Energy Reports 8 (2022) 4085–4103

Contents lists available at ScienceDirect

Energy Reports

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

Review article

A review on recent developments in control and optimization of micro grids

Saima Ishaq [a], Irfan Khan [b,c], Syed Rahman [d], Tanveer Hussain [a], Atif Iqbal [e,*], Rajvikram Madurai Elavarasan [c,f,g]

[a] *Electrical Engineering and Computer Science, South Dakota State University, United States*
[b] *Marine Engineering Technology Department in a Joint Appointment with Electrical and Computer Engineering, Texas A & M University, United States*
[c] *Clean and Resilient Energy Systems (CARES) Laboratory, Texas A & M University Galveston, TX 77553, United States*
[d] *Department of Electrical and Computer Engineering, Texas A & M University, United States*
[e] *Department of Electrical Engineering, Qatar University, Qatar*
[f] *Department of Electrical and Electronics Engineering, Thiagarajar College of Engineering, Madurai 625015, India*
[g] *Subject Matter Expert at Research and Development Division (Power& Energy), Nestlives Pvt Ltd, Chennai 600091, India*

ARTICLE INFO

Article history:
Received 24 December 2020
Received in revised form 8 January 2022
Accepted 12 January 2022
Available online 23 March 2022

Keywords:
Microgrid structures
Hierarchical control
Optimization
Distributed energy resources (DERs)
Renewable energy
Islanded
Grid-connected
Centralized

ABSTRACT

Modern utility grid is experiencing a transition from conservative centralized generation structure to a more distributed and decentralized structure. To achieve this transition, decentralized energy sources and loads must be seamlessly integrated and isolated from main grid structure. Realization of one such approach is termed as "Microgrid". Microgrids (MGs) are a source of clean, efficient, and an economical way to integrating renewable energy sources and loads to the main grid. Higher penetration levels of MG would lead to significant perturbations with time periods being lower than conventional dynamic responses. This may pose problems of stable operation for the entire utility grid. For addressing this problem, this paper gives an in-depth literature review on the different control structure of MGs. As control dynamics required vary significantly, depending upon the integrated source, connected loads and ratings of the MG, it is important to understand the different structures of MG. Thus, categorization of MG based on different criteria such as distributed energy resources (DERs), type of distribution systems, modes of operation, and types of communication links used are first studied. As modern control structures are layered to achieve dynamic responses at different time constants, hierarchical controls are implemented. To address this concern, different levels of hierarchical controls are also discussed along with the control strategies of integrating various renewable energy resources in MGs. Different methods of controls are analyzed and assessed in each category and the major issues faced in the current infrastructure are noted. As the grid is moving towards optimal design of microgrid structures this manuscript reviews a number of optimization techniques along with their benefits and drawbacks.

Contents

* Corresponding author.
E-mail address: irfankhan@tamu.edu (I. Khan).

https://doi.org/10.1016/j.egyr.2022.01.080

1. Introduction

As the demand to switch from fossil fuels to renewable energies is increasing day by day, the need to set up a reliable and robust system which integrates alternative energy resources is rising. A MG is a group of distributed generators (DGs), energy storage systems (ESSs) and loads that operate in coordination with one another to provide reliable electricity. Each of these components form an important part of the MG and its control is therefore necessary. For example, all renewable sources, except wind energy, provide DC power which is fed to the main grid after converting it to AC. The frequency and voltage at which this power is transmitted must therefore be controllable. For grid connected mode of operation the grid dictates the values of voltage and frequency (the energy source acts as a current source). In islanded mode, however, the loads control the voltage magnitude (as the source operates as a voltage source). Therefore, among many other challenges MG controls and protection are the most critical for efficient and reliable performance.

MGs have variables based on which it can be categorized into different types. These categories could be based on: a) Generation sources b) Type of control strategy c) Type of distribution (AC and DC MGs) and d) Modes of operation. These classifications are as shown in Fig. 1. The manuscript describes these categories of MGs and explains various control as well as optimization techniques used within these categories. A separate section titled "Optimization based control techniques in MGs" further explains how optimization techniques are used to enhance the modeling as well as controls of MGs. The current power systems is facing many problems due to voltage and line overloads. These can be resolved by introducing DGs which can then take part in voltage as well as frequency regulations. MGs are advantageous over conventional grids as they can be grouped together as DGs, storage systems and controllable loads. Also, it can operate in both islanded as well as grid connected mode. MGs can provide electricity to not only rural communities which are far away from the grid but can also make industrial areas independent from the main grid. MGs also have the advantage of being beneficial to not only utility companies but to consumers as well. Customers of MGs can take part in electricity markets as well as deliver ancillary services (Vandoorn et al., 2013c).

