical loads and their control strategies. The energy storage DGs plays a vital role to stabilize the system when power variation occurs.

The research on small signal stability mainly focuses on control gains' influence on the system, load fluctuation and the line impedance variation in the network, while the large signal or transient stability involves large disturbance such as open-circuit fault, short-circuit fault, loss of DG and large load variation. Small signal stability was considered for microgrid control in [17]-[18], while transient stability or large signal stability was proposed in [19].

2.3. Long-Term Microgrid Stability

This type of disturbance lasts long on the grid. It can be as a result of DG failure, serious fault on the transmission line, frequency or voltage collapse and so on. It is further subdivided into small and large signal disturbances and they mainly occur with microgrid operating in islanded mode.

3. Microgrid Control Approaches

There is the need to stabilize and control frequency, voltage and power sharing among all DGs whenever there is power variation or faults in a microgrid network within a short response time. In islanded mode, every DG in the network has the responsibility of regulating the voltage, frequency and also sharing of both the reactive and active powers. Any variation in the phase angle or voltage magnitude of each DG in the network can lead to a high circulating current. These problems have been researched on by using different control strategies to overcome them [7]. A good microgrid controller should be able to perform the following function [3]:

(a) transfer and power sharing should be properly done by the controller according to the capacity of the microgrid;
(b) a controller should have the ability to engaged and disengaged the microgrid from the utility grid;
(c) optimization of power production and power management with the main grid;
(d) controlling the charging and discharging characteristic of energy storage device to improve the microgrid reliability and efficiency;
(e) should be able to operate the microgrid through black-start whenever there is failure on the utility grid;
(f) sensitive loads such as computer servers, medical facilities should be constantly connected to electricity; and
(g) DGs should operate under predefined operating point so as to satisfy the operating boundaries of the microgrid.

Microgrid control can be classified into two categories. These are centralization and decentralization control approaches [3]-[7].

Centralization control approach: This type of control approach focuses on data collection from DGs. The central controller will perform the required calculation and allocate the appropriate control actions for all the DGs in the network. This type of controller requires high bandwidth of communication [20] between the controlled unit (DGs) and the controller and any failure in communication link can lead to system collapse [8]. The power source controllers (PCs) in centralized controller operate like the local controllers (LCs). The controller can be used for online energy management but does not support plug and play within the microgrid [21]. The centralized controller act as the interface between the distributed management system (DMS) and the microgrid [22]. The controller plays different roles ranging from the control of the local controller and has the responsibility of managing the microgrid operation [3]. The centralized control is good for microgrid that has the following characteristics: when the microgrid is to be controlled by the presence of an operator; and when the owners of DGs and the power consumers have common goals in order to meet their target.

Decentralization control approach: A decentralized controller is used to control each unit and it receives the local information from its neighboring units [7]. In a decentralized control approach, the major task of control is given to the DGs to produce maximum power so as to satisfy the power demand and provide maximum transfer of power to the grid [3]. The decentralized control is designed to manage the micro sources and the loads. In the decentralized control, all the DGs operate independently using measured signals. No particular source acts as a reference source. By so doing, deleting or adding sources will not cause disturbance to the operation of other sources. This method requires that all the resources can be dispatched. These types of control do not require communication link and a reference source [7]. In [23], a decentralized control was applied to transfer excess power from the main grid to a PV residential microgrid. This type of control is good for microgrid that has the following characteristics:

(a) the DGs can be owned by different people. In such a situation, several decisions can be taken independently;
(b) microgrid operating with several controller, each unit of the controller participating in the operation of the network should have a certain degree of intelligence; and
(c) the DGs have other operations other than supplying power to the networks, both also producing heat for local installations, to keep voltage and frequency constant and providing a backup system for emergency loads in case of main grid power failure.

3.1. Hierarchical Control

Hierarchical control is to standardize the performance and function of a microgrid. Hierarchical control is classified into three categories: primary control level, secondary control level and tertiary control level as shown in Fig. 3.

