Applied Energy 240 (2019) 583–607

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Microgrid control methods toward achieving sustainable energy management

M.F. Roslan[a], M.A. Hannan[a,*], Pin Jern Ker[a], M.N. Uddin[b]

[a] Institute of Power Engineering, Department of Electrical Power Engineering, College of Engineering, Universiti Tenaga Nasional, 43000 Kajang, Malaysia
[b] Department of Electrical Engineering, Lakehead University, Thunder Bay, ON P7B 5E1, Canada

HIGHLIGHTS

- MG technologies and their methods provide an immune contribution on the EMS.
- Comprehensive reviews on the MG control strategies and EMS are explained.
- Main focus is the MG control methods for sustainable energy utilization.
- MG technologies are performing; however, further research is needed for future sustainable operation.
- Factors and challenges are highlighted for future MG control technologies.

ARTICLE INFO

Keywords:
Microgrid
MG control method
Energy management system
Sustainable energy
Renewable energy sources

ABSTRACT

Microgrid (MG) technologies exhibit attractive features such as high power quality, reliability, sustainability and environmental friendly energy to the consumers using control and energy management system (EMS). However, renewable energy sources integrated with MGs are intermittent due to their stochastic behavior. Therefore, a proper control technique is essential to ensure a smooth transition of MG power to sensitive loads and the main grid. This study comprehensively reviews MG control strategies and their classifications in terms of protection, energy conversion, integration, advantages, disadvantages, and EMS. It focuses on conventional and advanced control methods that are used in MG applications for sustainable energy utilization. The algorithms, advantages, and disadvantages of conventional and advanced control methods are explained, and possible improvements or hybridization for future grid control applications is highlighted. Maximum Power Point Tracking control algorithms are also highlighted to maximize the power generation of renewable sources in the MG system. The rigorous review indicates that existing control technologies can be used for MG operation; however, further technological development of control methods is needed to achieve sustainable MG operation and management in the future. This review also underscores many factors, challenges, and problems related to the sustainable development of MG control technologies in next-generation smart grid applications. Thus, this review will strengthen the efforts to develop economic, efficient, and long-lasting MGs for future smart grid use.

1. Introduction

Distributed energy resources (DERs) are electricity-producing resources or controllable loads. Examples of DERs include solar panels, combined heat and power plants, fuel cells, electric vehicles, electricity storage, and wind power. These energy sources are directly connected to local distribution systems or host facilities within local distribution systems. The adoption of DERs changes the manner of energy transmission through utility power grids, which provide flexibility in energy utilization. A high penetration of distributed generation (DG) into grids brings challenges to the operation and stability of power systems. Hence, proper microgrid (MG) architecture and control techniques for DERs are important to ensure the stability, safety, and efficiency of power systems [1]. One of the most attractive features of MG technology is its capability of operating under grid-connected and autonomous modes [2,3]. In recent years, substantial research has been conducted on the design, control, management, and operation of MGs. In an MG system, an energy management system (EMS) is used to manage the power and energy between sources and loads and to provide high quality, reliable, sustainable, and environment-friendly energy to

* Corresponding author.
E-mail address: hannan@uniten.edu.my (M.A. Hannan).

https://doi.org/10.1016/j.apenergy.2019.02.070
Received 24 October 2018; Received in revised form 9 February 2019; Accepted 12 February 2019
Available online 20 February 2019

consumers [4]. The EMS is a vital supervisory controller in an MG system. Therefore, its voltage and frequency in the MG system, especially during autonomous operations. must be regulated.

Although MGs can function in grid-connected and islanded modes, their configurations are mainly classified as alternating current MG (ACMG), direct current MG (DCMG), and hybrid MG. A hybrid MG consists of AC and DC networks and a power converter located between both networks that regulates power flow to the grid; it combines the advantages of AC and DC networks provide good system features [5]. Several features, such as adequate power sharing of renewable energy sources (RESs) and energy storage system (ESS) units, voltage and frequency stability, optimal power exchange between grids and MGs, and operational control and transition for both modes of MGs, were reviewed in [1,6].

MGs comprise various DGs such as photovoltaic (PV) systems, wind turbines, fuel cells (FCs), ESSs, and loads. Energy production based on these sources is intermittent due to their stochastic behavior. Therefore, a proper control technique is essential to ensure a seamless transition of power in MGs, especially after disconnection from the main grid. A proper control technique also improves the power quality of MGs and keeps the voltage and frequency fluctuations and phase angles within acceptable levels because once MGs are disconnected from the grid, they keep the voltage and frequency stable in order to supply and sustain electricity generation to consumers properly. Conventional methods have been utilized for both modes of MG systems to ensure their efficiency and robustness [7].

In an MG system, integrating numerous DG results in difficulties in system control, which in turn lead to poor power quality, security, stability, and reliability [8]. The improper control of MGs leads to the instability of the dynamic and transient response of the entire grid because a power sharing method emerges in MGs, especially when the grid is on islanded mode in cases of power disturbance. For example, the control of voltage source inverters (VSIs) for MG systems is necessary for proper power management because of the power sharing parallel inverters in MGs. Hence, several studies on power sharing methods indicate that the integration of DG units into MG systems affects transient stability [9]. Frequency, voltage, and power quality are the three main parameters that need to be considered in stability analysis and require a proper control scheme to meet acceptable standards [10]. In recent studies, the reliability of MG systems was assessed by considering the constraints of reactive power compensation to achieve voltage control, reduction of power loss, and spinning reserve to support generation outages; such consideration exerts a positive impact on distribution networks [11]. The present study aims to review and briefly discuss the evolution of controllers and their applications according to need, classification, implementation, stability, and protection of MG systems toward the enhancement of reliability, efficiency, and power quality.

2. Energy management system of MGs

The EMS of MGs determines the optimal dispatch and schedules of DERs and is responsible for their economical and reliable operation [2]. The management of MGs as multi-generation sources ensures an uninterrupted power supply to the load. The EMS of MGs is comprehensively discussed according to the various types of management because the proper management of energy from different sources must be guaranteed and scheduled to satisfy demands. The EMS of MGs comes in the form of supervisory controllers that provide the necessary functions of power quality control, optimization of operation, and economic analysis through the enhancement of their intelligence level [12]. Fig. 1 shows a typical configuration of an EMS in an MG system.

The EMS is aimed at attaining an economically feasible MG and maximizing the reliability of the operation of the MG system for consumer satisfaction. The recent research on EMSs developed accurate algorithms to optimize DERs while minimizing the objective functions with consideration of all constraints of integrated systems. These constraints were considered in [13–15]. The EMS also provides MG systems with the ability to resynchronize the responses to the operating transition between interconnected and islanded modes on the basis of real-time operating conditions and status of the MG systems [16,17]. Harmonics may be generated due to the intermittent energy generation of DER units and thus interfere with controller performance. This interference can be minimized by introducing a supervisory control system, such as SCADA and Zigbee devices, which are able to control, monitor, manage, and direct the flow of energy among various sources to ensure the effective use of such resources [18–21].

2.1. Classical method-based MG EMS

According to extensive critical reviews, many strategies have been developed and solved by researchers to provide efficient and optimal solutions to the application of EMSs to MGs. Ref. [22] proposed a mixed-mode EMS strategy for MGs to operate at a low cost. This method combines the continuous run mode, which is assigned to FC operation to continuously deliver output power to meet load demands; power sharing mode, which is characterized by power trading with the main grid; and on/off mode, which covers the connection status of the main grid, FCs, and ESSs. The sizing of ESSs is also considered in these strategies because this factor influences the operating cost and EMS of the MG system. In a previous study, an optimized EMS was proposed to control the MGs of a remote military base [23]. These classical methods are considered to improve the size of ESSs in MGs according to the days of operation with power electronic interfaces for bidirectional power flow decisions. In another study, a mixed integer nonlinear EMS model was proposed for the optimal operation of different generation technologies with consideration of islanded MGs [24]. The minimization of the generation cost of electricity from a dispatchable DG unit is formulated as an objective function, and the active and reactive power of AC-side DG units have droop control as a constraint in the proposed model. These MG EMS strategies are mostly used in a centralized supervisor control architecture, which focuses on DG optimization in MGs.

2.2. Energy box-based MG EMS

The energy box is a central control unit that provides an EMS for an electrical power system that coordinates and manages electricity use, storage, and energy trading with the main grid for small consumers of electricity [25]. In other words, the energy box is capable of coordinating net electricity consumption time scales in seconds and minutes to provide energy savings for consumers and facilitate the creation of a smart demand management application to fulfill consumer requirements (comfort, load shedding, and financial savings). The automated synchronization system of an energy box is a major concern in grid management because it is used to coordinate and respond to the oscillation prices of electricity and to control the net electricity consumption in demand management [25]. Hence, this automated response system requires a sequential decision-making process to balance the net electricity consumption between consumers and the grid. This system covers scheduling and shifting electricity consumption in DG units for consumers and comprises local storage devices to achieve a global optimum controller in EMSs. Approaches such as stochastic dynamic programming and communication infrastructure have been presented to provide reliable and flexible EMSs. One proposed algorithm is integrated in an energy box system as a decision-making strategy under uncertain conditions to determine an optimal control signal for using, storing, and selling electricity among consumers and grids based on forecasting methods [26]. An active distribution network fully integrated with demand and DERs provides a framework for the energy box system by integrating it with the aggregator level of controllers to provide a smart EMS to consumers. This approach focuses on

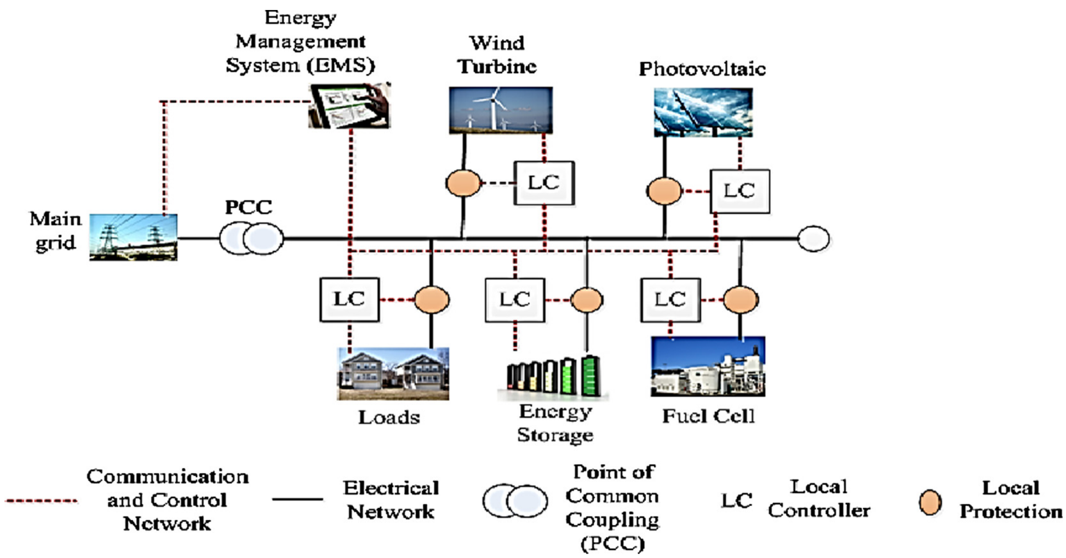

Fig. 1. Energy management system of an MG.

domestic and small commercial consumers with consideration of active demand response and provides a smart control of the net electricity of consumer levels via a signal associated with average power consumption and power ranges over a specific period [27]. The design and implementation of the presented framework were also addressed in the study associated with smart communication methods. Another researcher presented a concept of a virtual power plant as an energy box controller, which aggregates small capacity generation, storage, and demand units into one large system that operates as a single entity. In this concept, the energy box controls the electricity generation from RESs and the storage and consumption of each consumer. This approach presents a real-time EMS framework, which can control distributed generators, loads, and devices for local electricity storage [28].

2.3. MG mode of operation

According to the Consortium for Electric Reliability Technology Solutions (CERTS), MGs consisting of clusters of DERs, storage systems, and loads can operate in two modes, namely, grid-connected and islanded modes [29]. In this section, these modes are discussed in detail.

2.3.1. Grid-connected mode

In the grid-connected mode, the MG can supply or draw power from the local grid contingent upon the generation and load demand of the system [30]. Typically, an MG is connected to the main grid via a single point of common coupling (PCC) regarded as the point of interconnection and is usually linked to a distribution system at low or medium voltage (MV) levels. The integration of battery energy storage systems (BESSs) in MGs considerably benefits operations because BESSs act as a power supply under discharging mode and as a load under charging mode [31,32]. BESSs in MGs are able to maintain voltage and frequency fluctuations within acceptable limits to ensure the sustainability of MG systems. In general, BESSs are utilized in combination with RESs in MGs to provide backup generation and peak load operation during prolonged grid outages, grid stability services to control voltage and frequency regulations, and demand responses under grid-connected mode. Several attempts have been made to solve issues such as BESS sizing, optimal scheduling, energy management strategy, and control of MGs in grid-conned modes to achieve efficient generation [31–36]. Fig. 2 shows the general configuration of the grid-connected mode of an MG, which consists of a PCC.

2.3.2. Islanded mode

In islanded mode, the MG is separated from the upstream distribution grid and provides a reliable power supply to consumers on the basis of DG bids. With the integration of a BESS into the MG system, the reliability and efficiency of the system increases, and the system is able to smooth out power fluctuations in renewable energy generation. In emergency situations, such as the disengagement of the MG from the main grid due to faults at MV networks, the MG operates autonomously in islanded mode with the help of DG and the BESS to maintain its integrity [37,38]. The main aim is to control and maintain the voltage and frequency of the system. After islanding, the synchronization of the reconnection of the MG is achieved autonomously using frequency differences between the islanded mode and the utility grid [36,39–42]. Fig. 3 shows the configuration of the islanded mode of an MG with static switch for transition purposes.

3. Classification of microgrids

According to the modes of operation stated by CERTS in [29], the MG system is classified into three types. As shown in Fig. 4, the classifications are alternating current MG (ACMG), direct current MG (DCMG), and hybrid ACDC MG.

3.1. Alternating current microgrid (ACMG)

The power sources and load in an ACMG are connected [43]. An ACMG is connected to a utility grid through a PCC or point of interconnection (POI), in which switches transition the modes of the MG. DERs that generate a DC voltage in the system, along with storage systems, require a power electronic interface to connect to an AC bus system. Fig. 5 shows a general configuration of an ACMG system connected to a utility grid through PCC modes.

An ACMG is easy to integrate to existing power systems to provide reconfigurable systems. The loads, generator, and storage device must be compliant with the grid because the latter contains the same feeders. The main drawback of the ACMG system is its requirement of large and complex power electronic interfaces to synchronize DERs with the utility grid and thereby prevent harmonic impact on the system [44]. However, parameters such as frequency, phase angle, and voltage magnitude need to be matched and balanced with the grid. This requirement limits the application of ACMGs to power systems. In general, ACMGs involve more conversion steps than DCMGs do [44,45].

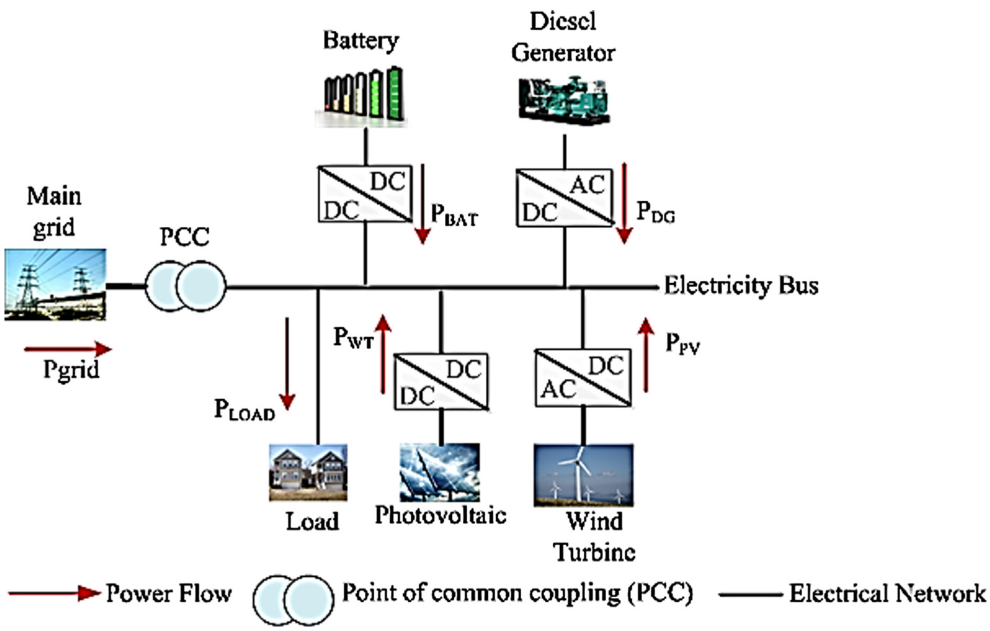

Fig. 2. Grid-connected mode of MG configuration.

3.2. Direct current microgrid (DCMG)

A DCMG is a system that is connected to DC power sources and loads. This system can be easily incorporated with DG units because it only controls DC voltage. Energy storage and RESs operate in DC mode. The DCMG is connected to a utility grid via a PCC at a distribution system. In this mode, the PV, DC loads, and energy storage can be easily connected to the DC bus via a DC–DC converter. Wind turbines and diesel generators are connected to DC buses via AC–DC converters. Fig. 6 illustrates the configuration of a DCMG system.

This type of MG has a simpler structure than an ACMG does because it does not require the grid synchronization of DERs, harmonics, and reactive power flow. This configuration results in a simple structure and control requirement and can thus improve system efficiency [44]. Reliability issues arise in this type of MG because of the use of a power electronic converter, which is serially connected to the system and leads

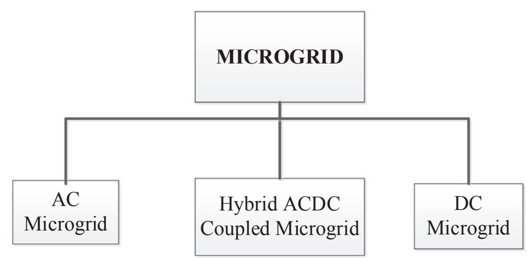

Fig. 4. Classification of microgrids [42].