Due to the stochastic generation from renewable energy sources, their power output shows sudden discontinuities. This highlights the need of advanced optimization and control methods that design an optimal MG system. The increasing research on the development of standalone hybrid renewable energy systems, calls for an optimal layout of many renewable energy sources. The control, optimization, and design of MGs comes with a lot of complexities. Currently, a number of advanced algorithms are being implemented to improve the layout of MGs and to provide optimal sizing of its components. Therefore, optimization techniques coupled with control aspects for the design of MGs is a rising area of research. This manuscript discusses a number of control strategies as well as optimization methods for MG designs.

MG has been an emerging concept, deeply embedded with other concepts such as distributed generators, emerging predictive control models, internet of things, and digitalization of industry. For optimization of energy cost, reliability and cybersecurity of MG, there is a growing consensus to study the overall factors contributing to efficient operation, optimal control, and reliability of MGs. In the existing literature, review of MG has been presented in the following categories: (a) AC microgrids (MGs) (Rajesh et al., 2017; Kaviri et al., 2017; Mohammed et al., 2019), (b) DC microgrids (Meng et al., 2017; Bharath et al., 2019; Jian et al., 2013), (c) PV systems (Jordehi, 2016), (d) wind energy systems (Menezes et al., 2018; Jena and Rajendran, 2015),

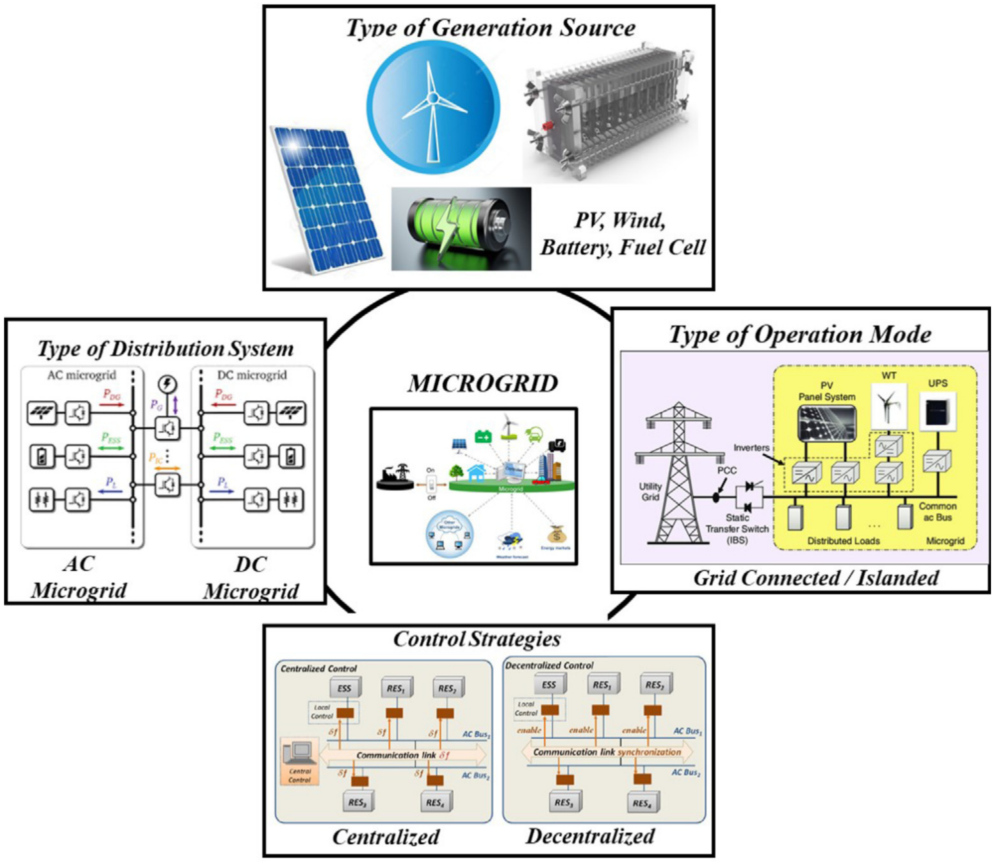

Fig. 1. Different types of MG structures based on type of generation sources, distribution system, operation modes and control strategies.