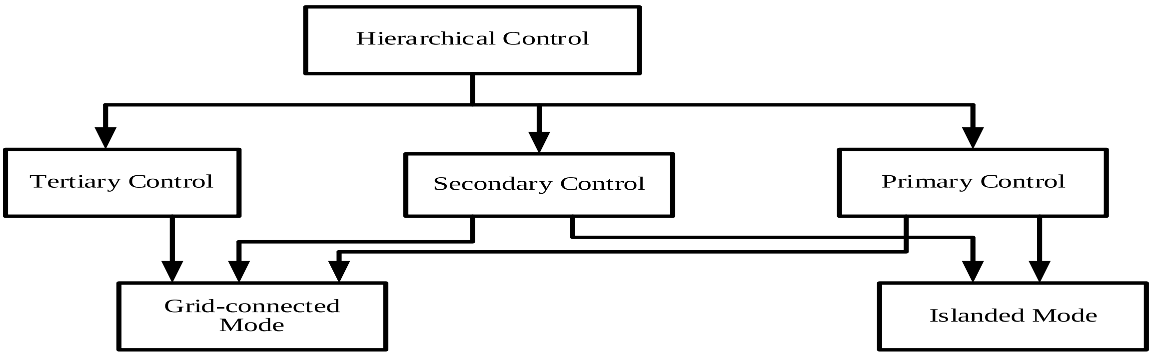

Fig. 3 Hierarchical Control.

Primary control level: The primary control level can be called a local controller or internal controller. This control is focused on local measurement and does not require communication link. The controller's response speed depends on the local measurements. The primary control has the ability to determine the reliability of the system's performance, the stability of the system voltage and frequency by adjusting the output voltage and frequency to form a new voltage and frequency references for the voltage loops and current loops. For effective sharing of power, every inverter on the grid has an output voltage and current loops based on the droop control. Droop control has no communication link, flexible, easy to implement and it accommodates different kind of DGs with different power ratings. It has some challenges like supplying power under unbalanced conditions, slow dynamic responses, pure harmonic sharing, active and reactive power sharing problem, dynamic instability and so on [7]. Primary control performs the following functions:

(a) frequency and voltage stability;
(b) plug and play of DGs;
(c) the internal control of DGs to meet voltage and frequency reference; and
(d) have the ability to work in both grid-connected and off-grid connected network.

Secondary control: This type of controller has the ability of restoring the voltage and frequency of a microgrid and synchronizing the network. The secondary control method ensures that voltage and frequency steady error must be equal to zero after being subjected to any disturbance within the microgrid. The voltage and frequency of a microgrid can be measured and compared with the reference voltage and frequency of the network [7]. The secondary control can perform the following functions:

(a) to improve power quality in the network;

(b) synchronization of the microgrid with the main grid; and

(c) restoration of voltage and frequency of the network.

Tertiary control: This type of control level helps to manage the power flow of a microgrid when operating with the main grid. That is, it has the ability of managing and regulating the power flow between the main grid and the microgrid, as well as carrying out optimal power flow by supplying power balance between the main grid and the microgrid. The tertiary control do not only manage the power flow in the microgrid network, but also manage the economic status of the system and restore the secondary control reserve and support the secondary control level when necessary [7]. The main functions carried out by the tertiary controller are:

(a) power flow management and control in grid-connected mode; and

(b) optimal power management in grid-connected mode.

3.2 Conventional Control Strategy

A conventional control strategy requires a lot of mathematical computation and is more complex compared to the artificial intelligent control. In conventional control strategies, a lot of control techniques have been employed by different researchers. The control techniques for Droop control have been presented in [24]-[25]. A reverse droop control strategy without any communication link was applied and tested on a severe fault, load changing condition and the disconnection of one of the DGs were considered in [26]-[27]. An improved droop control with distributed secondary power optimization deployed for frequency and voltage stability was considered in [28]. In [29]-[30], robust controller was deployed to control the voltage and frequency of a microgrid. In [5], robust controller was used to track the output voltage while optimal and regional pole placement controls were applied to achieved optimal control objective in order to improved transient responses. Fractional order PID (FOPID) control with static Var compensator (SVC) was applied to improve the reactive power and voltage stability of a standalone microgrid in [31]-[32]. A mathematical investigation using algebraic-type virtual synchronous generator to suppress frequency and voltage variation of a microgrid was carried out in [33]. A robust control was developed in [34] to minimize the frequency deviation in a microgrid cause by the stochastic nature of the load and renewable energy sources.