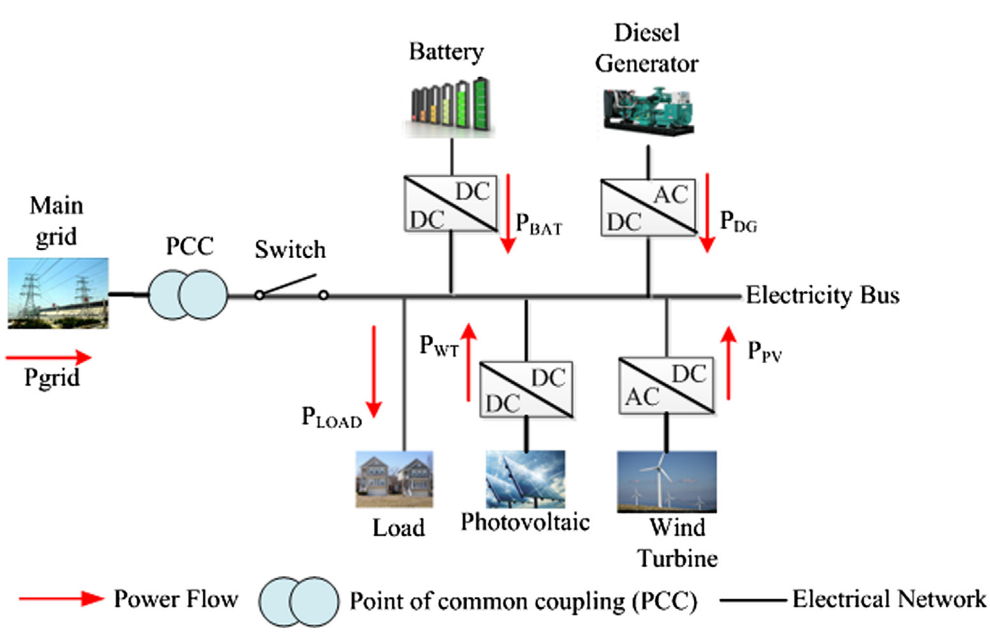

Fig. 3. Islanded mode of MG configuration.

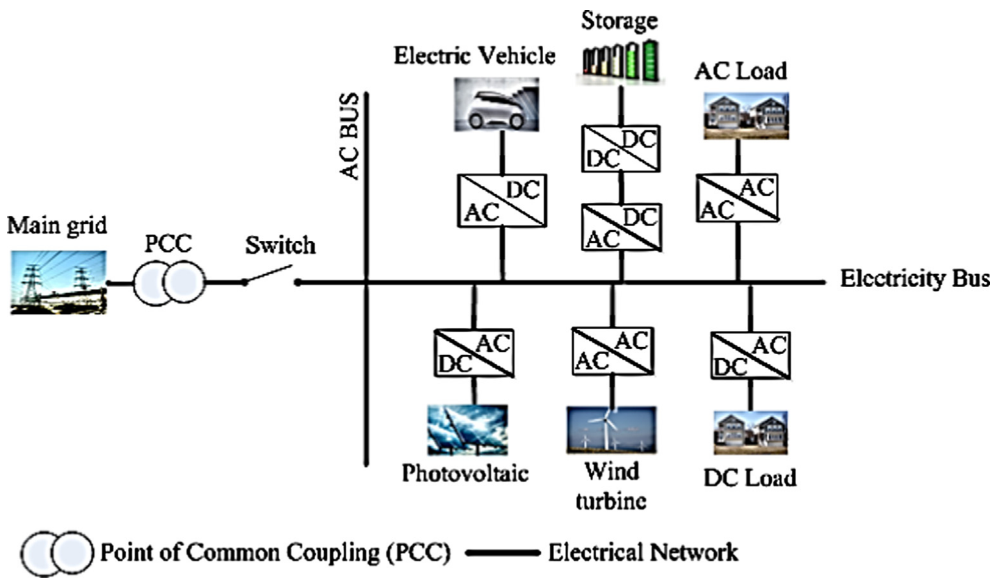

Fig. 5. Typical ACMG architecture [1].

to the inefficient handling of the power flow from/to the distribution grid [46].

3.3. Hybrid AC–DC microgrid (HMG)

A hybrid microgrid (HMG) consists of connected ACMG and DCMG. Generally, an ACMG is directly connected to the PCC, and a DCMG uses a bidirectional AC/DC converter to connect to the AC bus [5]. The controller for various converters in the HMG is essential to ensure the stability and efficiency of the MG system. As shown in Fig. 7, the controller is located between the utility grid and the system bus because an AC–DC converter acts as the main converter in the architecture to manage the power flow between the ACMG and the DCMG and the voltage of the DC bus. The major advantages of this HMG are listed in Table 1. The issues concerning the control strategies of the HMG are discussed in [6].

Table 1 presents the comparison of different MG infrastructure with respect to the type of operation. A few experimental studies on MGs corresponding to the type of operation in several countries have been carried out, as described in [47].

4. MG control methods

The MG is the most interesting system in renewable energy generation because it can minimize consumption and cost in a specific geographical area by providing cheap and green energy to users. Therefore, a proper control technique is essential to meet the above objective in terms of power flow between MGs and the main grid to ensure a seamless transition and automation in cases of sudden disconnection. Furthermore, a proper control method is needed to control the stochastic generation behavior of DG units in MGs. The conventional control described below can be classified into a few methods that are applied to MG systems to enhance their efficiency and reliability and thus meet consumer satisfaction. Fig. 8 presents a detailed classification of MG control methods commonly used in MG operations [7,49–51].

4.1. Conventional MG control method

Conventional control methods have been widely applied in MGs to maintain voltage and frequency stability and regulation, especially

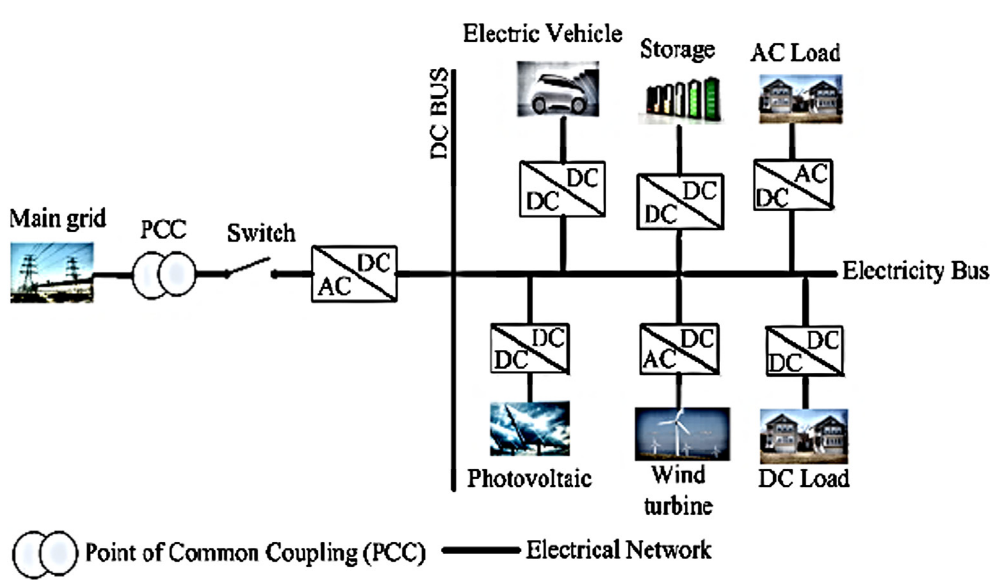

Fig. 6. Typical DCMG architecture [1].

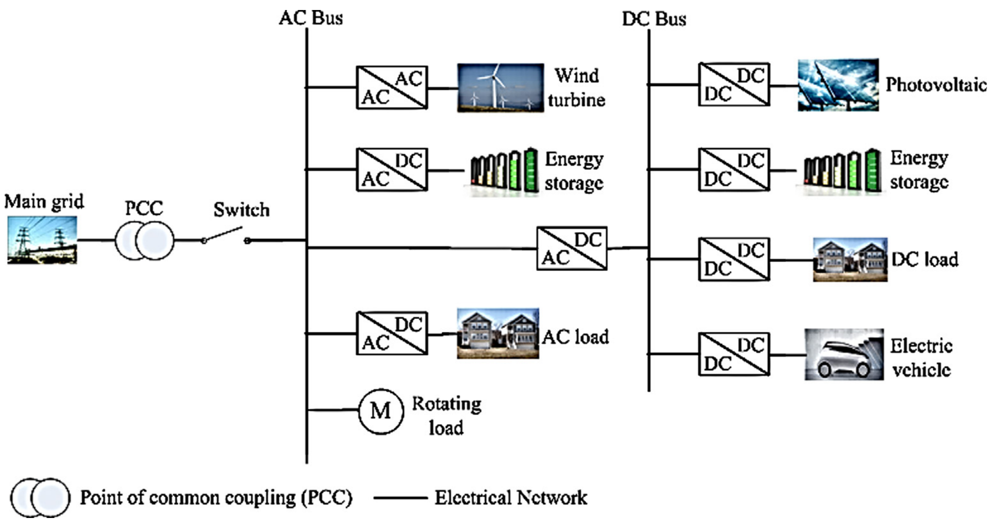

Fig. 7. Typical HMG architecture [6].

during network events. In general, MG voltage and frequency are regulated with power generation dispatch in a hierarchical control level structure [52]. Hierarchical control comprises tertiary, secondary, and primary control levels. Primary control levels are considered to be the most challenging because of the need to ensure real-time frequency and voltage stability upon disturbance [52]. The following section describes the conventional control methods for obtaining voltage and frequency within acceptable levels in MG applications. Table 2 provides a summary of the conventional control methods in MG applications.

4.1.1. Droop control method

The conventional droop control method aims to adjust active and reactive power (power quality, PQ) output on the basis of frequency and voltage deviations to avoid using communication links among parallel-connected converters. In grid-connected mode, the main objective is to ensure the efficiency of the EMS in organizing energy production or dispatch and scheduling each DG unit. In islanded mode, the goal is to control or maintain the voltage and frequency of the system within a specific desired limit or level. Hence, the output voltage frequency and amplitude of the inverter must be able to independently compensate for active and reactive power imbalance via load sharing [2,53–55]. Many droop control schemes have been proposed for linear load sharing in MGs [42,53,54,56]. However, they are limited by their slow transient response that requires a low-pass filter, unbalanced sharing of harmonic currents, and the inherent trade-off of voltage and power sharing [42,53]. In the droop control method, each unit uses frequency to control the active power flows instead of the power or phase angles because of the uncertainties of the initial phase values among the units in the stand-alone system. A block diagram of the droop control strategy is shown in Fig. 9. The frequency and terminal voltage deviations are measured in the input controller. The drop characteristic is selected to rate the unit capacity to prevent overloading.

4.1.2. Virtual output impedance

Several droop control techniques have been proposed to overcome the limitations of conventional droop control techniques and to improve the performance of parallel-connected inverters in DG systems. The virtual output impedance method was introduced to increase power sharing accuracy in MGs [57,58]. This control scheme is aimed at improving the steady state and transient response of parallel-connected inverters while providing good active and reactive power

Table 1
Summary of MG classifications.

Type	Protection scheme	Voltage conversion	Integration	Advantages	Disadvantages	References
ACMG	Over current relays; reclosers; sectionalizers (SCB); miniature circuit breaker (MCB); fuses	Uses AC/DC/AC converter for stable coupling; AC load directly connected to bus line; requires AC/DC converter for DC loads	Requires conversion levels to integrate with DCDG units; AC needs synchronization; integrated with high frequency ACDG units	Easy reconfiguration by existing grids; required synchronization of DG units	Difficult synchronization with host grid while maintaining frequency, phase angle, and voltage magnitude; low efficiency and reliability; complex architecture and controller	[1,48]
DCMG	Utility protection; fuses; molded-case circuit breaker (MCCB); power circuit breaker (CB); static switch (SS); isolated case (CBs)	Bidirectional DC/DC and DC/AC (inverter) power converter connected to bus line	Easy to integrate with PV cells, wind turbines, and FCs	DC loads can connect directly to DC bus; low number of power converters required	Voltage is not standardized; required additional power stage to generate AC voltage; cannot be reconfigured from existing grid; protection is complicated	[1,46,48]
HMG	AC and DC links connected through two transformers and two four-quadrant operating three-phase converters	Uses a transformer for the AC side for voltage conversion; uses DC–DC converter for the DC side for voltage conversion	Direct integration; suitable for DC-based generation (examples: PV, electric vehicles, FCs, energy storage); does not require power converters	Direct connection to the grid; does not require synchronization of DG units because it can directly connect to the AC or DC network; controllers are simplified; reduces energy loss	Low reliability; complex controller and management, especially in islanded mode; combined architecture of ACMG and DCMG	[5,6]

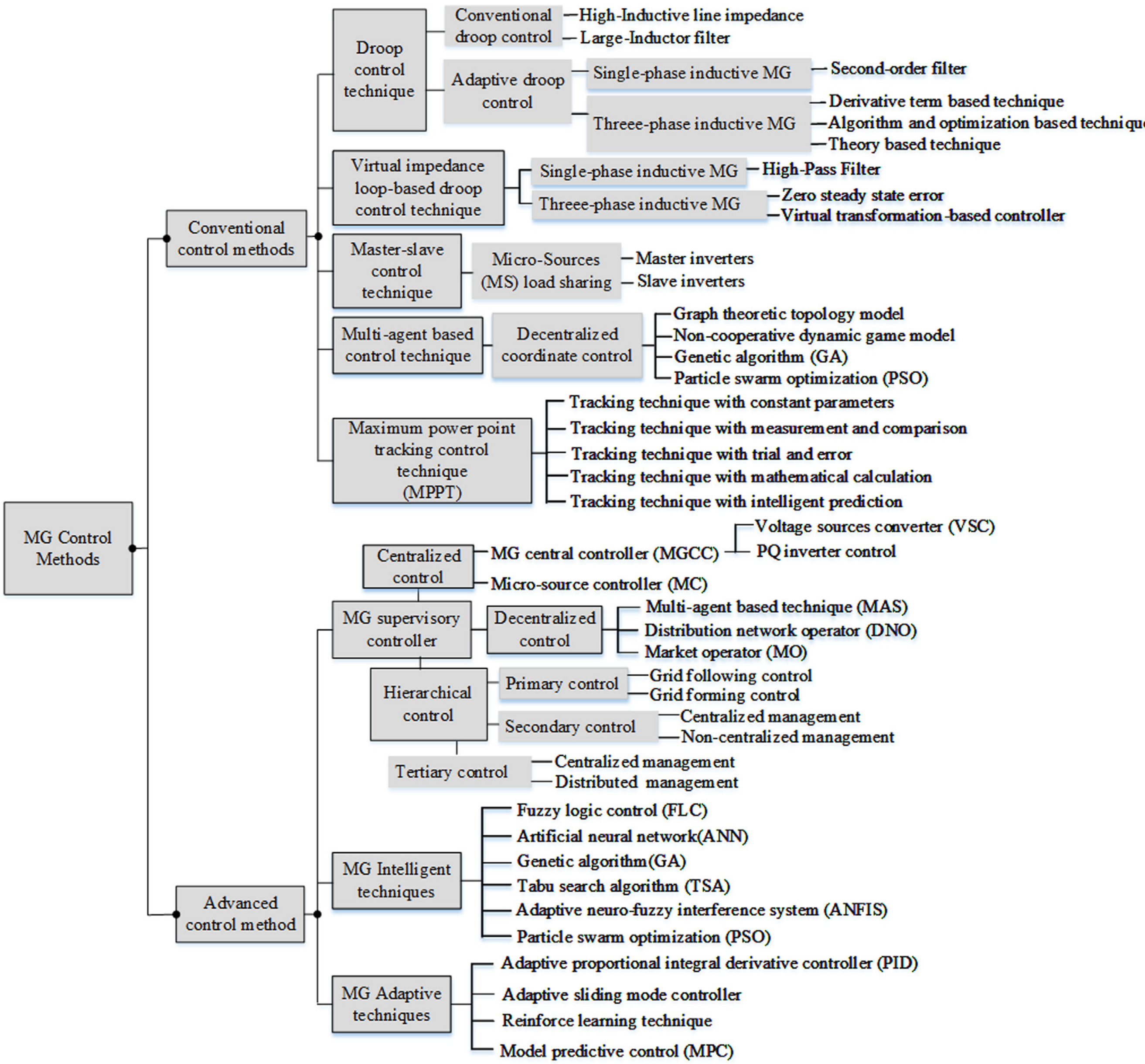

Fig. 8. Classification of MG control methods in terms of their technique formations.

sharing capabilities [53,54]. This technique is implemented by dropping the output voltage references to the output current proportionally and fixing the phase and magnitude of the output impedance. The output and line impedance of DGs involves the consideration of inductive and damped oscillation [54,55]. Other extensive research on virtual output impedance in droop control methods is available in [42,59,60].

4.1.3. Master–slave control method

The master–slave control method has been widely used in MG systems, especially in controllers comprising microsources (MSs) as a major element in coordinating the operation of the interface converter for each DG unit. Once the MG is connected to the grid, all MSs contain a master converter, which provides voltage and frequency references. For example, when the main power supply is lost or when a power outage event occurs, the slave takes voltage references from the master and works in PQ mode. The control of low voltage MGs with the master–slave architecture, which governs the interaction between utility and MGs at the PCC, was proposed [61]. In the grid-connected mode, the grid works as the master, and the master converter in the MG acts as the slave, with the central command unit generating reference control signals. In islanded mode, the master DG operates as a voltage control source while all slave DG units operate in current controlled sources. Therefore, a reliable and fast communication link is important for a centralized controlled unit to send command control signals to all DG units efficiently [62].

4.1.4. Multi-agent system (MAS)-based control method

MAS-based control methods have been widely used in MGs because they are fully rooted in decentralized control, in which two or more interacting agents follow their own rules and goals and perform functions autonomously [63]. An MAS can control and stabilize voltage output, frequency, and power with a changing environment and load with uncontrollable RESs. One strategy is to coordinate power sharing between ultracapacitors and batteries distributed in the DCMG [64]. A decentralized coordinate control scheme based on an MAS has also been proposed to improve the stability and security of MGs [65]. A similar control strategy based on frequency is employed in islanded

Table 2
Summary of MG control methods.

Control method	Parameters	Technique	Advantages	References
Droop control	Voltage and frequency of the inverter; active, P power; reactive, Q power	Balanced load current sharing by adjusting output voltage and frequency under voltage v/s current droop characteristic	Provides power sharing based on MG to eliminate communication link in decentralized control; increases system reliability and flexibility by allowing active power sharing of DERs	[1,42,51]
Virtual output impedance	Voltage reference; voltage impedance; active, P power; reactive, Q power	Summation of virtual output impedance to balance reactive and Q power sharing	Provides proper transient response of active and reactive power sharing without frequency deviations; excellent current sharing with minimized harmonic circulating current in parallel-connected converters of DG system	[51]
Master–slave control	Voltage; frequency; microsources (MS)	MS behaves as master controller under voltage mode control and provides voltage and frequency references to other MSs of each DG unit	Adjusts violation of voltage and frequency of DG units; can operate in centralized and decentralized control	[1]
Multiagent system (MAS)-based control	Voltage; MS	Allows each MS or load to represent an agent that can exchange information with neighboring agents to collaborate on mutual objectives and controlling components	Deals with economic power coordination and voltage coordination in EMS; improved control characteristics of MG with high reliability, security, and flexibility; solves coordination control in MGs	[1,71]
Maximum power point tracking (MPPT) control	DC/DC converter; irradiance; ambient temperature; load profile	The DC/DC converter inserted between the PV panel and the batteries can control the seeking of MPP and typical functions	To locate the maximum power generated by output RESs based on irradiance, temperature, and load profiles; acts as a converter to modify the duty cycle and input impedance of control signals; enhances efficiency of RES systems	[70]

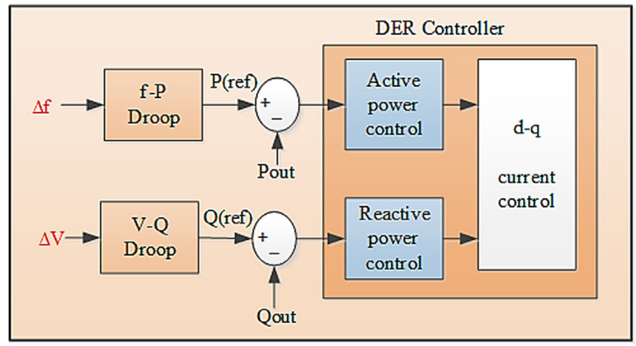

Fig. 9. Droop control strategy [2].