(e) hierarchical control strategies (Yamashita et al., 2020; Papadimitriou et al., 2015; Bidram and Davoudi, 2012) and (f) optimization methods in MGs (Dawoud et al., 2018; Fathima and Palanisamy, 2015). Although these reviews are extremely helpful to the readers, but they lack in providing a complete overview of MGs. This paper reviews the MGs as an entity consisting of various types, their respective control strategies, impact of distributed energy sources on the conventional MG performance, emerging optimization-based control leading to performance improvement. Finally, the authors have identified the key challenges/opportunities capable of shaping, improving and increasing reliance of future MGs. With this comprehensive approach, the authors believe this manuscript will provide better insight to the readers and help in identification of existing MG issues related to different segments of the MG.

In this paper, Section 2 covers all types of MGs whereas in Section 3 the controls of various types of MGs is reviewed. In Section 4 droop controls which are an important method of control in MGs is analyzed. Later, in Section 5 control strategies for various DERs is seen and Section 6 discusses the different optimization techniques used in modeling and control of MGs. Section 7 gives a summary on the recent advances in MGs and the challenges it is facing in the present world.

2. Types of MGs

2.1. Control methods in a MG

Control methodologies of MGs are classified as centralized, decentralized, and distributed as shown in Fig. 2. Following is a brief description of centralized and decentralized control structures.

2.1.1. Centralized controls

Centralized controls use a central controller which is linked to sources and loads through communication networks. A centralized control uses a MG central controller which obtains and then assesses information from all controllers so that optimal solutions can be reached without iterations (Li et al., 2018). A centralized controller is simpler as it controls power delivery from a single point. Larger MGs adopt a hierarchical control setup as opposed to smaller scale MGs where the units are attached to the central controller using a master slave scheme (Dragičević et al., 2015). Centralized control comprises of various levels of control which are explained in detail later. In one study, a central controller makes decisions on the basis of generation and load status (Manas et al., 2015). Another research introduced the development of central controller for an intelligent MG (iMG) lab in Aalborg university. A hierarchical setup is carried out to regulate any imbalances in voltage and restore voltage/frequency. Primary control loops are simulated in MATLAB and compiled in dSPACE whereas secondary and tertiary level controls are carried out in LabVIEW (Meng et al., 2015). Centralized control using communication links is discussed in Lopes et al. (2006). This method has an advantage of keeping the output voltage and frequency close to their ratings (Vandoorn et al., 2013a). Centralized control systems have issues for MGs in remote locations where it is not only unrealistic to have such a setup but also quite expensive (Mohamed and El-Saadany, 2008). However, a centralized scheme is not quickly scalable and distribution losses increase substantially at lower distribution voltages (Nasir et al., 2019).

2.1.2. Decentralized controls

In this scheme, a central controller is absent. Therefore a number of control centers have different control commands (Wu et al.,