Some of the drawback of the conventional control approach is that it requires proper parameter tuning and it is mathematically demanding.

3.2. Artificial Intelligent Control Strategy

The application of artificial intelligence in microgrid control and stability has been proven in literature to produce more accurate results and it is easy to implement compared to the conventional control strategy. The artificial intelligent controls that researchers have deployed for microgrid stability from past literature are reviewed as follows: The authors in [35]-[36], applied particle swarm optimization (PSO) to control the active and reactive powers of a microgrid. Authors in [37] presented an improved PSO with a regression neural network deployed to control a hybrid microgrid system with a static Var compensator (SVC), and it was observed that the voltage and the power were properly controlled in a changing environment. In [38], a fuzzy PI controller was used to stabilize frequency and to improve the power quality in an hybrid microgrid that contains a microturbine, fuel cell and electrolyzes. A goal representation adaptive dynamic programming (GRADP) was applied to control the load frequency of an islanded microgrid, the method gave a better result compared to PSO, PID and fuzzy logic controller as presented in [39]. An emotional controller with a self-tuning nature was adopted; the controller focuses on the emotional learning process of the human brain to regulate the load frequency of a microgrid. The controller was able to provide a good control against parameter changes and uncertainties occurrence in a microgrid. It was compared with other controllers like PI and fuzzy controller. A stochastic control and adaptive modified firefly algorithm were deployed to control and operate an hybrid microgrid in [40] and artificial bee colony (ABC) was used to tune a PI controller parameters for frequency and voltage stability for an hybrid microgrid in [41]. The load frequency performance for a multi-microgrid operating in an islanded mode was controlled using type-II fuzzy PID controller in [42], while an improved-salp swarm optimization (I-SSO) algorithm was used to tune the gain for the controller in [43]. Advanced intelligent controllers like multi-agent system (MAS) have been deployed by different researchers. MAS can be defined as a collection of multiple agent, which can function in a complex application to perform tasks based on their environment and tasks that are difficult to define analytically [44]. In MAS, an agent can share information about its goals and achievement with other agents, also agents have the ability to accept, reject, propose or counter-propose course of action by relating the information with other agents. From literature, several works have been done on microgrid control using MAS in [45]-[46]. In [47]-[48], MAS technique using model predictive control technique was used to control and optimize the operation of a microgrid, however voltage and frequency stability of the system still needed further improvement.

3.3. Optimization Control Strategies

In microgrid operation, there is need to improve the energy efficiency, cost of energy, reliability of the system, power quality, and voltage profile. Several research works have been carried out using optimization technique to improve microgrid operation. In [49]-[50], optimization algorithm was developed to control the operation of a microgrid. In [51], the authors applied seeker optimization and fuzzy logic for tracking solar energy for maximum output and energy cost management, the proposed method gave a better result when compared to PI controller in the area of power sharing. Sunflower optimization algorithm was used to tune a PI controller to improve the performance of an inverter based microgrid in [52] and the proposed method was tested when disconnected from the grid, on different fault condition and when operating on stand-alone. In [53], a two-level interactive optimization algorithm was deployed for active distribution network with microgrid to improve operating cost and voltage profile of the network. An hybrid algorithm which comprises of particle swarm optimization and bat colony was used to optimize the location of solar energy and improve the microgrid operation in [54] and firefly and particle swarm optimization was used to tune the parameters of proportional-integral-derivative (PID) controller for frequency control in microgrid [55]. Optimization technique was applied to optimize the maximum capacity, state of charge and discharge and state of health of the battery connected in microgrid in [56]. In [57], optimization technique was used to optimize the operational cost for a centralized microgrid control.