MGs to eliminate the fluctuations of frequencies in outage events [66]. The advantages include the ability to overcome uncertainty disturbance, improvement of efficient information sharing in a decentralized manner, and fast decision-making process and operation. Further architecture and level control of MAS methods are presented in [64,67]. The framework of the MAS-based MG is shown in Fig. 10. The agents include electrical equipment, such as battery energy storage, wind turbine, gas turbine, and loads. These agents monitor the status and control operations of electrical devices under the coordination by the MG central controller (MGCC).

4.1.5. Maximum power point tracking (MPPT) control

Generally, energy generation, such as that in PV cells and wind turbines, are stochastic or fluctuating and totally depends on environmental factors, including solar irradiance and ambient temperature. Based on nature, the MPPT takes action to harvest maximum energy from the output of installed PV arrays and acts as a controller located at local converter levels operated by embedded DC–DC converters. The MPPT method takes the maximum value of the power generated by PV cells and extracts it. The MPPT method is based on moving operational PV voltage or current to obtain maximum power. This method is also applied to other RESs, such as FCs and thermoelectric devices. Several studies were reviewed in [69]. The classifications and different MPPT techniques were also analyzed in [70]. The behavior of PV power can be written as Eq. (1) [70]. The general PV system scheme with the MPPT system is shown in Fig. 11.

$$P_{PV}(t) = F(V_{PV}(t), I_{PV}(t), \gamma(t)), \quad (1)$$

where γ denotes the variables other than the current and voltage and t is the time of the power curve that depends on PV parameters and climatological variables.

The strategy of developing PV panels to absorb maximum power has emerged in the literature because PV panels have been widely used in stand-alone and grid-connected systems of MGs. The tracking methods are categorized according to their techniques and are divided into five groups [70].

4.2. Advanced MG control techniques

Advanced control techniques have been widely applied to MG control systems to enhance control performance. Such techniques are intelligent and adaptive techniques for optimizing the parameters involved in control systems to provide robust controllers. The following section discusses the MG control techniques.

4.2.1. MG supervisory controller

MG supervisory controllers are categorized into two groups, namely, centralized and decentralized management. The aim is to provide necessary functions, such as power quality control, and to optimize system operation by enhancing the intelligence level. The following section discusses the corresponding group of supervisory

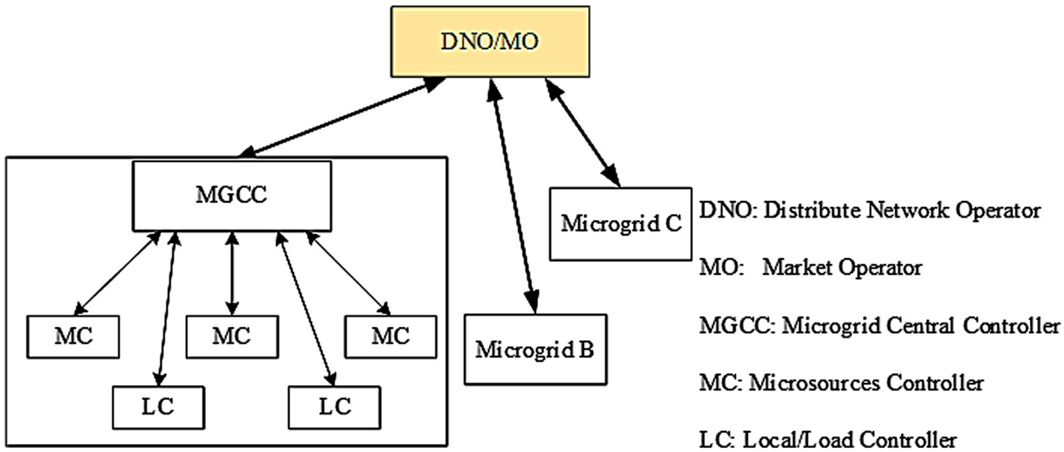

Fig. 10. Framework of MAS architecture [67,68].

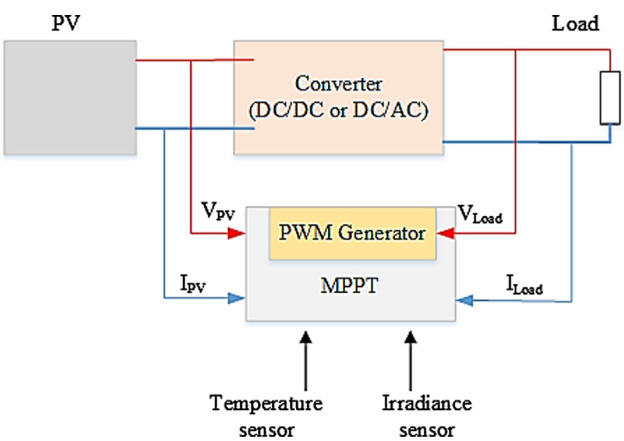

Fig. 11. General scheme of a PV with an MPPT system [70].

controllers with respect to EMS. Table 3 summarizes the comparison of centralized and decentralized management in terms of characteristics, advantages, and disadvantages.

4.2.1.1. Centralized MG. Centralized control management provides strong supervision, which includes straightforward implementation and real-time observability of the whole system. It requires data for the MG component and external grid to execute the optimization procedure for efficient operation. Secondary control for a centralized MG controller was reviewed in [72]. A centralized control of MGs can be explained on the basis of hierarchical control, which consists of primary, secondary, and tertiary system levels. In this hierarchical system, the controllers may be centralized or decentralized. In centralized control, microsource controllers (MCs), as shown Fig. 12, also act as intelligent controllers [73]. To provide load capabilities, local controllers (LCs) are installed at controllable loads. LCs are commonly used for distribution management systems (DMSs). In each MG system, MGCCs optimize the MG operations. The MCs and LCs follow orders and are dependent on the MGCC during grid-connected mode and perform their own control autonomously in islanded mode [74]. As part of the utility in MG systems, a DMS or distribution network operator also interfaces with the MGCC to manage the operation of medium and low voltage areas if multiple MGs exist. The architecture of centralized MG control is shown in Fig. 12.

4.2.1.2. Decentralized MG. Decentralized MG management, which enhances flexibility and expandability, has emerged in MG systems. This controller allows for great flexibility of operation and avoids a single point of failure because of the plug-and-play functionality. Frequency and voltage regulation, DER coordination, and energy management can be realized in a decentralized manner because of the level of decentralization. In decentralized control, MCs are mainly responsible for maximizing their production for demand satisfaction and exportation to grids given current market prices. The purpose is to automate MSs and loads maximally. One interesting research on this supervisory controller is the employment of an MAS-based EMS. A MAS is a system that consists of multiple intelligent agents that provide local information and interact with one another to achieve multiple global and local objectives with autonomy [67,71,72]. Furthermore, a MAS for real-time MG operation is established with a focus on generation scheduling and demand side management, as presented in [75]. Hence, many approaches for the MAS method for the decentralized

Table 3
Comparison of advantages and disadvantages of MG supervisory controllers.

	Characteristic	Advantages	Disadvantages	References
Centralized	Local controller (LC) dependent on central controller for decision making	• Central controller allows economic implementation and is easy to maintain • Real-time observability of the whole system • Straightforward implementation • Provides strong supervision and wide control of the entire system • Protected by a control unit	• Low flexibility and expandability • Entails single point of failure • Requires high data interchanges	[72,73]
Decentralized	LC provides own decision making	• Reduces computational burden • Avoids single point of failure • Easy realization of plug-and-play functionality • Provides maximum autonomy for DERs and loads at LC • Increased reliability and robustness	• Requires effective synchronization • Requires strong communication to achieve synchronicity • Requires fast periodical reconfiguration	[49]

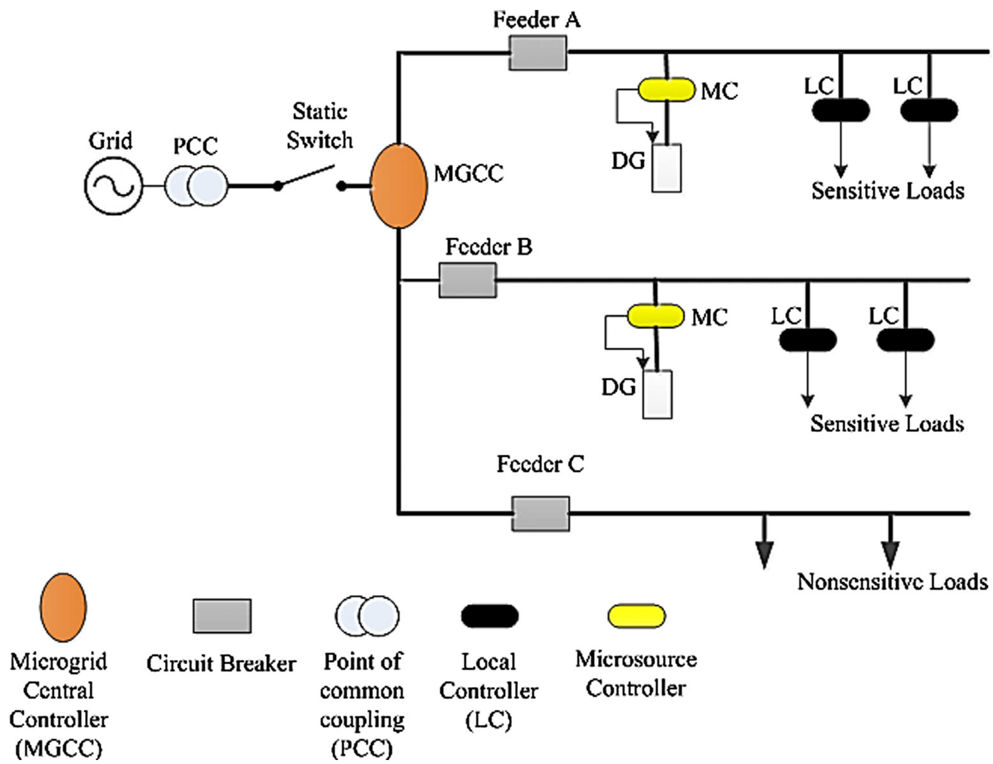

Fig. 12. Architecture of centrally controlled MG [73].

control of MGs exist, as further detailed and described in [76,77].

4.2.1.3. Hierarchical control of MG. Hierarchical control has been introduced in MG systems. It operates in ACMG and DCMG and is composed of tertiary, secondary, and primary control. Its main purpose is to provide control over the production of power from renewable sources. In grid-connected mode, the MG operates on the basis of IEEE 1547-2003 with proper implementation of the detection algorithm for the system to transition smoothly into islanded mode [78]. In islanded mode, the MG supplies the required active and reactive power with stable frequency and can operate within specified voltage ranges and limits [59]. Fig. 13 shows the most relevant classification of hierarchical control of MGs composed of levels and their functions. Further studies based on the literature and characteristics are discussed in detail in the following sections.

4.2.1.4. (a) Primary control. As DG and ESS units are integrated into MG systems to generate stable electricity for consumers, the current and voltage performance of the interface controller should be controlled. Ensuring voltage and frequency stability is important for this system to obtain optimal power management and power sharing. In the literature, three types of primary level control, namely, grid-forming, grid-feeding, and grid-supporting control, are distinguished [6]. The primary control studies usually focus on ACMG and DCMG and the interface converters

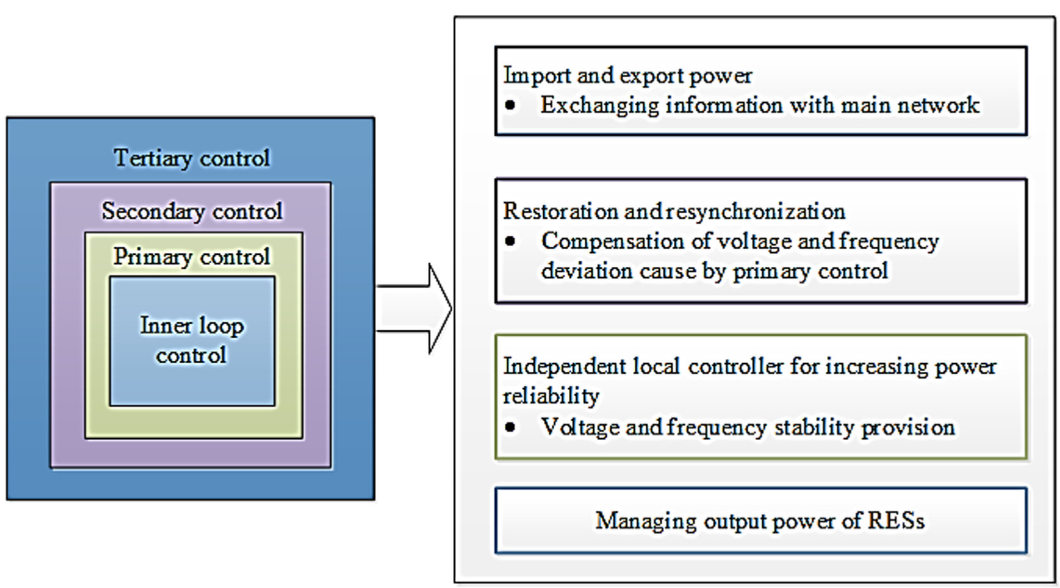

Fig. 13. Hierarchical control of MG [79].

between them. The following section discusses the types of primary control level.

i. **Grid-following control**: The voltage and frequency of MGs are controlled by utility grids in grid-connected mode. Hence, the purpose of grid-following control is to optimize the power sharing strategy of the network because the LCs of RESs operate under current control mode to extract maximum power from energy resources. An overview of distributed power generation systems based on renewable sources was discussed in [80]. The grid synchronization method was also reviewed in this study in case of AC-based DG units; examples include zero-crossing method, filtering grid voltage, and phase locked loop technique. An extensive review covered the hierarchical control of MGs from power generation through RESs to achieve synchronization with the main network in islanded mode [81–83].

ii. **Grid-forming control**: An optimal active and reactive power control should be realized to provide adequate power sharing between DG and ESS units and thereby stabilize the voltage and frequency of the AC and DC networks of MGs, especially under islanded mode. Two configurations have been identified for this control strategy: single grid-forming and multiple grid-forming units [6].

4.2.1.5. (b) Secondary control. The purpose of this control level is to compensate for voltage and frequency deviations in MG networks. During islanded mode, this control level ensures the resynchronization of the transition mode to regulate voltage and frequency references. This control strategy is categorized as centralized or noncentralized [6]. The summary of control categories for this level is provided in Table 4.

i. **Centralized management:** The variables of active and reactive power of DG units, ESS units, and loads under this management are collected to manage MGCC. In this centralized management, communication networking is essential and is linked to all hierarchical control levels [49]. The secondary centralized control aims to compensate for voltage and frequency variations in primary control levels on the basis of references from tertiary control levels when operating in grid-tied mode. A study presented an approach to hierarchical multilevel control to ensure the smartness and flexibility of MGs; the approach was composed of the droop method and output impedance virtual loop for ACMG and DCMG [59,84]. A reactive power management in islanded MGs was presented in another study to develop an algorithm for reactive power sharing and thereby achieve a balanced system and MGs with improved reliability [85].

ii. **Non-centralized management:** In this strategy, the power management of MGs is realized in the MGCC integrated with a local controller by avoiding the communications network with tertiary control level. During a disturbance event, the MG can operate normally after disconnection from a faulty unit of the grid. This strategy offers a simple communication network such as a plug-and-play approach toward the integration of MGs at the power distribution level [6,49,74]. In this strategy, two techniques without communication and integrated communication networks are combined. These techniques are called distributed secondary control and decentralized control.

4.2.1.6. (c) Tertiary control. The tertiary control level strategy, which is also called grid level control, is performed to manage the active and reactive power flows between the MG and the utility grid and to regulate the voltage and frequency of MGs. This technique can be implemented in centralized and distributed control strategies.

i. Centralized management: In centralized management, the power value is measured and compared at the PCC, which interfaces with the utility grid. In addition, the power quality, efficiency, and economic benefit are optimized on the basis of different variables. Some

Table 4
Summary of secondary control level.

Levels	Techniques	Advantages	Disadvantages	Communication	References
Centralized	Performs management of MG at MGCC Droop-based control	Provides high plug-and-play capabilities Suitable for small-scale MG management Integrates a small number of controller devices	High penetration of connected devices Cannot share interest among connected devices	Requires communication network in all levels	[6,49]
Noncentralized	Performs management of MG at MGCC Distributes secondary control Decentralized secondary control	MG can operate normally during faulty events Integration of MG at power distribution level Provides a high level of flexibility	Requires strong communication to achieve synchronicity Requires fast periodical reconfigurations	Simple communication network Provides plug-and-play connection	[74,86,87]

approaches involve distributed EMSs to achieve an optimal power flow for MGs with consideration of the underlying power distribution network and associated constraints [88]. In this review, the energy management of MGs was formulated as an optimal power flow problem, along with the MGCC and LCs, to compute an optimal schedule of MGs. The proposed EMS is effective in grid-connected and islanded modes of MGs. Another study provided a new hybrid distributed network based on a power control scheme using a centralized strategy to address the power sharing problem in a distributed manner [6,89,90].

ii. Distributed management: The tertiary level is normally located at the MCC of the main grid (e.g., in SCADA). Some studies suggested that the tertiary control level is located in a distributed manner in an MG system. An existing work observed the power quality disturbance in the generator side and the local bus during the implementation of distributed management to compensate for voltage imbalance in the critical bus [91]. The study developed an agent that implemented the optimization process using the dynamic consensus algorithm for global information discovery to exchange information through a communication network that links neighboring agents. The simulation showed that hierarchical control can maintain an unbalanced level in the critical bus while ensuring the acceptability of power quality in the local bus.