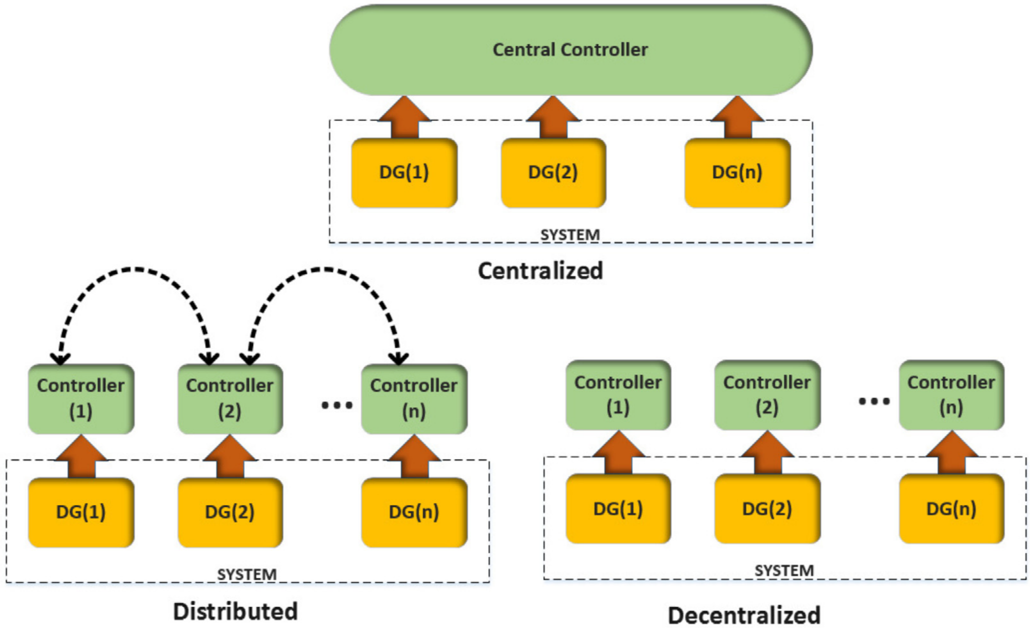

Fig. 2. Control structures of MG classified as Centralized, Distributed and Decentralized.

2018). A decentralized control uses only local information to find optimal solutions through iterations. Coordination techniques are used by local controllers (Dragičević et al., 2015). DC bus signaling is one of the popular decentralized schemes for DC MGs. Dou and Liu (2013) suggested a two-layered multi-agent system using decentralized control systems. This strategy tried to balance out any instabilities caused by external disturbances in the MG. Although decentralized control structures are advantageous as they do not rely on communication systems, however, their performance is not very high due to absence of information from other units. A comparison between centralized and decentralized schemes is shown in Table 1. gives an overview on the economic aspect of centralized and decentralized controls (Fiorini and Aiello, 2019).

2.1.3. Distributed controls

Distributed controls for systems that require power system applications, communications amongst various subsystems would decrease performance significantly. Hence, distributed control techniques are significant for such purposes. These control techniques allow interaction amongst subsystems, keeping in mind the limitations on sharing of data amongst different units. MGs are separated into areas where each area contains renewable energy resources, power lines as well as loads (Wan et al., 2016). Therefore, in distributed control approach, each operator works independently. Another advantage of this technique is better usage of computational facilities due to the smaller size of each subgroup (Yazdanian and Mehrizi-Sani, 2014; Khan et al., 2019).

2.1.4. Comparison between different control structures

Due to the rising number of DERs, MGs are now being considered as controllable systems. Today, MGs are getting highly dependent on controls as well as communication systems to provide optimal operations while meeting system constraints. For reduction of computational as well as communication burdens due to rising number of renewable resources, MG controls are moving towards a more distributed set of controls. Distributed as well as centralized controls have the advantage of being more reliable and can be used in changing infrastructures. On the other hand, although centralized controlled systems provide an optimized solution, they require point to point communication which increases their computational requirements. Table 1 provides this comparison amongst the three structures of control.

2.1.5. Key features of MG controls

The main concept of MGs revolves around its controls. In fact the main difference between a MG and a distribution system is the concept of control abilities of the two (Hatziargyriou, 2014). The main aim of controlling MGs is to maintain the MGs frequency and voltage, and also sharing its power. The main features that are most desirable for a MG are:

1. Control of output: The voltages as well as currents must limit themselves around their reference values. Alongside any oscillations should be damped.
2. Demand side management(DSM): Any portion of the load must be controllable by designing proper DSM mechanisms. Also cost effective DSM techniques must be designed for remote locations with the help of effective participation from locals of the community which would then help in frequency and load control designs.
3. Power Balance: DER units should be able to balance out any changes caused by active power unbalances. These unbalances if unchecked would lead to voltage and frequency exceeding the predefined values.
4. Transition between modes of operation: A MG should be able to work in standalone as well grid connected mode. Transition between these two modes must be achieved with minimal transient.
5. Economic dispatch: If DER units are dispatched appropriately, this would not only lower overall costs but may also increase profits. Additionally, it would also reduce the backup capacity (Olivares et al., 2014).