3.4. Nonlinear Control Strategy

Some researchers have applied nonlinear control in different areas of microgrid. In [58], a model predictive controller was deployed to control the voltage and frequency of an outer voltage loop control of a voltage source inverter, while sliding mode controller was designed to control current in the inner loop; however, the system stability was not considered in the work. The energy management of a microgrid was examined using model predictive controller in [59]-[60]. In [61], an adaptive second-order sliding mode controller was designed to control grid-connected microgrid, four different strategies were developed under uncertain condition with unknown uncertainty bound. Two of these strategies were able to exhibit stability properties. In [62], a fractional order sliding mode controller was designed to maintain the output voltage of the distributed energy resources (DER) regardless of the unbalanced load current and protect the inverter from external faults of a microgrid operating in islanded mode. A higher-order of sliding mode controller was designed to operate a microgrid both in grid-connected and islanded mode. A second-order sliding mode was proposed to operate the microgrid in grid-connected and a third-order sliding mode was proposed to operate a microgrid in islanded mode were presented in [63]. In [64], a fuzzy sliding mode based on unified power flow controller (UPFC) was used to analyze transient stability of a microgrid operating in islanded mode, the DGs were modeled using a linear small-signal model and was studied under varying loading conditions. In [65], adaptive sliding-mode was adopted to provide a new solution for inverters based microgrid in terms of control structure and configuration; the control structure such as the inner voltage control loop, the outer power control loop and the output impedance loop were controlled using three-order sliding mode controller. A robust sliding-mode control was applied to regulate the voltage and frequency of a microgrid in [66].

3.5. Hierarchical Control Strategy

Some researchers have been able to combine the primary and secondary control levels for the study of microgrid stability. In [67], a distributed secondary control level was deployed to restore frequency and voltage changes produced by droop control, which was applied to the primary control level with a low bandwidth communication link. In [68], the primary control level was equipped with a regulator for voltage and frequency stability design to be controlling the voltage source converters and this regulator consists of plug and play algorithm and virtual impedance loops. Microgrid primary control level has been controlled by some researchers using artificial intelligent control together with droop control or nonlinear control. In [41], active and reactive powers (PQ) control with droop control are deployed for microgrid control. The PQ control was used in controlling the active and reactive powers of the DGs according to their capacities. Two PI controllers were used to design the PQ control. An artificial bee colony (ABC) was used to tune the PI parameters while the droop control was used to share power among the DGs. In [69], a distributed secondary control using multi-agent controller was researched on. In the method, each of the DGs needed its information and the information from some of its neighboring DGs. The feedback was linearized by converting the secondary voltage control to a linear second-order problem, but it still requires the need for complex communication network. A comparison of the different control strategies is presented in Table 1.

Table 1 Comparative Analysis of the Control Strategies.

Control Strategies	Strength	Weakness
Droop control	Very easy to implement. It has a better load sharing ability.	Not suitable for network with high X/R ratio.
PID control	The gains can be estimated using artificial intelligent (AI) or optimization approach for a better performance.	It requires proper modeling of the DGs.
Artificial Intelligent control	The results are more accurate than the conventional control method. When deployed alone, it does not require the entire model of the system.	They are mainly restricted as a tuning method for microgrid control.
Optimization control	They are mainly deployed for energy cost and management on microgrid network.	They cannot be deployed for power stability purpose alone.
Nonlinear control	They are robust and give wide range of control compared to other methods.	They are mathematically demanding.