4.2.2. MG intelligent techniques

Various intelligent techniques have been implemented in power system applications to enhance the control system performance and stability of DG units by adjusting system parameters during the whole operation. Moreover, as DG units in MGs increase, the parameters in control systems become difficult to adjust or tune. Hence, several powerful techniques were also explored to control such parameters in MGs with consideration of economic load dispatch for load sharing in MG systems [7,92–96]. The following section discusses an intelligent technique and control approach in sustainable energy and MG applications to improve system performance. The summarized structure of corresponding techniques is provided in Table 5.

4.2.2.1. Homeostatic control and exergy management in sustainable energy. The concepts of high service quality, customer differentiation and choice, and system reliability have become contributing factors to the cost of installation of MGs, especially in rural and urban areas [97]. Hence, control strategies, such as EMSs, which comprise power electronic interfaces and supervisory controller systems, bring cost-effective and affordable solutions. Homeostatic control (HC), artificial intelligence, and data acquisition are another set of cost-effective options for EMSs and remote monitoring systems [98]. HC is designed for MG systems to provide sustainable energy equilibrium to customer demand strategies by maintaining an efficient equilibrium state under different circumstances and conditions, especially in the grid-connected mode of MGs [99–101]. This approach provides utility system efficiency in power supply, especially for large industrial and commercial customers [99]. HC was first introduced by Schweppe and his group at MIT; they linked homeostasis to the flexibility and stability of electric power systems under an efficient equilibrium state between energy supply and demand while considering the time based on customer demand response management through real-time communication [102,103]. In the grid-connected mode of MGs, the system supplies energy to consumers who can access relevant information about grid condition and energy usage dynamics, resulting in efficient and reliable EMSs in MG applications [99]. Moreover, the HC mechanism is implemented in an electric power system to enable consumers to manage their own decision making in terms of supply capacity and power dispatch of RESs in electric power infrastructure. This exergy is certainly needed in electric power systems, especially in the use of MG systems, to allow consumers to manage electricity economically and provide a flexible and efficient equilibrium state between supply and demand at any circumstance and

Table 5
Summary of the main features of intelligent control techniques.

Technique	Applications	Advantages	Disadvantages	References
Fuzzy Logic Control (FLC)	Selects an appropriate parameter of distributed controller; utilized to determine the required performance of four area systems with proportional integral control	Can solve nonlinear systems; effective for small-scale systems; combines regulation algorithm and logic reasoning, allowing for integrated control schemes	Comprises various parameters for adjustment; requires time to train data; many actual implementations are equivalent to look-up tables' interpolation schemes	[7,133]
Neural Network (NN)	Trains and optimizes control gains in real time; trains system parameters inserted with enough active power from batteries to eliminate load fluctuations	Can solve nonlinear systems in offline/online and real-time applications; effective for small-scale and large-scale systems	Sensitive to the distribution of membership; comprises various parameters for adjustment	[7,191]
Particle Swarm Optimization (PSO)	Automatically tunes gains of PI controller in the droop control method; optimizes DG placements composed of PSO and clonal selection algorithm; utilized to determine the optimal position of DGs to degrade power loss	Simple and easy to implement; can solve nonlinear systems; adjustable parameters	Near optimal; requires time to compute optimization	[131]
Genetic Algorithm (GA)	Starts with random generation of initial population, followed by selection, crossover, and mutation operations that are performed until the best population is determined	Optimized with continuous or discrete variables; deals with numerous variables; optimization done with encoded variables	Long calculation time; uncertain behavior leads to different results	[71,134]

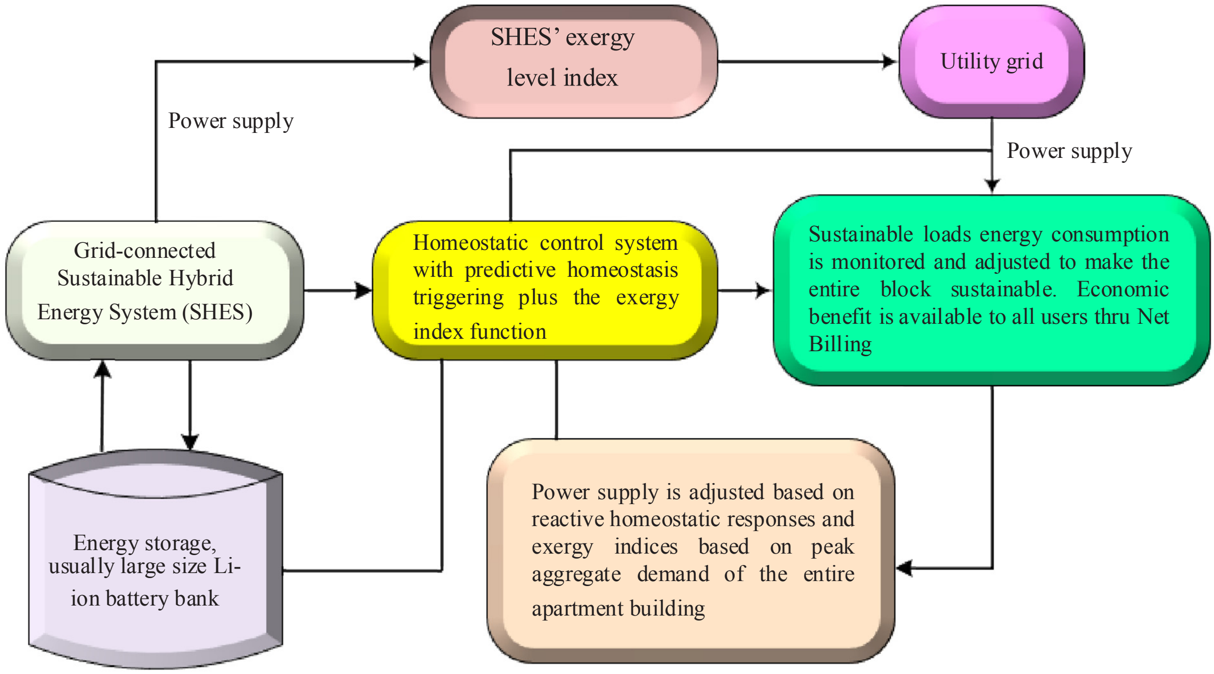

Fig. 14. Homeostatic control based on reactive and predictive homeostasis mechanism of sustainable energy system [105,106].

condition. Meanwhile, exergy expresses the quality of energy sources, which satisfy the demand for electricity and maximize energy production, thus ensuring system sustainability [101]. This intelligent mechanism strategy has been widely discussed and reviewed in the literature to obtain a sustainable, flexible, and stable energy system for consumer satisfaction [104–107].

4.2.2.2. (a) Sustainable energy systems for residential building users and utility grids. Today, decentralized power generation with more resilient and robust control of DG integrated MG system is important to mitigate the power outage and transmission line failure in effected area as well as provide a reliable electricity supply to consumers [107,108]. The sustainable energy system is adjusted by the homeostatic control and exergy indices based on aggregate energy demand of the building. However, the homeostasis in sustainable energy system requires an intelligent and effective control mechanism in determining the generalized state of energy equilibrium between supply and demands [109].

Fig. 14 illustrated the reactive and predictive homeostatic control of energy management from set of customers with DG solution incorporated in apartment building community with ESS and a supervisory controller operated by ENEL Distribution [106]. The reactive homeostatic control is driven by energy generation and supply versus consumption or expenditure of energy employed with sensing system and intelligent algorithm. The predictive homeostatic control manages energy of the building integrated with smart metering, PV generation and ESS to provide an optimal efficiency and cost effectiveness through communication between the customer demand and grid supply. The existing literature also demonstrated that the grid-connected MG is capable to maintain stable and efficient equilibrium with self-regulated system for the social and environmental sustainability [99,105,110].

The recent literature presented that the tremendous earthquake stroked on Chile in 2010 resulted a big disaster to the electric infrastructure especially on the operation of telecommunication network and electric power system (EPS) [104]. The centralized power generation and distribution system in Chile was attempted a vulnerable and ineffective system which resulted the large populated area was in complete darkness for several hours with less economic benefit, power quality and stability to consumers. To solve the issues, ENEL distribution has led the potential work on decentralization of energy grid to customize the operation of EPS, DG integrated MG systems are installed in residential buildings in Chile [100,105,106]. Incorporating intelligent control in DG with smart grid provides convenient solution to electric utilities in socially and economically to different region and localities as in Chile and mitigates the intermittent of renewables stochastic problem. Thus, intelligent control strategies in DG integrated residential building could be a promising approach in EPS that can promote and potentiate energy efficiency, thriftiness as exergy drivers and high capabilities between the building energy users and the utilities.

4.2.2.3. MG artificial intelligence techniques. An artificial intelligence-based method for EMS strategies in MG applications has been used to enhance the efficiency and performance of MG systems and thereby meet load demand with maximum electricity production. Ref. [111] presented an EMS model with fuzzy logic-based EMS to smooth the grid power profile with consideration of RESs and ESS units for grid-connected MGs. The generation and demand forecast anticipates the future behavior of MGs to smoothen the power profile exchange with the grid. The battery state of charge (SOC) was also considered in this approach, which maintained a level close to 75% of its rated capacity to increase its lifetime. A fuzzy genetic algorithm (GA) paradigm was introduced for EMSs in grid-connected MGs [112]. The hierarchical GA was tuned on the basis of a fuzzy inference system to obtain the minimal fuzzy rule set of the EMS model. The main aim was to provide an efficient power flow and maximize the energy trading profit with the main grid. The performance appears to be better than that of the classical fuzzy GA, which yields 67% of the account profit. The Lagrange programming neural network was presented to obtain the optimal scheduling of MGs and thus provide an efficient EMS with minimum cost function and maximum power generated by renewable sources [113]. The proposed approach shows that the best solutions obtained from this method are more efficient than those obtained by particle swarm optimization (PSO). Ref. [114] presented an intelligent dynamic EMS for MGs. The method generates energy dispatch control signals to maximize the generation of RESs and ESS units for critical load and strictly improve battery life. The performance of the proposed approach was better than that of a decision tree-based EMS. Fuzzy logic

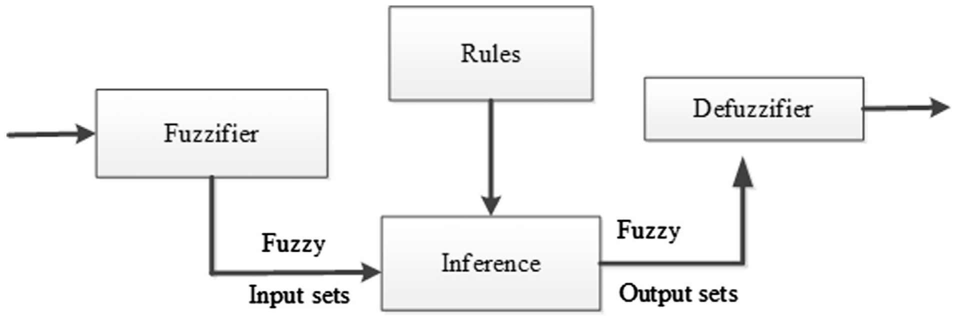

Fig.15. General architecture of fuzzy logic control (FLC) [118].

and neural networks are widely utilized for MG EMSs to provide an efficient operational solution for MG applications. These approaches consider forecasted values and improve battery lifetime and energy trading with grid.

Fuzzy logic control (FLC)

Fuzzy logic controllers have been incorporated in distributed control systems for the selection of appropriate parameters of distributed controllers for MG system performance [7]. Fuzzy logic control (FLC) is an interesting technique in MG systems. Substantial research applying fuzzy logic techniques to solve the parameters in MG systems has been conducted [7,115]. In [116], an automatic definition of a fuzzy rule for a fuzzy controller based on the Tabu search algorithm scheme was presented. Hybrid techniques have also been widely investigated in MG systems; for example, a study presented a GA-based fuzzy gain scheduling approach for the load frequency control of power systems, in which a fuzzy system is automatically designed by the GA to reduce the effort toward fuzzy system design and the number of fuzzy rules [117]. In general, three steps are involved in FLC design: fuzzification, fuzzy inference process, and defuzzification [118] (Fig. 15). FLC works on a formulated base rule to control an output similar to the “if–else” rule that is preceded by a condition and then followed with a conclusion [115].

Neural networks

Neural networks (NNs) have attracted much attention in the research field. NNs are one of the most effective techniques that can optimize, control, and identify system parameters in online or offline applications [7]. Moreover, NNs can solve problems with nonlinear data approaches in large-scale systems in MG systems. The scope of NN applications covers solving fault tolerance, stability system, prediction, parametric optimization and identification, self-learning, and load sharing. In addition, in grid-connected mode, the nominal voltage and frequency of the entire system are determined and sustained by the main utility grid. In islanded mode, MGs adjust and balance the voltage and frequency values to sustain the loads that are evenly incorporated with the storage system [7]. Despite this condition, the NN can fully determine and optimize system parameters by adjusting the active power to eliminate load fluctuations in the MG system. A literature survey on NN applications was also presented in [119–121]. Mathematically, an NN can be represented as weighted directed graphs. The architecture of NNs is shown in Figs. 16 and 17 [115].

4.2.2.4. Metaheuristic techniques. A novel scheduled algorithm was proposed with consideration of battery lifetime to reduce MG operational cost [123]. The method is based on goal programming approaches that assign different weights of fuel and battery use cost. The overall operational cost of MGs can be reduced by increasing the battery lifetime. Ref. [124] also proposed an EMS strategy for MG systems that uses a memory-based GA among several DERs to minimize energy production cost and provide optimal scheduling of DERs in MGs. The comparison showed that the performance of the proposed strategy is better than that of the GA, PSO with inertia factors, and PSO with constriction factors. With both modes of MG operation considered, a regrouped PSO was formulated as an EMS strategy for the economical operation of industrial MGs with high penetration of renewable energy [115,125]. The validation of performance proved that this approach can determine an optimal solution with less computation time than that needed by GA-based methods. This analysis of genetic and swarm optimization approaches is provided to solve EMS strategies in MG systems. An extensive review of these methods was presented in [126].

Particle swarm optimization

PSO has been widely applied to MG systems due to its contribution to the extension of uncertain parameters in optimization problems. PSO is an iterative algorithm that identifies the solution for a given objective function within a predefined space. It was first developed by Kennedy and Eberhart in 1995 [127]. In islanded mode, the MG must sustain the control performance of all DG units and the power quality during severe conditions [128]. An optimal allocation for DG units in a distribution system involves a hybrid technique that combines PSO and clonal selection algorithms to optimize different objective functions [129]. The optimum location of DG units is specified by introducing power losses and voltage profiles as variables into the objective function. The proposed hybrid technique is able to improve the accuracy of solutions and is considerably faster than previous techniques are. A detailed survey of hybrid PSO and other optimization techniques that deal with the economic dispatch problem in MG applications was presented in [7,130]. The basic concept of PSO was explained in [127,131]. The velocity and position of particles, which are updated at the end of each iteration, can be expressed in Eqs. (7) and (8), respectively [131]. The general flowchart of a PSO algorithm is shown in Fig. 18.

$$V_i^{k+1} = wV_i^k + C_1 r_1 [X_{pbest}^k - X_i^k] + C_2 r_2 [X_{gbest}^k - X_i^k] \quad (7)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (8)$$

Genetic algorithm (GA)

The GA is widely applied in MG operations to address optimization problems. The GA is an adaptive heuristic search algorithm based on evolutionary ideas of natural selection and genetics. It mimics the metaphor of natural biological evolution and consists of five components, namely, an initial random population generator, a “fitness” evaluation unit, and genetic operators for “selection,” “crossover,” and “mutation” operations [127]. The “selection” operator selects a predefined set of fit solutions. The “crossover” operator finds new solutions to produce high fitness values relative to their predecessors. “Mutation” enables the algorithm to escape the local minimum problem. The steps are repeated until the desired convergence is achieved. The general structures of GA operations are shown in Fig. 19. Many GA algorithms

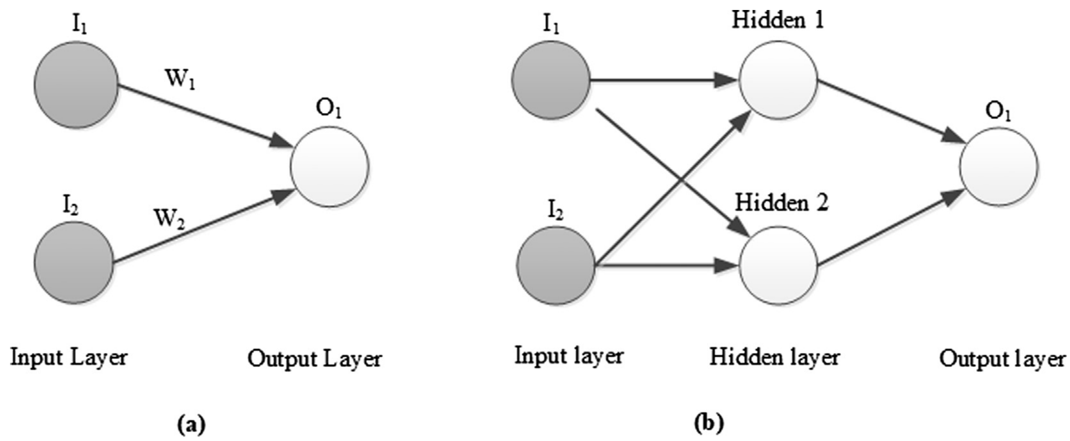

Fig. 16. Architecture of neural networks: (a) single-layer neural network; (b) multi-layer neural network.

have been applied to MG operations [71,132].

4.2.3. MG adaptive techniques

Adaptive control techniques have become an interesting topic for research in recent years. These techniques can be applied to MG applications to sustain system stability, robustness convergence, and optimization. Moreover, these techniques are mainly used to solve and cater to the uncertainty parameters and disturbance events in MG applications. The following section discusses a few adaptive techniques that are commonly utilized to tune the voltage and frequency fluctuations in MG applications and thereby obtain optimum values for power generation. The comparison of corresponding techniques is presented in Table 6.

4.2.3.1. Adaptive proportional–integral–derivative controller. In the proportional–integral–derivative (PID) technique, the PID controller must automatically regulate power disturbance or load variation events, as shown in the example in [135]. In this controller, the parameters are selected by trial and error or some other methodologies, such as those of Ziegler and Nicholas [136]. An improvement of load frequency control for small-scale MGs, which properly tunes the controller to reduce the mismatch between real power generation and load demands and to obtain minimum power and frequency deviations, has also been presented [136]. The proposed methods of Ziegler and Nicholas and the integral squared error tune the gain of the PID controller to obtain the frequency bias of the power system dynamics. In general, most PID controllers are used to regulate the frequency in MG systems; their control output is expressed in Eq. (9) [136]. The general structure of the PID controller process is shown in Fig. 20.

$$u(t) = K_p[\Delta f + \frac{1}{\tau_I}\int_0^t \Delta f dt + \tau_D\frac{d\Delta f}{dt}] \tag{9}$$

4.2.3.2. Adaptive sliding mode controller. MGs are exposed to various uncertainty controls to maintain power generation and loads, especially in islanded MG. When the MG becomes islanded during a power disturbance, sustaining the uncertainty parameters and constraints of the DG units and loads becomes a considerable challenge. The adaptive sliding mode controller (SMC) has become a beneficial technique for MG systems due to its reliability and effectiveness in catering to such issues. In grid-connected mode, the SMC is utilized as PQ control in the main bus to regulate the active and reactive power. This controller has also been used to stabilize voltage and frequency output in case of disturbance events. An adaptive sliding mode controller (ASMC) has been presented to mitigate generator power and load fluctuations for wind turbines. An ASMC was used to control the pump displacement while back-stepping a stroke piston controller to track pitch angle errors [137]. MG management is greatly affected by robust control and management. Hence, one of the ASMC approached of inverter for smart MG. The control structure that is based on an inner adaptive three-order sliding mode closed loop, immediate virtual output impedance loop, and outer power control loop was reviewed in [7,138,139], and [140].