2.2. Type of distribution systems in MGs

MGs can be differentiated based on distribution systems, i.e., either AC or DC as shown in Fig. 3. Since the 19th century AC power has been chosen as the means to transmit energy to commercial as well as residential loads. Most influencing factor in the selection of AC mode of transmission is the simple and efficient operation of transformers. With transformers, it is possible to step-up or step-down the voltage with ease. The power produced from generating stations is first stepped up to higher voltages to achieve high voltage ac transmission. This results in lower

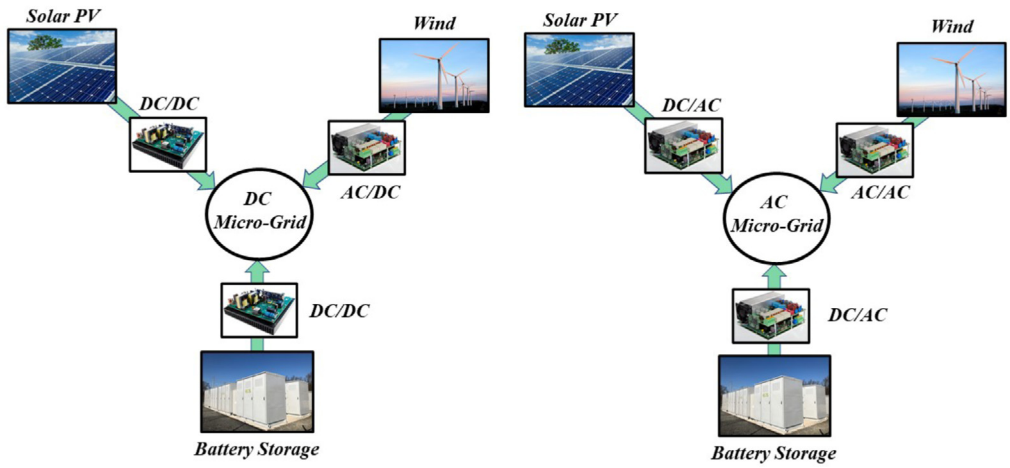

Fig. 3. AC and DC MGs structures with different sources and power converters.

Table 1
Advantages and Disadvantages of various MG structures.

Types	Output	Advantages	Disadvantages
Wind	AC	-Power can be generated throughout the day and night -Well developed RES -Clean and quiet source of energy	-Expensive -Requires storage of energy
PV	DC	-Can be setup according to electricity needs and space available -Is movable in case of changed electricity requirements -Environment friendly	-Only available in daytime -Requires storage devices -High upfront cos
Fuel Cell	DC	-Can be used for heat or electricity needs -Extremely silent RES	-Hydrogen extraction is extremely expensive -Infrastructure is expensive
DC MG		-Less complex -Easier to control -Low power losses and voltage drops	
AC MG		-Can step up or step down voltage -More advanced technology	-Requires both Active and Reactive power control
Islanded		-Works independent from the main grid -Can provide power to rural areas as well as critical loads -Allowable lower set point of frequency is relaxed	-Generation of DGs should be enough to meet demand
Grid Connected MG		-Host grid controls frequency and voltage -Grid can provide deficiency of generation from MG	-Synchronization with the grid is required -Can participate in cascading failures which can lead to blackouts
Centralized Controls		-More optimized solution -Can be easily synchronized to the main grid	-Less reliable -Requires point to point communication -Time consuming -Expensive computationally
Distributed Controls		-Computationally less expensive -Better reliability and security -Considers interaction between subsystems	-Increases complexity of system
Decentralized Controls		-Does not depend on one central unit -More reliable -Plug and play ability -Useful for changing infrastructure	

transmission losses. Also, for distribution side consumption, the voltage level can be stepped down, to reach the desired load current level. However, with the advent of modern power electronic improvements, it is possible to achieve desired dc voltage stepping with good accuracy. High Voltage DC (HVDC) transmission is now popular compared to HVAC for longer distances. With this background, now both AC and DC types of distribution are becoming quite competitive. It is even possible to have both AC and DC types of lines in a hybrid MG. Table 1 summarizes the key benefits and draw backs of both systems.

2.2.1. AC system

AC MGs requires all the connected devices to be synchronized at a given voltage and frequency. In three-phase systems, phase sequence also becomes a priority. This helps in preventing any unwanted power flow among the connected sources. AC systems, due to its lengthy experience of operation has developed into a more mature technology in terms of standardization, protection, control, and stability aspects. Continuous research and development on different aspects of ac MG has made the system more reliable and economic. For example, cost of simple AC circuit breakers is comparatively less when compared to dc circuit breakers which requires additional circuitry for making and breaking dc current. DC systems, on the other hand, requires converters which are more complicated as well as costly (Justo et al., 2013). Research methodologies for the control of AC MGs is detailed in Section 3.2.