4. Energy Storage Systems and Electricity Loads in a Microgrid Network

Energy storage systems (ESSs) in an electrical network system can be provided by using different kinds of technologies. These technologies can be grouped into pumped hydraulic energy storage devices (PHS), energy storage system with compressed air (CAES), flywheel energy storage devices (FWES), battery energy storage devices (BESS), superconducting magnetic energy storage devices (SMES) and super-capacitor or ultra-capacitor energy storage (SCES). ESSs can be classified based on the type of energy that is stored in them, for example a mechanical energy storage device can store kinetic or potential energy, while electrical energy storage system can store electrostatic or magnetic energy. The mostly used technologies of a microgrid today are BESS, FWES, SCES and SMES. However, BESS has proven to be more reliable and more economical [70].

The storage technologies can be classified into two categories: long-term and short-term storages. The long-term storage also called large-scale or grid-scale storage has the capability to store large amount of electricity ranging from few to hundreds of megawatts. Examples are large-scale battery, compressed air energy storage and pumped hydro storage. They can be applied for long-term voltage control, congestion management and energy arbitrage. The short-term storage also known as transient storage is manly used for frequency regulation, power quality improvement, and power smoothing and short-term voltage control. Examples are flywheel energy storage, superconducting magnetic energy storage, ultra-capacitor and small-scale batteries. Energy storage devices are used in microgrid as a backup to ease a balance between the supply and the demand side of the microgrid [71]. The unit can supply power to the grid by the process of discharging or taking surplus power from the grid by the process of charging [13].

The researches that have been done in this regard are reviewed as follows: A hybrid energy storage system (batteries and super capacitors) was used to stabilize the frequency of an autonomous microgrid in [72]-[73]. In [74], electric vehicle was used as energy storage device in the control of a microgrid. In [75]-[76], optimization method was used to size battery energy storage system for the control of frequency in a microgrid. Battery energy storage system (BESS) was used to control the frequency variation in a microgrid in [77].

The electrical load in a microgrid network can either be active or passive. An active load can be electrical machines, power converter which include the different types of configurations, and electronics appliances with unity power correction; while passive load can be an incandescent lighting, a resistive heater, a resistive or a resistive-inductor network [78]. In [78]-[79], active load was considered in the investigation of microgrid stability. A constant power load was applied when considering the stability of a microgrid in [1], [80]. In [81]-[82], electronics load was adopted in the control of frequency in a microgrid and a laboratory-scale prototype was used to verify the proposed method. A load shedding approach was used to stabilize a microgrid in [83].

4.1. Challenges on Energy Storage Devices in a Microgrid

The challenges on energy storage devices used in a micro grid are:

(a) energy storage systems (ESS) charging and discharging process is nonlinear which can act as a disturbance on the microgrid [84];

(b) the problem of aging of the electrical storage devices, imbalance charging device, cell parameter variation; and

(c) they are expensive, and their performance is not sufficient to realize good economy [71].

5. Further Research Areas/ Problems in Microgrid Stability

Areas of further research as well as problems associated with microgrid stability are:

(a) weather forecast of renewable DGs and load forecast need to be researched on for the investigation of microgrid stability;
(b) there is need for more advanced intelligent and nonlinear controller for microgrid stability and control;
(c) there is need for more research on the mathematical modeling of DGs and all the components in a microgrid operating in islanded or grid-connected mode to understudy transient stability;
(d) further research on the modeling and control of a self-configured microgrid using automated load management; and
(e) renewable energy sources (RES) and the electrical loads are nonlinear in nature.
(f) from the literature, researchers have not really modeled renewable energy sources in their stochastic nature together with the electrical loads so as to use the stochastic variables to control the microgrid operation.

6. Conclusion

Microgrid is a fast-growing sector in the power industry. Several research works have been done on microgrid in the past which includes: stability, power flow, reliability, energy management, hybrid system, multi-microgrid system and so on. Different control strategies such as droop control, conventional control, optimization control, nonlinear control, and intelligent control that have been applied by different researchers to study stability problem and energy management in microgrids were reviewed in this work. Additionally, the application of energy storage devices and different types of electrical loads in the area of microgrid stability were also reviewed. From the available literature, gaps identified were listed and the current research problems in the area of microgrid control were also presented for further research in scientific community.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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