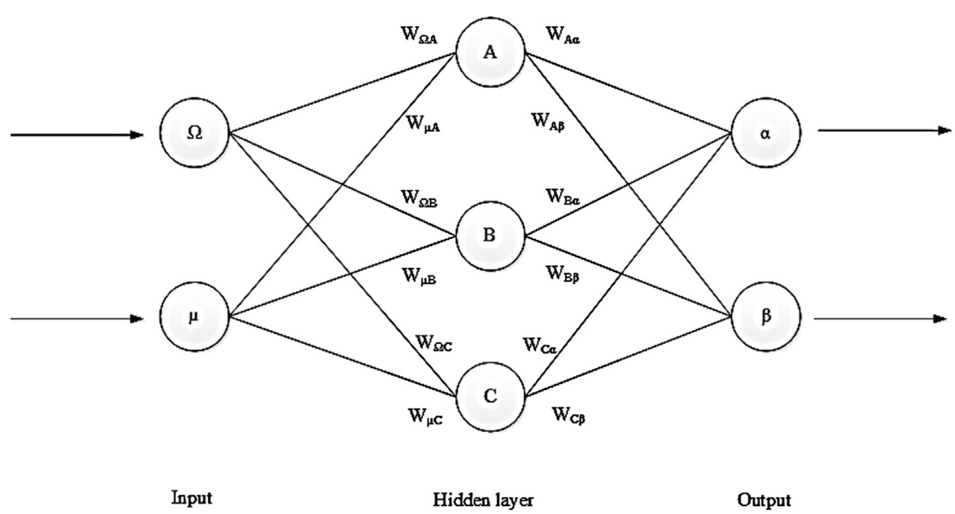

Fig. 17. Back-propagation algorithm [122].

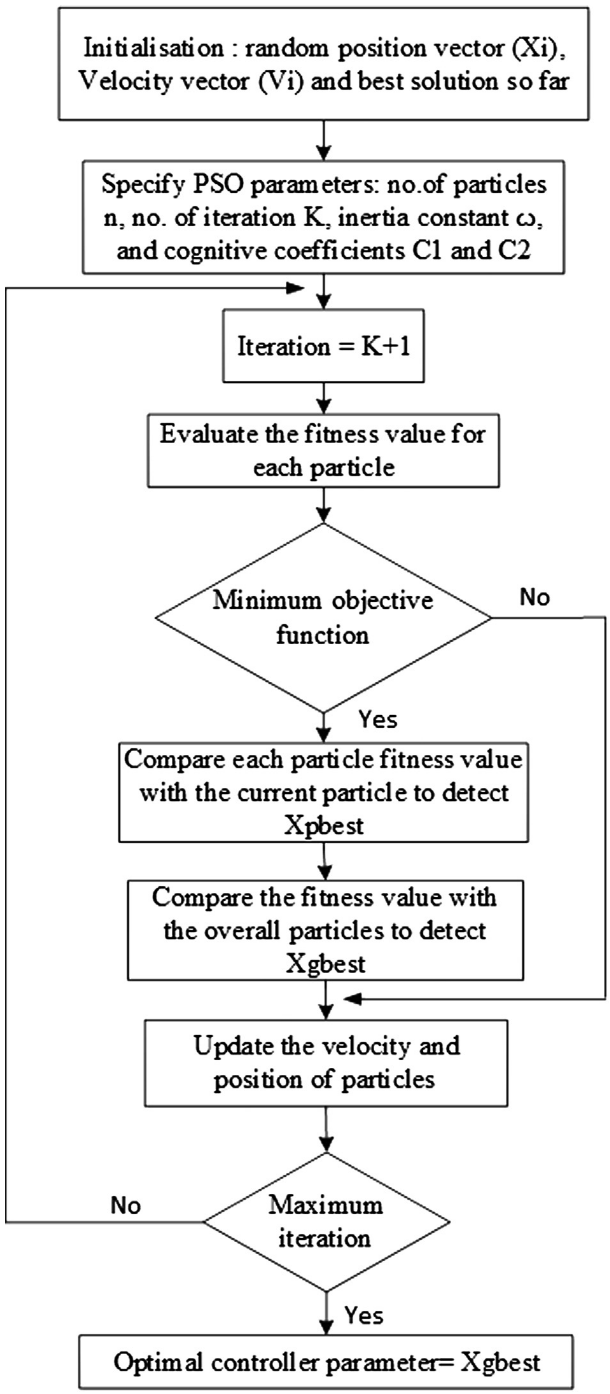

Fig. 18. Flow process of particle swarm optimization.

4.2.3.3. Reinforced learning. The reinforced learning technique has been widely introduced to MG control systems to control the uncertainties of parameter constraints in islanded mode. For example, reinforced learning has been utilized to handle load fluctuations in MG systems. Additionally, reinforced learning can handle optimal policy decisions, enhanced management processes, stabilization of DG generation, and voltage and frequency regulation, especially in islanded MG. A specific reinforced learning algorithm is called Q-learning. The literature on reinforced learning applications in MG control systems was extensively discussed in [7]. Fig. 21 shows a simple reinforced learning scheme [141]. Reinforced learning has also been applied to several operations, such as power management and economic issues. Reinforced learning can determine optimal policy decisions and provides the best objective function to improve system performance [142].

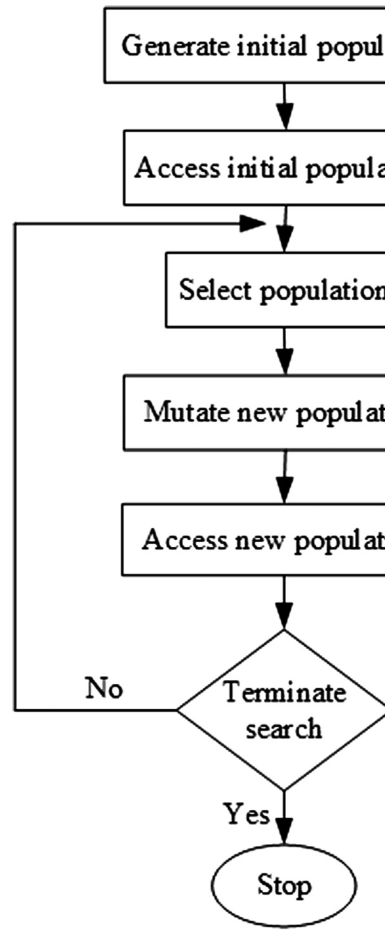

Fig. 19. General structure of genetic algorithm.

4.2.3.4. Model predictive control. A model predictive control (MPC) technique has been widely used in power electronic converter control to regulate the inverter output voltage and thereby ensure stability in power sharing among DG inverters in MG operations during islanded mode. The MPC technique has remarkable advantages over traditional linear control techniques as it can handle multi-objective optimization problems and easily manage system constraints. Moreover, fast microprocessors have made MPC techniques effective and popular among grid voltage source converters (VSCs). The power electronic interface is an important element of MG systems as it handles interconnections with utility grids and the connection of different MG modules. Hence, the proper control of power electronic converters is most crucial in MG applications to guarantee good voltage and frequency stability for local loads that would satisfy international standards (IEEE Std. 1547.4) for islanded MG performance requirements [143]. Traditional control techniques, such as PI-based approaches, direct power control, and internal control-based models, suffer from a slow dynamic response and require the retuning of parameters in case of parameter changes [144]. Hence, MPC techniques have the potential to eliminate the aforementioned issues. Generally, an MPC consists of three layers, namely, extrapolation, predictive model, and minimization of cost function (Fig. 22). MPC provides a control action sequence for the system by optimizing user-defined cost functions. The application of MPC to power electronic converters for MG operations has been extensively studied [145,146].

Table 6
Comparison of adaptive techniques for MGs.

Techniques	Parameter	Applications	Advantages	Disadvantages	References
Adaptive PID Controller	Voltage source converter (VSC)	The gain parameter of an adaptive PID controller depends on optimal tuning	Easy implementation; does not require system dynamics for realization; only three parameters to optimize	Unable to eliminate steady-state errors for sinusoidal signals; cannot guarantee the robustness of PID closed-loop systems; not robust to fit load variations	[7,133]
Adaptive Sliding Mode Controller	Voltage and frequency; power quality control	Based on changing the control structure that lets the method track the system output in predefined limits; low steady-state tracking error	Robustness under system parameter changes and external and internal distortions; fast dynamic response; nonlinear controller	Proper transient and zero steady-state error; chattering phenomenon	[7,119]
Reinforced Learning	Load frequency control; reactive power control	Describes how one or more agents achieve an optimal or near-optimal control policy by interacting with their environment to reach the goal	Can determine optimal policy decisions; provides a robust system performance	Finite set of state and action called Markov decision process	[131]
MPC	VSC; droop control technique	Regulates inverter output voltage references of power electronic converters in MG operations for stable power sharing	Fast dynamic response; can incorporate constraints; no modulator and varying switching frequency; does not require pulse width modulator	High computational requirement	[71,134]

5. MG architecture

An MG is a cluster of DER units consisting of a DG unit and a storage unit. It supplies electrical energy in dual operation mode to end users, such as residential, commercial, and industrial consumers. The MG system is interconnected to MV distribution networks and can work independently in case of grid disturbance or fault [36]. Each integrated DER unit is associated with the main grid at one point, which is known as the PCC, and it consists of a low voltage network, DG, storage device, loads, and hierarchical type of management. The structure of MG architecture systems is shown in Fig. 23.

5.1. Distributed generators

DG units are normally connected from medium to low voltage grids within a distributed system. By integrating all DG units, storage and loads form an MG. DG sources, such as diesel engines, fossil fuels, biomass, PV arrays, wind turbines, and hydro turbines, are small-scale power generators with minimal cost, low voltage, robust reliability, and ability to reduce emissions within the scale of MGs [36,147]. Storage systems in MG applications have become important elements as they operate as backup systems for PV and wind turbines due to the uncertainty of generation and attachment to DG units at any of the MV or LV side of a distribution network. A block diagram of DG units is shown in Fig. 24 to demonstrate the interconnection of DG units; it consists of primary energy sources, interface medium, and inverters at a point of connection. In a conventional DG unit, the rotating generator converts the power from primary energy sources to electrical power and then interfaces with the MG, whereas in an electronically coupled DG unit, the converter provides conversion or control, such as voltage and frequency control, and then interfaces with the MG [2,36]. The primary energy sources are connected to the electrical system through power electronic interfaces to analyze energy characteristic generation and convert one form of energy into another MG classification. A DG power system provides environmental benefits and an efficient way to generate and distribute electricity.

5.2. Energy storage system (ESS)

An ESS acts as an energy buffer to mitigate the impact of the fluctuating outputs of RESs and to provide marginal economic performance and good operational efficiency [148,149]. An ESS improves transmission capability, power imbalance, power quality, MG islanded operation, electric vehicle technologies, and active distribution systems; it may also improve dynamic and transient stability, voltage support, and frequency regulation to provide an efficient power system [72]. Fig. 25 illustrates the storage unit replaced as the storage medium at primary energy sources. An ESS can be categorized as (1) mechanical system (pumped hydro, compressed air energy storage, flywheels), (2) electrical system (capacitors, ultracapacitors, superconducting magnetic energy storage), and (3) chemical/electrochemical system (metal–air, flow batteries, Li-ion batteries, NaS battery, hydrogen energy storage) [148,150]. A detailed comparison of ESS applications in power systems in terms of their types and classification was carried out in [151–155]. An ESS in MG applications can maintain and improve voltage and frequency fluctuations within an acceptable range and may be able to perform many charge or discharge cycles and recharge with minimum energy in a short period of time. Storage units can be combined with nondispatchable DER units, such as wind and solar energy, to become dispatchable units.

5.3. MG loads

Loads exert considerable impact on MG performance, including its voltage, frequency, and transient stability. MGs are responsible for controlling and understanding the characteristics of loads and can

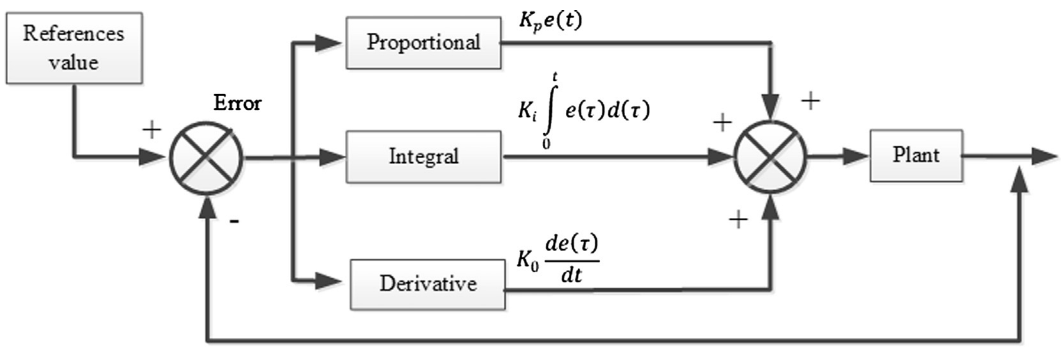

Fig. 20. General structure of PID controllers.

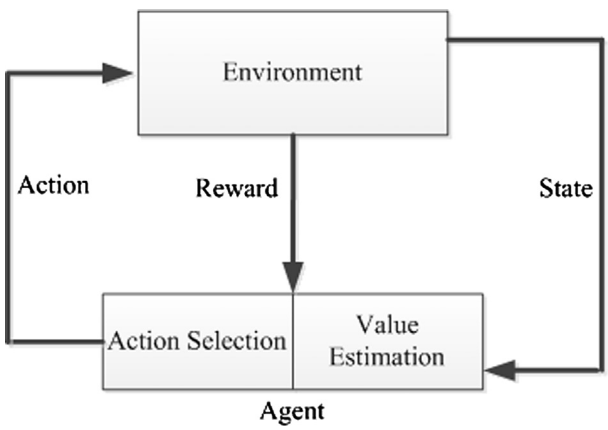

Fig. 21. Reinforced learning scheme [141].

provide thermal and electrical loads to users. A typical MG shown in Fig. 25 comprises radial feeders that consist of critical and noncritical loads [36]. Feeder A has no local generator represented as noncritical load and could fail to balance the system during islanded mode. The critical loads are present as Feeders B, C, and D, which have local generators and sensitive loads. These sensitive loads are isolated during grid disturbance or fault and continuously operate by using local voltage and currents. The MS is responsible for acting as a reliable DG to supply energy in critical feeders continuously [36].

5.4. Exergy in distributed generation

Exergy, also known as available energy, can be obtained from the energy flow produced during operation as it reaches equilibrium with the reference environment [156]. The quality of an energy carrier in energy management is measured by exergy, especially in thermodynamics, to determine the accuracy and efficiency of the system. Exergy analysis exposes the magnitude and location, as well as the source, of energy sources that are wasted in the system. Exergy analysis was introduced to obtain the available functions and operations of a given system and its energy capacity [157]. The authors presented an exergy analysis with a focus on the power generation system of a proton exchange membrane (PEM) FC and PEM-based combined heat and power (CHP) system at different operating parameters while considering the energy efficiency of the system. Another recent analysis also discussed the generation of an integrated system that combines heating, cooling, and high-temperature PEM FCs to assess exergy efficiency while considering the effects of temperature, net power consumption, cell performance, pressure, and cathode and anode ratio efficiency [158]. Several studies performed an exergy analysis of a power generation system for building environments [156,159,110]. An optimized operation strategy for a DG system was also discussed in the literature to reduce the total energy cost and exergy loss during energy conversion for DERs and to provide a high-quality system to end users [156,160]. A comparative approach to exergy assessment in DG system design optimization for waste energy reduction and increase in exergy efficiency was proposed in [161]. The method reduces 20%–30% of the total annual cost and primary exergy input relative to conventional energy

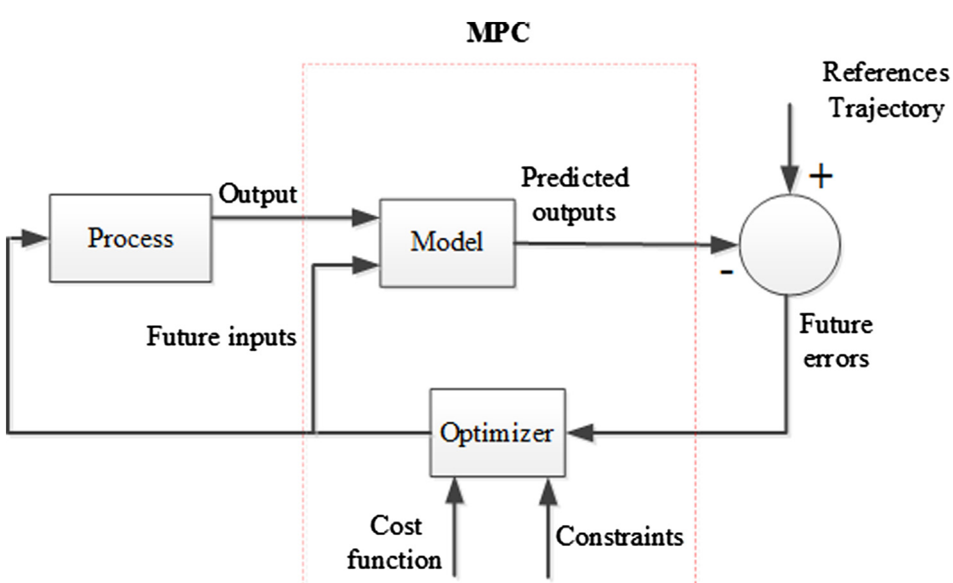

Fig. 22. General architecture of MPC system.