2.2.2. DC system

The research to integrate DC power into the existing AC power systems is still underway. MG combined with DC power systems is a more attractive alternative for local generation and synchronization with the utility grid (Siraj and Khan, 2020). This is due to dc nature of power generation of renewable energy resources, electric vehicles, and energy storage systems. DC systems are easier to control and manage as compared to AC power systems. Due to absence of reactive power, DC systems have the advantage of lower power losses as well as voltage drops and a higher capacity of lines (Asad and Kazemi, 2012). DC systems connection to the grid only requires control of active power whereas AC systems need reactive power control as well. Different approaches used in the control of DC MGs are described in Section 3.1.

2.2.3. Hybrid AC/DC system

MGs can support both AC and DC transmission systems. Each system has its own merits and demerits in terms of transmission, control and protection. Guerrero et al. (2013) and Justo et al. (2013) give a good comparison between AC and DC MGs. Such

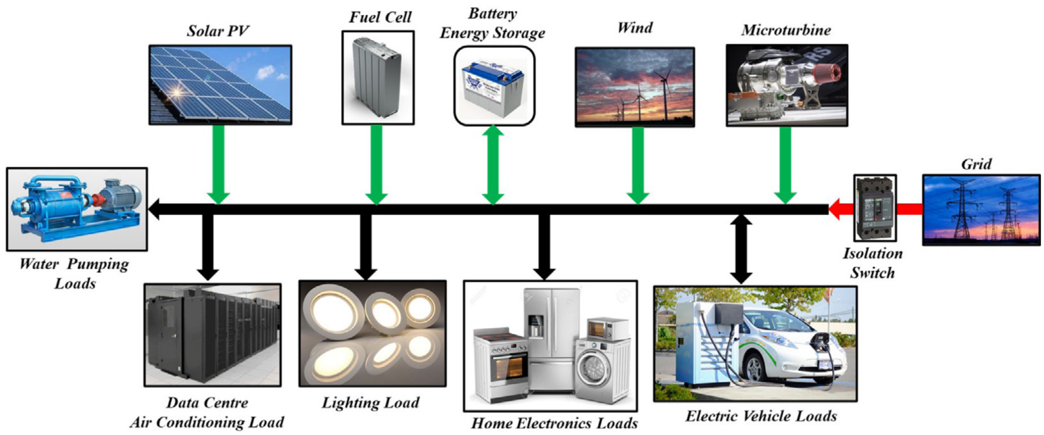

Fig. 4. MG structure interconnected to the main grid via isolation switch for transition from grid mode to islanded mode.

a hybrid MG system links both AC and DC MGs through bidirectional AC/DC converters. It also establishes a scheme where both AC and DC sources and loads can be integrated into the system. Combining both AC and DC MGs to gain benefits is therefore an emerging field.

2.3. Modes of operation in a MG

A MG can operate in isolation or by connecting to the grid with each having its own benefits and short falls (Table 1). Following is a brief definition of both types of operation.

2.3.1. Grid connected

For a grid connected MG (Fig. 4), the voltage as well as the frequency are decided by the host grid. In a grid connected mode, a MG acts as a current source and synchronizes its voltage with the grid. In this mode, all the local sources of MG feed power to the main grid. This power is then consumed by all the connected loads. This setup provides higher reliability as power can be consumed from multiple sources. In this mode the main objective of the MG is to control the active and reactive powers generated by distributed energy resources. However, in case of a fault there is inrush of current which requires diagnosis and protection. One of the first steps during a fault is to detect it and isolate the system from the main grid (i.e., where the fault has occurred). However, in case of a fault there is small inrush of current which makes the detection of fault difficult. In some other cases, for example scheduled maintenance, the main grid can be disconnected. During this time, the MG must generate, transmit and consume power on its own i.e., it should behave as a local habitat for connected load.

2.3.2. Standalone/Islanded mode

In islanded mode of operation, the MG behaves as voltage sources. In this mode, the loads rather than the grid (as in grid connected mode) define the voltage and frequency needed from the source. The stand alone mode of the MG is a more crucial operation whereby, the demand and load balance must be kept in equilibrium and local generation must power the loads without any assistance from main grid. Islanded mode of operation (Fig. 4) takes place under specific circumstances such as grid faults, grid maintenance or outage of a major generating unit (Vandoorn et al., 2011b). This mode may be selected intentionally or can take place accidentally. Planned islanding/intentional islanding is to deliberately create separated sections of the power system which are then provided power through DGs. This can be done during an outage, to continuously supply power to consumers, which reduces outage damages and increases reliability (Londero et al., 2010).