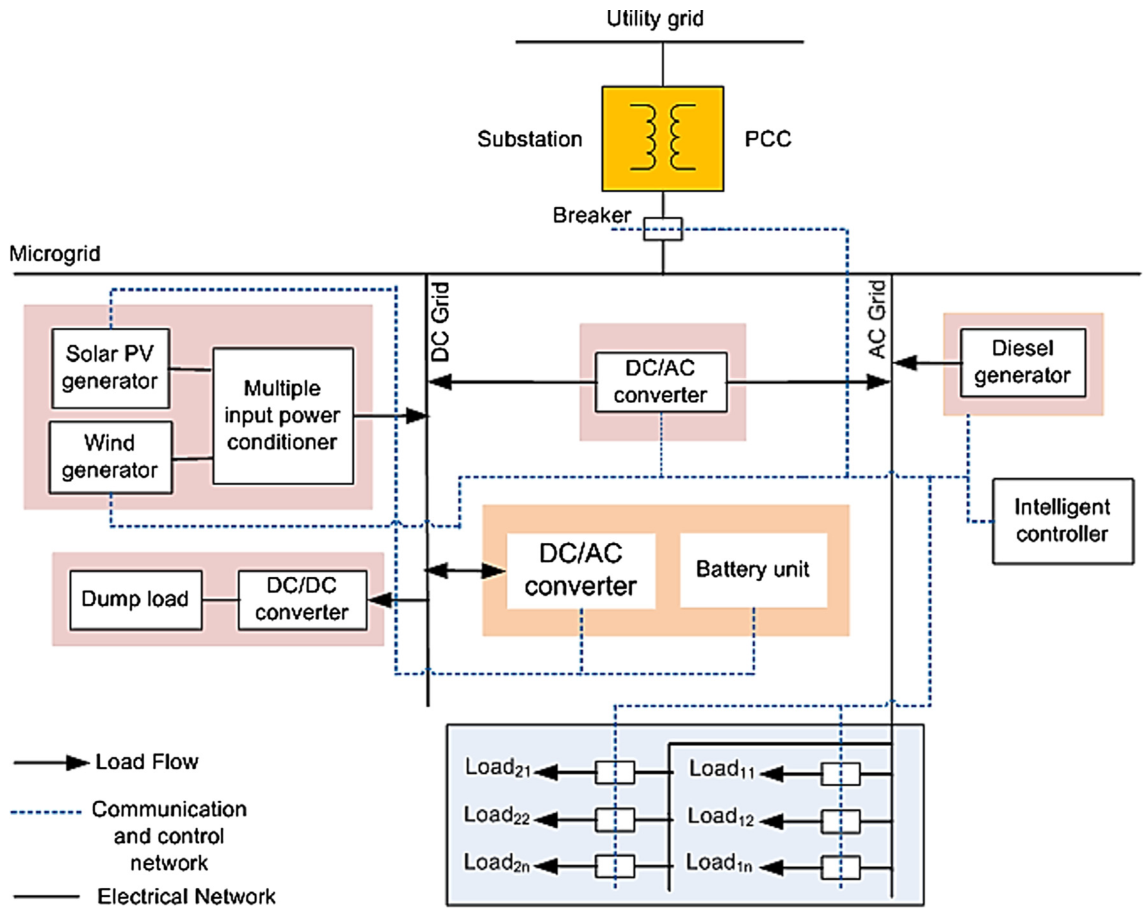

Fig. 23. Microgrid structure [2,36].

systems.

6. Issues and recommendations

According to CERTS, MGs can be defined as a micro power system that consists of multiple DG units and local storage to meet power quality and reliability requirements. When penetration obtained from distributed resources increases, the direct interconnection with the distribution system becomes difficult to control due to their intermittency. The protection system of MGs should be able to react when faults occur in the grid-connected and islanded mode of MGs [162]. Moreover, a suitable control strategy is necessary to anticipate the differences in the increased number of MGs.

6.1. Power quality

In grid-connected mode, PQ is the most important aspect because improper control strategies yield poor results on grid electricity pricing, especially in market sensitivity. Intermittent operations in DG units, switching devices, and sensitive and nonlinear loads in MGs influence PQ and strictly affect system performance. Adopting advanced control technologies is desirable to reduce intermittency elements, especially from DG-connected grids. The existing literature discusses a scheme for controlling the intermittency issue in MGs to enhance the PQ and reliability of the system [162–164]. MGs should be able to operate under unbalanced and nonlinear load degradation, which is due to the lack of voltage and frequency from the utility grid, leading to a PQ problem. In

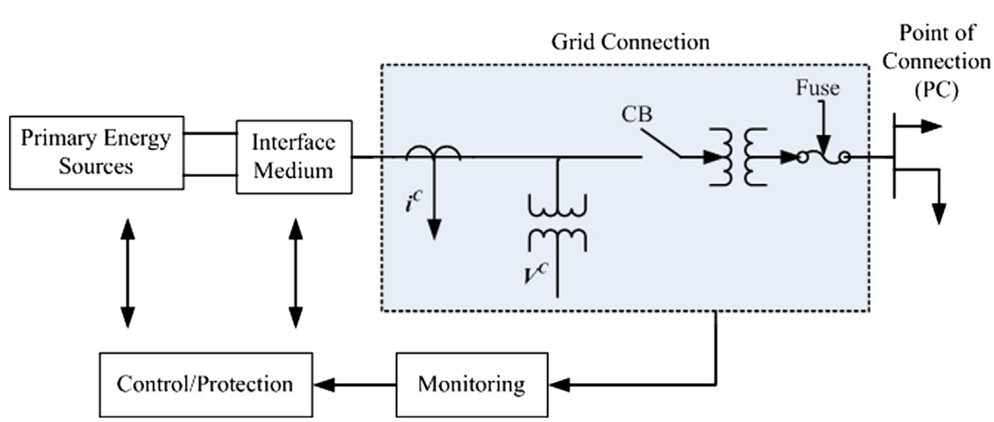

Fig. 24. Block diagram of DG units [2,36].

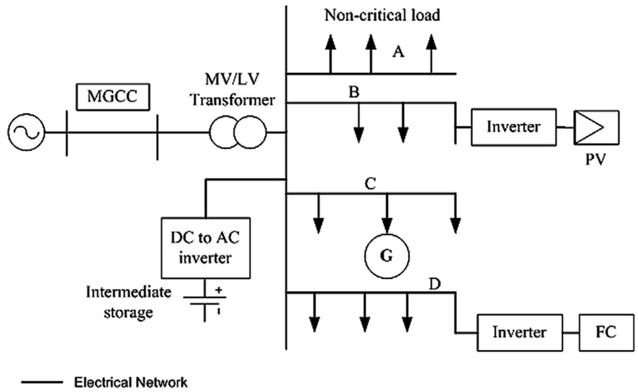

Fig. 25. Feeders in a typical MG [36].

islanded mode, each DG unit should be able to supply a certain amount of total load that equals a power rating by considering power sharing among DG units. Power sharing has several issues, such as accuracy and voltage deviation, unbalanced harmonic current sharing, and high dependency on line impedances. Hence, the proper control of VSIs can yield various voltage imbalance and harmonic compensation capabilities [163].

6.2. Stability issues

The general architecture of an MG system can be connected to the main grid via AC and DC connections. In an MG system, some RESs generate DC output, and some operate at AC mode with variable frequencies. Given such structure, a power electronic converter is needed to adjust and balance the MG frequency output to match the electrical network. Hence, VSIs are widely implemented to such a parameter bounded with proper control schemes. An appropriate control method for VSIs for MG systems is important to obtain a proper management of energy and power balance in systems. The improper control of MGs leads to the instability of the dynamic and transient properties of the entire grid [9]. Many studies have explored MG instability, especially when MGs are islanded in case of disturbances, via power sharing methods and integration of DG units [9,165,166]. A few researchers have studied the effects of transient stability on the integration of DG units in MG systems. Hence, a proper control method for VSIs is required to control and maintain grid stability and thereby supply the load demand with appropriate reactive power. Power sharing among DG units in an MG system is necessary to supply the load demand efficiently, especially when disturbance occurs. Thus, DG units need to be connected in parallel to match the loads.

6.3. Reliability and economic issues

DG is the best approach to enhance the performance and reliability of power systems. A major element of smart power system technologies is the balance between supply and demand. Hence, DG integration constitutes an MG system. The integration of DG units in an MG system not only reduces power loss and voltage profiles but also increases the reliability of the system, especially during a power outage. When disconnected from the main grid, DG units can sustain electricity generation, meet load demands, and reduce the cost of power taken during a high electricity process. Evaluating and maintaining power system reliability are important in enhancing customer satisfaction and providing sustainable electricity generation because the cost of interruptions and power outages leads to severe economic impact on utility and consumers. Different techniques have been used to conduct reliability analyses and ensure economic effectiveness [167–169]. Reliability assessment is a major aspect of distribution systems as a modern distribution network presence for utilities and customers in order to obtain reliable power system. A reliable system is important as it minimizes interruptions and cost in power systems to meet consumer satisfaction.

6.4. Protection and safety

Protection is the most crucial challenge for MGs because it refers to both modes of operation. Fault current magnitude in a system depends on the MG operation mode and changes considerably between grid-connected and autonomous operations [170]. Therefore, MGs require a protection scheme to prevent faults, such as short circuit, which may harm components and consumer equipment. Protective relays have to be installed in power systems to detect abnormal conditions automatically and initiate circuit breakers to isolate faults [171]. Protection schemes that change relay settings online to ensure that the MG system is protected have been proposed [172]. Another solution involves coordinating DG units and noncritical loads to avoid tripping problems in MGs based on a central control unit [173]. Several studies have presented protection schemes for MGs [174].

6.5. Integration of distributed energy resources

DERs help solve the performance problem of distribution systems during MG operations. Distributed resources are always operated in parallel with utilities and supply-sensitive loads, which can be shut down as required, e.g., in case of power disturbances. When a power system disturbance occurs in the distribution system due to line faults, momentary voltage sag happens in the distribution lines [174]. The fundamental characteristic of DERs is that they contain generation resources, such as PV systems, wind energy systems, FCs, CHP-based microturbines, and storage systems. The integration of DERs also involves dynamic active and reactive power control, including load side control [174–176]. Emerging generation technologies, with the proposed MG concept to provide efficient and reliable power systems for utilities and consumers, were reported in [3]. The power electronic interfaces introduced to interface with the power network and its loads help cater to MS issues by providing rapid control of voltage magnitude in the conversion sector. Clusters of microgenerators could be designed to operate in islanded and grid-connected modes to provide some form of storage that can balance initial energy production and ideal system frequency [3,174]. The feasibility of MGs is required in industrial applications as the evolution of the MG concept rapidly increases.

6.6. Power electronic interfaces

Power electronic interfaces are the most crucial components of MG operations. Related devices are designed and integrated with the main grid voltage to control the interfaces among DER units, DC links, AC links, and surrounding power systems operated in both MG modes. This component has become a master device in MG operations because it can cause critical failure to the system, with most MSs being based on power electronics. This component also provides a flexible controlled operation as a single aggregate system [177]. All energy resources and storage systems can produce and deliver power according to their natural characteristics regardless of the efficiency and optimal supply of voltage and current. The improper management of control operation and distribution results in low performance, poor power quality, low reliability, power loss and abuse, unexpected explosions of storage and other forms of damage, restricted behavior, and life loads [178]. The power electronic interface is necessary in MG applications, including storage systems for handling power conditions, power flow control, power conversion, energy management control, charging balance, and safe operation, as it optimizes the power durability and efficiency of the system [179]. The existing power electronic interface system is constrained by its size, efficiency, voltage stress, flexibility, and cost [151]. Moreover, complex high switching frequency interfaces may generate electromagnetic interferences, which degrade system efficiency.

Accordingly, in some cases, a simple electronic circuit such as a single stage converter could be a suitable option to convert RESs in MG operations [180]. Further research is necessary to optimize power use and efficiency by reducing losses of power electronic interfaces.

6.7. Communication system

The integration of RESs with storage systems and distributed loads requires effective communication and coordination to monitor, analyze, and stabilize the grids at various hierarchical levels. The National Institute of Standard and Technology uses a standard communication technology for smart grids, including power line communication technology, IEEE 802.15.4 (ZigBee); IEEE 802.11 (WLAN or Wi-Fi); and IEEE 802.16 (WiMAX), GSM, GPRS, and DASH7 [148]. These wireless technologies have been improved in terms of their security capabilities, and their low robustness has become an interesting solution to distributed MG communication links. A distinct group of wireless technologies in power system applications was reviewed in [181,182]. Communication technologies must be cost efficient and must have good transmittable range, security features, bandwidth, PQ, and minimum number of repetitions, especially in smart meter systems for power grids [183]. Traditionally, wired communication is employed to transfer information due to its good performance, reliability, security, and bandwidth properties in electrical grids, although it entails high deployment cost for installation. In addition, the network scheme has become considerably complex and unable to provide decentralized communication in a reliable manner [184]. Wired technologies that are commonly used in MGs have been reviewed [185]. Other categories of communication networks in MG applications were discussed in [186,187]. The unsatisfactory performance of a communication system leads to potential damages to the grid system and limits smart grids from achieving full energy efficiency and service quality [189,190].

6.8. Data management

An MG is a cluster of DG units, energy storage, and loads, which are interconnected by a network of feeders, and can operate in grid-connected and islanded modes. In grid-connected mode, network voltage and frequency regulation are fixed by the grid, and DG units can control their corresponding power supply. Hence, the mismatched power generation by each DG and load requirements are fixed by the grid. During islanded mode, voltage and frequency regulation are not fixed; hence, DGs must regulate the feeder voltage and frequency within acceptable limits [191]. Therefore, a proper control and communication scheme is needed in MGs for each LC of each DG unit to update the information of the MG operating mode. The parameters in MGs, such as voltage magnitude, phase angle, root mean square, frequency, and active/reactive power, should be monitored and controlled. Moreover, the SOC of energy storage should be within real-time measurements. Ref. [191] stated that traditional monitoring methods, which collect and send data through a computer via a serial port, have many shortcomings and fail to serve multiple users. This drawback causes the instability of MG systems. Wireless technology communication has been widely considered in power system applications because it provides low installation cost, is suitable for remote areas, and is flexible for future expansions [20,191–195]. As renewable energy penetrates systems well, the integration of wireless power transfer technology could be effective in the harvest of renewable energy to meet the power demand of future generations, and the rate of penetration can be further increased [196].

7. Conclusion and recommendations

MGs are a promising technology that can increase the reliability and economy of energy supply to sustain customer satisfaction. The integration of MGs with RESs has emerged in power generation, transmission, and distribution. Accordingly, many researchers have been involved in the design, control, energy management, and operation of MGs to provide quality, reliable, and sustainable energy to consumers. Therefore, a proper control technique is essential for regulating voltage and frequency to ensure a seamless transition in MGs, especially during autonomous operations. However, RESs, adequate power sharing, voltage and frequency stability, optimal power exchange between grids and MGs, operational control and transition for both modes of operation, and others remain as challenging issues. Moreover, energy production by RESs and intermittency due to their stochastic behavior is difficult to predict. Integrating various DG units also leads to difficulties in controlling the MG system, which in turn result in the lack of PQ, security, stability, and reliability. This review highlights the different control methods for MGs, their architecture, control strategies, algorithms, and advantages and disadvantages to provide a concrete overview that should ensure the sustainability of future MG systems. These control methods enhance the efficiency and reliability of MG systems, can satisfy consumer demands, and solve environmental and global economic problems. Conventional control methods, such as droop control, virtual output impedance, master–slave, multiagent-based, and MPPT control methods, are explained in terms of their control operation and capability of maintaining the voltage and frequency of MG systems. In advanced MG control methods, supervisory control and intelligent and adaptive techniques are investigated to show how these techniques optimize MG operation and enhance the control system performance and stability of DG units by adjusting system parameters in the entire MG operation. Among these control techniques, supervisory control (centralized, decentralized, and hierarchical control), intelligent control (FLC, NNs, PSO, and GA), and adaptive control (PID, sliding mode, reinforced learning, and MPC) are discussed. Moreover, MGs consisting of DG units, ESS units, and load characteristics are analyzed to mitigate the impact of fluctuating RESs; improve transmission capability in terms of power imbalance, PQ, islanded operation, and active distribution system; and enhance dynamic and transient stability, voltage support, and frequency regulation for an efficient MG power system.

This rigorous review suggests that a reliable advanced control method requires minimizing interruptions and cost, controlling and maintaining grid stability, supplying appropriate reactive power in the load, and anticipating the number of MGs. Furthermore, a fast and satisfactory communication system updates the information of the MG operating mode and avoids the potential damage of MGs. To obtain superior performance with a reliable operation, this study also reveals that suitable control methods can make the MG concept increasingly attractive in terms of sustainable energy management in different applications. Accordingly, this review highlights various factors, challenges, and possible solutions and suggestions for next-generation smart MG applications, which might help the academe, researchers, and industries in modifying and improving existing MGs. Thus, the key contribution of this research is the comprehensive analysis of different control methods in MG applications that is aimed at providing a comprehensive idea about the deployment of advanced and future MG networks. This review proposes some important and selective suggestions for the further technological development of control methods in MG applications.

- Advanced research is required to improve next-generation control methods for MG applications. Some issues on MGs pertaining to EMS, control interface, reliability, sustainability, RESs' stochastic behavior, and environmental impact need to be addressed to achieve proper system functionality and market acceptance.
- A control technology should be adopted to decrease DG intermittency and thus enhance PQ and reliability under unbalanced and nonlinear load degradation, which is due to the lack of voltage and frequency in grid-connected and islanded modes of operation.
- An investigation into wireless power transfer techniques and control methods is necessary to harvest renewable energy for future

sustainable small and medium power applications.

- An advanced and simple power electronic control circuit may be developed to overcome complex switching and reduced circuitry robustness and thereby address reliable RES conversion in efficient MG operations.
- An appropriate control method for converters is required to control and maintain grid stability and supply the load demand with appropriate reactive power during disturbances.
- An advanced power electronic control system may be developed to overcome switching challenges and safety circuitry issues and to address overheating and RES conversion in efficient MG operations.
- A thorough investigation should be undertaken to develop a reliability assessment and economic impact analysis model to enhance customer satisfaction and sustainable power generation and to forecast economic impact on utility and consumers.
- Protection is a crucial challenge in MG operations. Thus, an advanced protection scheme should be prioritized to prevent faulty conditions in MGs and to coordinate between protective devices to avoid tripping problems in grid-connected and islanded modes of MG operations.
- Further research needs to be conducted on the integration of DERs to solve the performance problem of distribution systems and thereby obtain efficient and reliable active and reactive power control for the utility grid and consumers.
- An advanced research on power electronic interfaces is necessary to optimize power use for handling power conditions, power flow, energy conversion and management, and safe operation; and to improve the size, efficiency, voltage stress, flexibility, and cost of MGs.
- An advanced internet of energy based on an effective communication and coordination model is required to monitor, analyze, and stabilize the grids at various hierarchical levels. Good transmittable range, security features, bandwidth, PQ, and minimum number of repetitions for MG operations must be considered.
- Further studies on MG data management system should be performed for proper control and communication. Remote area data transmission and future extension of stable MG systems for utilities and consumers should be considered.

These suggestions would be remarkable contributions toward the maturity of MG technologies, which will dominate the electricity market in the future. Advanced research based on this review may overcome the shortcomings of existing MG technologies to meet the requirements of sustainable energy utilization in the future.

Acknowledgement

The authors gratefully acknowledge the financial support provided by Ministry of Higher Education, Malaysia under the project 20190101LRGS and Universiti Tenaga Nasional, Malaysia under grant J510050797.

References

[1] Zhou Y, Ngai-Man Ho C. A review on Microgrid architectures and control methods. 2016 IEEE 8th Int Power Electron Motion Control Conf IPEMC-ECCE Asia; 2016. p. 3149–56.
[2] Katiraei F, Iravani R, Hatziargyriou N, Dimeas A. Microgrid management. IEEE Power Energ Mag 2008;6(june):54–65.
[3] Lasseter B. Microgrids [distributed power generation]. 2001 IEEE Power Eng Soc Winter Meet PES 2001 – Conf Proc, vol. 1, no. C; 2001. p. 146–9.
[4] Falahi M, Lotfifard S, Ehsani M, Butler-Purry K. Dynamic model predictive-based energy management of dg integrated distribution systems. IEEE Trans Power Deliv 2013;28(4):2217–27.
[5] Unamuno E, Barrena JA. Hybrid ac/dc microgrids –- Part I: Review and classification of topologies. Renew Sustain Energy Rev 2015;52:1251–9.
[6] Unamuno E, Barrena JA. Hybrid ac/dc microgrids – Part II: Review and classification of control strategies. Renew Sustain Energy Rev 2015;52:1123–34.
[7] Mahmoud MS, Alyazidi NM, Abouheaf MI. Adaptive intelligent techniques for microgrid control systems: a survey. Int J Electr Power Energy Syst 2017;90:292–305.
[8] Kaur S. Power quality issues and their mitigationtechniques in microgrid system – a review; 2016.
[9] Al Habri W, Magid YLA. Power system stabilizer for power sharing control of parallel inverters in a grid – connected micro-grid system. 2011 IEEE PES Conf Innov Smart Grid Technol – Middle East, ISGT Middle East 2011. 2011.
[10] Abu-Sharkh S, et al. Can microgrids make a major contribution to UK energy supply? Renew Sustain Energy Rev 2006;10(2):78–127.
[11] Brown RE, Freeman LAA. Analyzing the reliability impact of distributed generation. Proc IEEE Power Eng Soc Transm Distrib Conf 2001;2(SUMMER):1013–8.
[12] Sbordone DA, Huq KMM, Baran M. An experimental microgrid for laboratory activities. 2015 IEEE 15th Int Conf Environ Electr Eng EEEIC 2015 – Conf Proc. 2015. p. 363–7.
[13] Bernal-Agustín JL, Dufo-López R. Simulation and optimization of stand-alone hybrid renewable energy systems. Renew Sustain Energy Rev 2009;13(8):2111–8.
[14] Bazmi AA, Zahedi G. Sustainable energy systems: role of optimization modeling techniques in power generation and supply – a review. Renew Sustain Energy Rev 2011;15(8):3480–500.
[15] Logenthiran T, Srinivasan D, Khambadkone AM, Raj TS. Optimal sizing of an islanded microgrid using Evolutionary Strategy. 2010 IEEE 11th Int Conf Probabilistic Methods Appl to Power Syst PMAPS 2010; 2010. p. 12–7.
[16] Basu AK, Chowdhury SP, Chowdhury S, Paul S. Microgrids: energy management by strategic deployment of DERs – a comprehensive survey. Renew Sustain Energy Rev 2011;15(9):4348–56.
[17] Alsayegh O, Alhajraf S, Albusairi H. Grid-connected renewable energy source systems: challenges and proposed management schemes. Energy Convers Manag 2010;51(8):1690–3.
[18] Olatomiwa L, Mekhilef S, Ismail MS, Moghavvemi M. Energy management strategies in hybrid renewable energy systems: a review. Renew Sustain Energy Rev 2016;62:821–35.
[19] Dumitru C-D, Gligor A. SCADA based software for renewable energy management system. Proc Econ Financ 2012;3(12):262–7.
[20] Batista NC, Melício R, Matias JCO, Catalão JPS. Photovoltaic and wind energy systems monitoring and building/home energy management using ZigBee devices within a smart grid. Energy 2013;49(2013):306–15.
[21] Al-Ali AR, El-Hag A, Bahadiri M, Harbaji M, Ali El Haj Y. Smart home renewable energy management system. Energy Proc 2011;12:120–6.
[22] Sukumar S, Mokhlis H, Mekhilef S, Naidu K. Mix-mode energy management strategy and battery sizing for economic operation of grid-tied microgrid. Energy 2017;118:1322–33.
[23] Anglani N, Oriti G, Colombini M. Optimized energy management system to reduce fuel consumption in remote military microgrids. IEEE Trans Ind Appl 2017;53(6):5777–85.
[24] Helal SA, Najee RJ, Hanna MO, Shaaban MF, Osman AH, Hassan MS. An energy management system for hybrid microgrids in remote communities. IEEE 30th Canadian conferences on electrical and computer engineering 2017.
[25] Livengood D, Larson R. The energy box: locally automated optimal control of residential electricity usage. Serv Sci 2009;1(1):1–16. https://doi.org/10.1287/serv.1.1.1.
[26] Black JW, Black JW, Larson RC. Strategies to overcome network congestion in infrastructure systems. Int J Ind Syst Eng 2007;1(2):1–25.
[27] Rodriguez-Mondejar JA, Santodomingo R, Brown C. The ADDRESS energy box: design and implementation. 2012 IEEE international energy conference and exhibition (ENERGYCON 2012). 2012. p. 629–34.
[28] Ioakimidis CS, Oliveira L, Genikomsakis KN, Rycerski P. A virtual power plant with the use of the energy box in a smart grid concept key words. International conferences on renewable energies and power quality (ICREPQ'13), no. 11. 2013.
[29] Lasseter RH. Smart distribution: coupled microgrids. Proc IEEE 2011;99(6):1074–82.
[30] Pedrasa M, Spooner T. A survey of techniques used to control microgrid generation and storage during island operation. Proc Aust Univ Power Eng Conf (AUPEC), no. August 2016. 2006. p. 10–3.
[31] Bahmani-Firouzi B, Azizipanah-Abarghooee R. Optimal sizing of battery energy storage for micro-grid operation management using a new improved bat algorithm. Int J Electr Power Energy Syst 2014;56:42–54.
[32] Wu Z, Gu W, Wang R, Yuan X, Liu W. Economic optimal schedule of CHP microgrid system using chance constrained programming and particle swarm optimization. IEEE Power Energy Soc Gen Meet. 2011. p. 1–11.
[33] Liang G, Liyuan P, Ruihuan L, Fen Z, Jinhui L, Xin W. Study on economic operation for micro-grid based on scenario and PSO. POWERCON 2014–2014 Int Conf Power Syst Technol Towar Green, Effic Smart Power Syst Proc, Powercon 2014:3152–6.
[34] Wang Y, Jiang H, Xing P. Improved PSO-based energy management of Stand-Alone Micro-Grid under two-time scale. 2016 IEEE Int Conf Mechatronics Autom. IEEE ICMA; 2016. p. 2128–33.
[35] Mehrizi-Sani A, Iravani R. Potential-function based control of a microgrid in islanded and grid-connected modes. IEEE Trans Power Syst 2010;25(4):1883–91.
[36] Bakar NNA, Hassan MY, Sulaima MF, Im Mohd Nasir MN, Khamis A. Microgrid and load shedding scheme during islanded mode: a review. Renew Sustain Energy Rev 2017;71(June 2015):161–9.
[37] Lede AMR, Molina MG, Martinez M, Mercado PE. Microgrid architectures for distributed generation: a brief review. 2017 IEEE PES Innov Smart Grid Technol Conf – Lat Am (ISGT Lat Am). 2017. p. 1–6.
[38] Planas E, Andreu J, Gárate JI, Martínez De Alegría I, Ibarra E. AC and DC technology in microgrids: a review. Renew Sustain Energy Rev 2015;43:726–49.
[39] Piagi P, Lasseter RH. Autonomous control of microgrids. 2006 IEEE Power Eng Soc

Gen Meet; 2006. p. 8.
[40] Oliveira DQ, Zambroni de Souza AC, Santos MV, Almeida AB, Lopes BIL, Saavedra OR. A fuzzy-based approach for microgrids islanded operation. Electr Power Syst Res 2017;149:178–89.
[41] Olivares DE, Cañizares CA, Kazerani M, Member S. A centralized optimal energy management system for microgrids. 2011 IEEE power and energy society general meeting. 2011. p. 1–6.
[42] Solanki BV, Bhattacharya K, Cañizares CA. Integrated energy management system for isolated microgrids. 19th Power Syst Comput Conf PSCC 2016. 2016.
[43] Kaur A, Kaushal J, Basak P. a review on microgrid central controller. Renew Sustain Energy Rev 2016;55:338–45.
[44] Deng N, Zhang XP, Wang P, Gu X, Wu M. A converter-based general interface for AC microgrid integrating to the grid. 2013 4th IEEE/PES Innov Smart Grid Technol Eur ISGT Eur 2013. 2013. p. 1–5.
[45] Patrao I, Figueres E, Garcerá G, González-Medina R. Microgrid architectures for low voltage distributed generation. Renew Sustain Energy Rev 2015;43:415–24.
[46] Planas E, Gil-De-Muro A, Andreu J, Kortabarria I, Martínez De Alegría I. General aspects, hierarchical controls and droop methods in microgrids: a review. Renew Sustain Energy Rev 2013;17:147–59.
[47] Kzaviri SM, Pahlevani M, Jain P, Bakhshai A. A review of AC microgrid control methods. 2017 IEEE 8th Int Symp Power Electron Distrib Gener Syst PEDG 2017. 2017.
[48] Tayab UB, Bin Roslan MA, Hwai LJ, Kashif M. A review of droop control techniques for microgrid. Renew Sustain Energy Rev 2017;76(May 2016):717–27.
[49] Zhao H, Hong M, Lin W, Loparo KA. Voltage and frequency regulation of microgrid with battery energy storage systems. IEEE Trans Smart Grid 2017;3053(c):1–12.
[50] Guerrero JM, Matas J, De Vicuña LG, Berbel N, Sosa J. Wireless-control strategy for parallel operation of distributed generation inverters. IEEE Int Symp Ind Electron 2005;II:845–50.
[51] Guerrero JM, Matas J, de Vicuna LG, Castilla M, Miret J. Decentralized control for parallel operation of distributed generation inverters using resistive output impedance. IEEE Trans Ind Electron 2007;54(2):994–1004.
[52] Savaghebi M, Jalilian A, Vasquez JC, Guerrero JM. Autonomous voltage unbalance compensation in an islanded droop-controlled microgrid. IEEE Trans Ind Electron 2013;60(4):1390–402.
[53] Eid BM, Rahim NA, Selvaraj J, El Khateb AH. Control methods and objectives for electronically coupled distributed energy resources in microgrids: a review. IEEE Syst J 2016;10(2):446–58.
[54] Borup U, Blaabjerg F, Enjeti PN. Sharing of nonlinear load in parallel-connected three-phase converters. IEEE Trans Ind Appl 2001;37(6):1817–23.
[55] Li YW, Kao CN. An accurate power control strategy for power-electronics-interfaced distributed generation units operating in a low-voltage multibus microgrid. IEEE Trans Power Electron 2009;24(12):2977–88.
[56] He J, Li YW. An enhanced microgrid load demand sharing strategy. IEEE Trans Power Electron 2012;27(9):3984–95.
[57] Guerrero JM, Vasquez JC, Matas J, De Vicuña LG, Castilla M. Hierarchical control of droop-controlled AC and DC microgrids – a general approach toward standardization. IEEE Trans Ind Electron 2011;58(1):158–72.
[58] Guerrero JM, de Vicuna LG, Matas J, Castilla M, Miret J. A wireless controller to enhance dynamic performance of parallel inverters in distributed generation systems. IEEE Trans Power Electron 2004;19(5):1205–13.
[59] Xiao Z, Wu J, Jenkins N. An overview of microgrid control. Intell Autom Soft Comput 2010;16(2):199–212.
[60] Verma V, Talpur GG. Decentralized Master-Slave operation of microgrid using current controlled distributed generation sources. PEDES 2012 – IEEE Int Conf Power Electron Drives Energy Syst. 2012.
[61] Mao M, Jin P, Hatziargyriou ND, Chang L. Multiagent-based hybrid energy management system for microgrids. IEEE Trans Sustain Energy 2014;5(3):938–46.
[62] Han Y, Zhang K, Li H, Coelho EAA, Guerrero JM. MAS-based distributed coordinated control and optimization in microgrid and microgrid clusters: a comprehensive overview. IEEE Trans Power Electron 2017;8993(c).
[63] Dou C, Lv M, Zhao T, Ji Y, Li H. Decentralised coordinated control of microgrid based on multi-agent system. IET Gener Transm Distrib 2015;9(16):2474–84.
[64] Liu W, Gu W, Sheng W, Meng X, Wu Z, Chen W. Decentralized multi-agent system-based cooperative frequency control for autonomous microgrids with communication constraints. IEEE Trans Sustain Energy 2014;5(2):446–56.
[65] Dimeas AL, Hatziargyriou ND. Operation of a multiagent system for microgrid control. IEEE Trans Power Syst 2005;20(3):1447–55.
[66] Seyedmahmoudian M, et al. State of the art artificial intelligence-based MPPT techniques for mitigating partial shading effects on PV systems – a review. Renew Sustain Energy Rev 2016;64:435–55.
[67] Karami N, Moubayed N, Outbib R. General review and classification of different MPPT Techniques. Renew Sustain Energy Rev 2017;68(July 2015):1–18.
[68] Olivares DE, et al. Trends in microgrid control. IEEE Trans Smart Grid 2014;5(4):1905–19.
[69] Banerji A, et al. Microgrid: a review. c2013 IEEE Glob Humanit Technol Conf South Asia Satell GHTC-SAS 2013 2013:27–35.
[70] Zamora R, Srivastava AK. Controls for microgrids with storage: review, challenges, and research needs. Renew Sustain Energy Rev 2010;14(7):2009–18.
[71] Meng L, Riva E, Luna A, Dragicevic T, Vasquez JC, Guerrero JM. Microgrid supervisory controllers and energy management systems: a literature review. Renew Sustain Energy Rev 2016;60:1263–73.
[72] Logenthiran T, Srinivasan D, Khambadkone AM, Aung HN. Multiagent system for real-time operation of a microgrid in real-time digital simulator. IEEE Trans Smart Grid 2012;3(2):925–33.
[73] Liang H, Choi BJ, Abdrabou A, Zhuang W, Shen X. Decentralized economic dispatch in microgrids via heterogeneous wireless networks. IEEE J Sel Areas Commun 2012;30(6):1061–74.
[74] De Muro AG, Jimeno J, Anduaga J. Architecture of a microgrid energy management system. European Trans Electr Power 2011;21(2):1142–58.
[75] Automation D, Committee S. IEEE standards for interconnecting distributed resources with electric power system. IEEE Std 1547 2004;2004(October).
[76] Blaabjerg F, Teodorescu R, Liserre M, Timbus AV. Overview of control and grid synchronization for distributed power generation systems. IEEE Trans Ind Electron 2006;53(5):1398–409.
[77] Palizban O, Kauhaniemi K. Hierarchical control structure in microgrids with distributed generation: Island and grid-connected mode. Renew Sustain Energy Rev 2015;44:797–813.
[78] Rocabert J, Luna A, Blaabjerg F, Paper I. Control of power converters in AC Microgrids.pdf. IEEE Trans Power Electron 2012;27(11):4734–49.
[79] Rodriguez P, Candela I, Citro C, Rocabert J, Luna A. Control of grid-connected power converters based on a virtual admittance control loop. 15th Eur Conf Power Electron Appl. 2013. p. 1–10.
[80] Vasquez JC, Josep M. Universitet hierarchical control for multiple DC-microgrids clusters. IEEE Trans Energy Convers 2014;29(4):922–33.
[81] Milczarek A, Malinowski M, Guerrero JM. Reactive power management in islanded microgrid – proportional power sharing in hierarchical droop control. IEEE Trans Smart Grid 2015;6(4):1631–8.
[82] Shi W, Xie X, Chu CC, Gadh R. Distributed optimal energy management in microgrids. IEEE Trans Smart Grid 2015;6(3):1137–46.
[83] Kahrobaeian A, Mohamed YARI. Networked-based hybrid distributed power sharing and control for islanded microgrid systems. IEEE Trans Power Electron 2015;30(2):603–17.
[84] Wang J, Chang NCP, Feng X, Monti A. Design of a generalized control algorithm for parallel inverters for smooth microgrid transition operation. IEEE Trans Ind Electron 2015;62(8):4900–14.
[85] Meng L, Dragicevic T, Guerrero J, Vasquez J. Agent-based distributed unbalance compensation for optimal power quality in islanded microgrids. IEEE 23rd international symposium on industrial electronics(ISIE) 2014:2535–40.
[86] Hassan MA, Abido MA. Optimal design of microgrids in autonomous and grid-connected modes using particle swarm optimization. IEEE Trans Power Electron 2011;26(3):755–69.
[87] Hamad AA, El-Saadany EF. Multi-agent supervisory control for optimal economic dispatch in DC microgrids. Sustain Cities Soc 2016;27:129–36.
[88] Augustine N, Suresh S, Moghe P, Sheikh K. Economic dispatch for a microgrid considering renewable energy cost functions. 2012 IEEE PES Innov Smart Grid Technol 2012:1–7.
[89] Xiaoping L, Ming D, Jianghong H, Pingping H, Yali P. Dynamic economic dispatch for microgrids including battery energy storage. 2nd Int Symp Power Electron Distrib Gener Syst 2010;2:914–7.
[90] Chen C, Duan S, Cai T, Liu B, Hu G. Smart energy management system for optimal microgrid economic operation. IET Renew Power Gener 2011;5(3):258.
[91] Hatziargyriou N, Nick N, Strbac G, Lopes JA, Ruela J, Engler A, et al. Microgrids-large scale integration of microgeneration to low voltage grids. Proc of CIGRE 41st annual session conference 2006.
[92] Yanine FF, Córdova FM, Valenzuela L. Sustainable hybrid energy systems: an energy and exergy management approach with homeostatic control of microgrids. Proc – Proc Comput Sci 2015;55(Itqm):642–9.
[93] Fernando F, Caballero FI, Sauma EE, Córdova FM. Homeostatic control, smart metering and efficient energy supply and consumption criteria: a means to building more sustainable hybrid micro-generation systems. Renew Sustain Energy Rev 2014;38:235–58.
[94] Cordova FM, Yanine FF. Homeostatic control of sustainable energy grid applied to natural disasters building the case for decentralized power systems (DPS) and the penetration of DG. Int J Comput Commun 2013;8(1):50–60.
[95] Yanine FF, Sauma EE, Cordova FM. An exergy and homeostatic control approach to sustainable grid-connected microgrids without energy storage 1. Appl Mech Mater 2014;472:1027–31.
[96] Yanine F, Sanchez-Squella A, Barrueto A, Sahoo SK, Cordova FM. Smart energy systems: the need to incorporate homeostatically controlled microgrids to the electric power distribution industry: an electric utilities' perspective. Int J Eng Technol 2018;7(2):64–73.
[97] Schweppe FC, Tabors RD, Kirtley JL, Outhred HR, Pickel FH, Cox AJ. Homeostatic utility control. IEEE Trans Power App Syst May 1980;PAS-99(3):1151–63.
[98] Yanine F, Sanchez-Squella A, Barrueto A, Cordova F, Sahoo SK. Engineering sustainable energy systems: how reactive and predictive homeostatic control can prepare electric power systems for environmental challenges. Proc Comput Sci 2017;122:439–46.
[99] Yanine FF, Caballero FI, Sauma EE, Córdova FM. Building sustainable energy systems: homeostatic control of grid-connected microgrids, as a means to reconcile power supply and energy demand response management. Renew Sustain Energy Rev 2014;40:1168–91.
[100] Yanine F, Sanchez-squella A, Barrueto A, Tosso J, Cordova FM, Rother HC. Reviewing homeostasis of sustainable energy systems: how reactive and predictive homeostasis can enable electric utilities to operate distributed generation as part of their power supply services. Renew Sustain Energy Rev 2018;81(2):2879–92.
[101] Amin SM, Wollenberg BF. Toward a smart grid. IEEE Power Energ Mag 2005;3(5):34–41.
[102] Bozchalui MC, Hashmi SA, Hassen H, Cañizares CA, Bhattacharya K. Optimal operation of residential energy hubs in smart grids. IEEE Trans Smart Grid 2012;3(4):1755–66.
[103] Yildiz A, Güngör A. Energy and exergy analyses of space heating in buildings. Appl