In this mode, the local grid performance is dictated by distributed energy resources and loads. The power balancing in a standalone MG is either done through local controllers or by a central controller which communicates predefined set points to different distributed energy resource units as well as controllable loads. The main aim of such a setup is to make sure that all units take part in supplying the load in a predefined mechanism. A high circulating current could be an outcome of any mismatches of amplitude or phase angle of the output voltage (Olivares et al., 2014). This must be avoided for stable and sustained operation. Islanded MGs should be operated on techno-economic purposes (Rezaei et al., 2020).

2.3.3. Switching between islanded and grid connected modes

Islanding of a MG can be done intentionally or accidentally as mentioned before. Intentional islanding is done for a planned period for maintenance or repair purposes. Accidental islanding, however, occurs when the main grid is suddenly disconnected. This may cause voltage and frequencies to exceed pre defined limits. Switching from grid connected to islanded mode of operation creates many stability issues. Vandoorn et al. (2013b) enables the MG to switch easily between islanded to grid connected mode and is able to limit the transients when switching from one mode to another. The power switch is made reliant on terminal voltages through modified voltage droop control method which enables a smooth change from one mode to another. Zhang et al. (2017) have tracked voltage and phase to switch between islanded to grid connected mode. The proposed method ensures smoothness and continuity of supply during the switching period. Similarly, for the switching operation, Shoeiby et al. (2014) uses proportional resonant regulators to regulate the frequency and voltage and share power equally amongst all DGs. Renewable energies have converters based on their energy source. PV panels and fuel cells for example use a DC/AC converter to be connected to the grid. Wind turbines or high speed micro turbines on the other hand need AC/AC converters for connection to the main grid. Outputs of DERs like diesel generators can be controlled to be reliable and constant over an indefinite period of time. However, power generated from renewable energy sources (RESs) (Fig. 5) like wind or sun is highly variable in nature and without any additional hardware and control it would be impossible to control power generation (Olivares et al., 2014). Research carried out on the controls of various renewable energy sources is further detailed in Section 5.

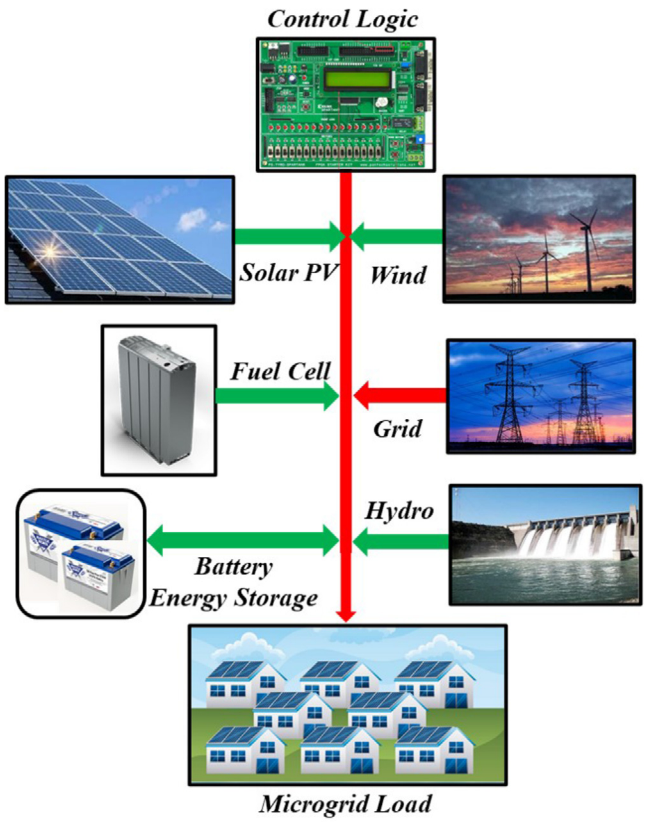

Fig. 5. Different DERs and battery storage connected to MG via distributed controllers.