Energy 2009;86(10):1939–48.
[104] De Santis E, Rizzi A, Sadeghian A. Hierarchical genetic optimization of a fuzzy logic system for energy flows management in microgrids. Appl Soft Comput J 2017;60:135–49.
[105] Wang T, He X, Deng T. Neural networks for power management optimal strategy in hybrid microgrid. Neural Comput Appl 2017.
[106] Venayagamoorthy GK, et al. Dynamic energy management system for a smart microgrid. IEEE Trans Neural Network 2016;27(8):1643–56.
[107] Jha J, Sharma S, Sharma KB, Tomar A. Literature review on various control strategies for hybrid photovoltaic and fuel cell power generating systems. International conferences on computer, communications and electronics (Comptelic). 2017. p. 633–8.
[108] Denna M, Mauri G, Zanaboni AM. Learning fuzzy rules with tabu search-an application to control. IEEE Trans Fuzzy Syst 1999;7(3):295–318.
[109] Arcos-aviles D, Pascual J, Guinjoan F, Marroyo L, Sanchis P, Marietta MP. Low complexity energy management strategy for grid profile smoothing of a residential grid-connected microgrid using generation and demand forecasting. Appl Energy 2017;205(May):69–84.
[110] Juang C, Lu C. Power system load frequency control by genetic fuzzy gain scheduling controller. J Chinese Inst Eng 2005;28(6):1013–8.
[111] Chamorro HR, Member IS, Ramos G, Member I. Microgrid central fuzzy controller for active and reactive power flow using instantaneous power measurements. 2011 IEEE power energy conference. 2011. p. 4–9.
[112] Mohamed YARI, El-Saadany EF. Adaptive discrete-time grid-voltage sensorless interfacing scheme for grid-connected DG-inverters based on neural-network identification and deadbeat current regulation. IEEE Trans Power Electron 2008;23(1):308–21.
[113] Latha R, Kanakaraj J. Adaptive Neuro-Fuzzy Inference system-particle Swarm Optimization based stability maintenance of power system networks. Am J Appl Sci 2013;10(8):779–86.
[114] Sun C. Sizing of hybrid energy storage system in independent microgrid based on BP neural network. 2nd IET Renew Power Gener Conf (RPG 2013), no. 8, p. 3.45. 2013.
[115] Chalise S, Sternhagen J, Hansen TM, Tonkoski R. Energy management of remote microgrids considering battery lifetime. Electr J 2016;29(6):1–10.
[116] Askarzadeh A. A memory-based genetic algorithm for optimization of power generation in a microgrid. IEEE Trans Sustain Energy 2018;9(3):1081–9.
[117] Li H, Eseye AT, Zhang J, Zheng D. Optimal energy management for industrial microgrids with high-penetration renewables 2017:1–14.
[118] Fahad M, Elbouchikhi E, Benbouzid M. Microgrids energy management systems: a critical review on methods, solutions, and prospects. Appl Energy 2018;222(March):1033–55.
[119] Fathima AH, Palanisamy K. Optimization in microgrids with hybrid energy systems – a review. Renew Sustain Energy Rev 2015;45:431–46.
[120] Chung I-Y, Liu W, Cartes DA, Schoder K. Control parameter optimization for a microgrid system using particle swarm optimization. 2008 IEEE Int Conf Sustain Energy Technol. 2008. p. 837–42.
[121] Sedighizadeh M, Fallahnejad M, Alemi MR, Omidvaran M, Arzaghi-haris D. Optimal placement of distributed generation using combination of PSO and clonal algorithm. PECon2010 – 2010 IEEE Int Conf Power Energy. 2010. p. 1–6.
[122] Abbas G, Gu J, Farooq U, Asad MU, El-Hawary M. Solution of an economic dispatch problem through particle swarm optimization: a detailed survey – part i. IEEE Access 2017;5(c):15105–41.
[123] Al-saedi W, Lachowicz SW, Habibi D, Bass O. Electrical Power and Energy Systems Power quality enhancement in autonomous microgrid operation using Particle Swarm Optimization. Int J Electr Power Energy Syst 2012;42(1):139–49.
[124] Elsied M, Oukaour A, Gualous H. An advanced energy management of microgrid system based on genetic algorithm. IEEE 23rd international symposium on industrial electronics (ISIE). 2014. p. 2541–7.
[125] Singh A. GA optimized PID controller for frequency regulation in standalone AC microgrid. 2016 7th India international conference on power electronics (IICPE). 2016.
[126] Mallesham G, Mishra S, Member S, Jha AN, Member S. Ziegler-nichols based controller parameters tuning for load frequency control in a microgrid. 2011 International conference on energy, automation and signal. 2011. p. 1–8.
[127] Yin XX, Lin YG, Li W, Liu HW, Gu YJ. Adaptive sliding mode back-stepping pitch angle control of a variable-displacement pump controlled pitch system for wind turbines. ISA Trans 2015;58:629–34.
[128] Liu Y, Zhang Q, Wang C, Wang N. A control strategy for microgrid inverters based on adaptive three-order sliding mode and optimized droop controls. Electr Power Syst Res 2014;117:192–201.
[129] Gopalan SA, Sreeram V, Iu HHC. A review of coordination strategies and protection schemes for microgrids. Renew Sustain Energy Rev 2014;32:222–8.
[130] Chen Z, Luo A, Wang H, Chen Y, Li M, Huang Y. Electrical Power and Energy Systems Adaptive sliding-mode voltage control for inverter operating in islanded mode in microgrid. Int J Electr Power Energy Syst 2015;66:133–43.
[131] Leo R, Milton RS, Kaviya A. Multi agent reinforcement learning based distributed optimization of solar microgrid. 2014 IEEE Int Conf Comput Intell Comput Res. 2014. p. 1–7.
[132] Hadidi R, Member S, Jeyasurya B, Member S. Near optimal control policy for controlling power system stabilizers using reinforcement learning. IEEE power and energy society general meeting 2009:1–7.
[133] Li K, Hu J, Chen M. Model predictive control of parallel distributed generation inverters in smart microgrids. 2016 IEEE 8th Int Power Electron Motion Control Conf IPEMC-ECCE Asia 2016. 2016. p. 3414–8.
[134] Rana MJ, Abido MA. Energy management in DC microgrid with energy storage and model predictive controlled AC–DC converter. IET Gener Transm Distrib 2017;11(15):3694–702.
[135] Wang B et al. A DC microgrid integrated dynamic voltage restorer with model predictive control.
[136] Zhang Y, Gatsis N, Giannakis GB. Robust energy management for microgrids with high penetration renewables. Energy Pol 2005;33(6):787–98.
[137] Reddy KS, Kumar M, Mallick TK, Sharon H, Lokeswaran S. A review of Integration, Control, Communication and Metering (ICCM) of renewable energy based smart grid. Renew Sustain Energy Rev 2014;38:180–92.
[138] Tina GM, Scandura PF. Case study of a grid connected with a battery photovoltaic system: V-trough concentration vs. single-axis tracking. Energy Convers Manag 2012;64:569–78.
[139] Yoldaş Y, Önen A, Muyeen SM, Vasilakos AV, Alan İ. Enhancing smart grid with microgrids: challenges and opportunities. Renew Sustain Energy Rev 2017;72(January):205–14.
[140] Hannan MA, Hoque MM, Mohamed A, Ayob A. Review of energy storage systems for electric vehicle applications: issues and challenges. Renew Sustain Energy Rev 2017;69(December 2016):771–89.
[141] Hannan MA, Lipu MSH, Hussain A, Mohamed A. A review of lithium-ion battery state of charge estimation and management system in electric vehicle applications: challenges and recommendations. Renew Sustain Energy Rev 2017;78(August 2016):834–54.
[142] Koohi-Kamali S, Tyagi VV, Rahim NA, Panwar NL, Mokhlis H. Emergence of energy storage technologies as the solution for reliable operation of smart power systems: a review. Renew Sustain Energy Rev 2013;25:135–65.
[143] Hasan NS, Hassan MY, Majid MS, Rahman HA. Review of storage schemes for wind energy systems. Renew Sustain Energy Rev 2013;21:237–47.
[144] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: a critical review. Prog Nat Sci 2009;19(3):291–312.
[145] Authayanun S, Hacker V. Energy and exergy analyses of a stand-alone HT-PEMFC based trigeneration system for residential applications. Energy Convers Manag 2018;160(August 2017):230–42.
[146] Yakaryılmaz AC. ScienceDirect a review: exergy analysis of PEM and PEM fuel cell based CHP systems. Int J Hydrogen Energy 2018;43(38):17993–8000.
[147] Yan B, et al. Exergy-based operation optimization of a distributed energy system through the energy-supply chain. Appl Therm Eng 2016;101:741–51.
[148] Schmidt D. Low exergy systems for high-performance buildings and communities. Energy Build 2009;41(3):331–6.
[149] Yan B, et al. Energy-efficient management of eco-communities. 2013 IEEE Int Conf Autom Sci Eng. 2013. p. 106–11.
[150] Di Somma M, et al. Design optimization of a distributed energy system through cost and exergy assessments. Energy Proc 2017;105:2451–9.
[151] Manoj Kumar MV, Mishra MK, Kumar C. A grid-connected dual voltage source inverter with power quality improvement features. IEEE Trans Sustain Energy 2015;6(2):482–90.
[152] Han Y, Shen P, Zhao X, Guerrero JM. An enhanced power sharing scheme for voltage unbalance and harmonics compensation in an islanded microgrid. IEEE Trans Energy Convers 2016;31(3):1037–50.
[153] He J, Li YW, Wang R, Zhang C. Analysis and mitigation of resonance propagation in grid-connected and islanding microgrids. IEEE Trans Energy Convers 2015;30(1):70–81.
[154] Filho RMS, Seixas PF, Cortizo PC, Gateau G, Coelho EAA. Power system stabilizer for comunicationless parallel connected inverters. IEEE Int Symp Ind Electron 2010:1004–9.
[155] Zeljković ČV, Rajaković NL, Zubić SJ. Customer-perspective approach to reliability evaluation of distributed generation. 2011 IEEE PES Trondheim PowerTech Power Technol a Sustain Soc POWERTECH 2011; 2011. p. 1–6.
[156] Duttagupta SS, Singh C. A reliability assessment methodology for distribution systems with distributed generation. Simulation 2006:1–7.
[157] Falaghi H, Haghifam M-R. Distributed generation impacts on electric distribution systems reliability: sensitivity analysis. EUROCON 2005 – Int Conf "Computer as a Tool". 2005. p. 1465–8.
[158] Stadler M, et al. Value streams in microgrids: a literature review. Appl Energy 2016;162:980–9.
[159] Soshinskaya M, Crijns-Graus WHJ, Guerrero JM, Vasquez JC. Microgrids: experiences, barriers and success factors. Renew Sustain Energy Rev 2014;40:659–72.
[160] Tao L, Schwaegerl C, Narayanan S, Zhiang Jian Hui. From laboratory microgrids to real markets-challenges & opportunities. 8th international conferences on power electronics (ECCE). 2011.
[161] Wang B, Sun M, Dong B. The existed problems and possible solutions of distributed generation microgrid operation. Asia-Pacific Power Energy Eng Conf APPEEC 2011. no. 50877021.
[162] Basak P, Chowdhury S, Halder Nee Dey S, Chowdhury SP. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renew Sustain Energy Rev 2012;16(8):5545–56.
[163] Eto J, Budhraja V, Martinez C. Research, development, and demonstration needs for large-scale, reliability-enhancing, integration of distributed energy resources. Hawaii Int Conf Syst Sci, vol. 0, no. c; 2000. pp. 1–7.
[164] Marnay C, Blanco R, Hamachi KS, Kawaan CP, Osborn JG. LBNL-46082 consortium for electric reliability technology solutions integrated assessment of dispersed energy resources deployment. Lawrence Berkeley National Laboratory; 2000.
[165] Lasseter R et al. Consortium for electric reliability technology solutions white paper on integration of distributed energy resources the CERTS microgrid concept. Program, Transm Reliab Syst Energy Program, Integr Interes Public Comm Calif Energy, no. April; 2002. p. 1–29.

[166] Rashid MH. Power electronics handbook; 2007.
[167] Luo FL. Advanced Dc/Dc converters; 2004.
[168] Ankita, Sahoo SK, Sukchai S, Yanine FF. Review and comparative study of single-stage inverters for a PV system. Renew Sustain Energy Rev 2018;91:962–86.
[169] Mahmood A, Javaid N, Razzaq S. A review of wireless technlogy in smart grid. Renew Sustain Energy Rev 2015;41:248–60.
[170] Llaria A, Terrasson G, Curea O, Jiménez J. Application of wireless sensor and actuator networks to achieve intelligent microgrids: a promising approach towards a global smart grid deployment. Appl Sci 2016;6(3):61.
[171] Depuru SSSR, Wang L, Devabhaktuni V, Gudi N. Smart meters for power grid – challenges, issues, advantages and status. 2011 IEEE/PES Power Syst Conf Expo. 2011. p. 1–7.
[172] Marzal S, Salas R, González-Medina R, Garcerá G, Figueres E. Current challenges and future trends in the field of communication architectures for microgrids. Renew Sustain Energy Rev 2018;82:3610–22.
[173] Kabalci Y. A survey on smart metering and smart grid communication. Renew Sustain Energy Rev 2016;57:302–18.
[174] Su W, Wang J. Energy management systems in microgrid operations. Electr J 2012;25(8):45–60.
[175] Wang W, Xu Y, Khanna M. A survey on the communication architectures in smart grid. Comput Netw 2011;55(15):3604–29.
[176] Adamiak M, Patterson R, Melcher J. Inter and intra substation communications: requirements and solutions. Conference: 57. Annual American power conference, Chicago, IL; 18–20 Apr 1995.
[177] Muttaqi KM, Aghaei J, Ganapathy V, Nezhad AE. Technical challenges for electric power industries with implementation of distribution system automation in smart grids. Renew Sustain Energy Rev 2015;46:129–42.
[178] Kang DJ, Lee JJ, Kim BH, Hur D. Proposal strategies of key management for data encryption in SCADA network of electric power systems. Int J Electr Power Energy Syst 2011;33(9):1521–6.
[179] Setiawan MA, Shahnia F, Rajakaruna S, Ghosh A. ZigBee-based communication system for data transfer within future microgrids. IEEE Trans Smart Grid 2015;6(5):2343–55.
[180] Zhuang J, Shen G, Yu J, Xiang T, Wang X. The design and implementation of intelligent microgrid monitoring system based on WEB. Proc Comput Sci 2017;107:4–8.
[181] Langhammer N, Kays R. Performance evaluation of wireless home automation networks in indoor scenarios. IEEE Trans Smart Grid 2012;3(4):2252–61.
[182] Zhang Y, Wang L, Sun W, Ii RCG, Alam M. Distributed intrusion detection system in a multi-layer network architecture of smart grids. IEEE Trans Smart Grid 2011;2(4):796–808.
[183] Liu T, Gui Y, Sun Y, Liu Y, Sun Y, Xiao F. SEDE: state estimation-based dynamic encryption scheme for smart grid communication. Sac 2014;5(3):539–44.
[184] Chhawchharia S, Sahoo SK, Balamurugana M, Sukchai S, Yanine FF. Investigation of wireless power transfer applications with a focus on renewable energy. Renew Sustain Energy Rev 2018;91:888–902.
[185] Zhi N, Zhang H, Liu J. Overview of microgrid management and control. 2011 Int Conf Electr Control Eng. 2011. p. 4598–601.
[186] Papadimitriou CN, Zountouridou EI, Hatziargyriou ND. Review of hierarchical control in DC microgrids. Electr Power Syst Res 2015;122:159–67.
[187] Huang C. Neural network based microgrid voltage control, M.Sc Thesis. The University of Wisconsin-Milwaukee; 2013.
[188] Justo JJ, Mwasilu F, Lee J, Jung JW. AC-microgrids versus DC-microgrids with distributed energy resources: a review. Renew Sustain Energy Rev 2013;24:387–405.
[189] Yazdanian M, Mehrizi-Sani A. Distributed control techniques in microgrids. IEEE Trans Smart Grid 2014;5(6):2901–9.
[190] Chandorkar MC, Divan DM, Adapa R. Control of parallel connected inverters in standalone ac supply systems. IEEE Trans Ind Appl 1993;29(1):136–43.
[191] Chang CS, Weihui F. Area load frequency control using fuzzy gain scheduling of PI controllers. Electr Power Syst Res 1997;42(2):145–52.
[192] Elsied M, Oukaour A, Gualous H, Hassan R. Energy management and optimization in microgrid system based ongreen energy. Energy 2015;84:139–51.
[193] Ghanbarian MM, Nayeripour M, Rajaei A. Design and implementation of a new modi fi ed sliding mode controller for grid-connected inverter to controlling the voltage and frequency. ISA Trans 2016;61:179–87.
[194] Lopes JAP et al. Control strategies for microgrids emergency operation. 2005 Int Conf Futur Power Syst, vol. 2, no. 3; 2005. p. 6.
[195] Schweppe FC, Tabors RD, Kirtley JLL. Homeostatic Control for Electric Power Usage: a new scheme for putting the customer in the control loop would exploit microprocessors to deliver energy more efficiently. IEEE Spectr 1982;19(7):44–8.
[196] Delghavi MB, Yazdani A. An adaptive feedforward compensation for stability enhancement in droop-controlled inverter-based microgrids. IEEE Trans Power Deliv 2011;26(3):1764–73.