3. Control strategies for different types of MGs

3.1. Control of DC MGs

DC MGs have gained much popularity due to feasibility of penetration of renewable energy sources and less complexity of controlling the system. As the renewable energy technologies are decentralized by nature, they are connected in parallel via converters. Research clarifies that the best utilization of DC MGs is when the generation sources is DC, like PV, the appliances or loads to be served are inherently DC and the inter connection network is also DC (Opiyo, 2019). The main issue faced by DC MGs is the control of these power electronics interfacing converters, especially in load power sharing. Trinh et al. (2018), for example, focus on three phase grid connected inverters and the elimination of DC as well as harmonic currents caused due to voltage measurement errors. The controller consists of proportional resonant controller and a repetitive controller. The proposed system not only has a good steady-state performance but also responds faster to changes in DC offset errors or a reference change in current.

A blend of fuzzy control and scheduling control to regulate voltage using converters for energy storage is provided in Kakigano et al. (2011). The paper also claims to be able to operate DC voltage regulation control and stored energy balancing control at the same time. It is shown through experiments that voltage of the distribution system was between 340 ± 5 V. Droop control is the basic control method in DC MGs. An application of P/V droop control is carried out in Vandoorn et al. (2011a). A low voltage MGs power is stabilized using controls which changes the value of the rms voltage of the MG as a function of DC-links voltage. As a result the output power of the DG is changed in response to the grids voltage. In contrast to conventional droop control, Lu et al. (2014) have suggested a low bandwidth communication-based droop control. This control system uses the low bandwidth communication network and local controllers to transfer information between converter units and therefore does not require a central secondary control unit.

3.2. Control of AC MGs

MGs have very short lines for transmission and therefore, the automatic voltage regulators used to regulate voltage which are usually employed in long transmission lines are not suitable. A small change in the voltage amplitude may cause significant variation in the reactive power (Schiffer et al., 2016). Hence droop controls have been applied to voltages of MGs with an aim to distribute reactive power. A common method is to use proportional controls to setup voltage amplitudes, the feedback of this is used to generate the reactive power across a reference set point (Sao and Lehn, 2008; Khan et al., 2016, 2017). A load sharing technique based on the P/V droop control is presented in Jin et al. (2017). The method is carried out on the basis of improved P/V droop coefficient which makes load sharing amongst parallel inverters under different line impedances possible. Quantitative analysis based on modified coefficient iterative algorithm is performed to show a relation between line impedance and modified coefficient of P/V droop. Droop controller should be able to share load accurately and should be able to generate similar voltage set points for inverters in a MG. Zhong (2013) have put forward an improved droop controller that does not require the above two conditions to be met in order to achieve accurate load sharing. Similarly, proportional integral controller is applied in Gaonkar et al. (2018) to improve the output voltage of inverters. P-V/Q-f and P-f/Q-V droops are adopted for matching the output impedance of inverters. For a wider range of impedances the setup can control the flow of active and reactive powers independently.

Also the mismatching of line impedances makes it difficult to share reactive power accurately in conventional droop controls. Therefore, Han et al. (2015a) suggest a droop control technique to recover voltage as well as helps in error reduction operation. The error reduction operation causes a drop in voltage amplitude. Hence, voltage recovery operation improves that droop.

The interest in hybrid MGs is increasing as these can utilize the benefits of both AC and DC renewable energy sources. Loh et al. (2013) have investigated the independent operation of hybrid MGs and the sharing of power amongst the AC and DC grids. This is done by droop control method and both systems are linked by using converters which determine the proportional power to be shared amongst the hybrid systems. Although this active power sharing is tested and shown to work but the drawback of such a scheme is that it may cause an alteration in the steady state of voltage and frequency as it uses the coefficients of droop control. Ma et al. (2015) have proposed a control structure for coordination and control of Power flows in hybrid MGs in grid connected as well as islanded mode. This method increases the tested systems stability. Researchers have also suggested a three level hierarchical control scheme where all the DERs are connected to the lowest level of hierarchy. This is particularly beneficial as each level can be controlled by the next level of hierarchy (Jiang and Dougal, 2008; Jiang and Yu, 2009; Gupta et al., 2018).

3.3. Hierarchy of control in MGs

For the stability as well as economical operation of a MG it is essential to have a proper control system in place. A control system has vital functions to perform such as voltage and frequency stability both in grid connected and islanded mode,

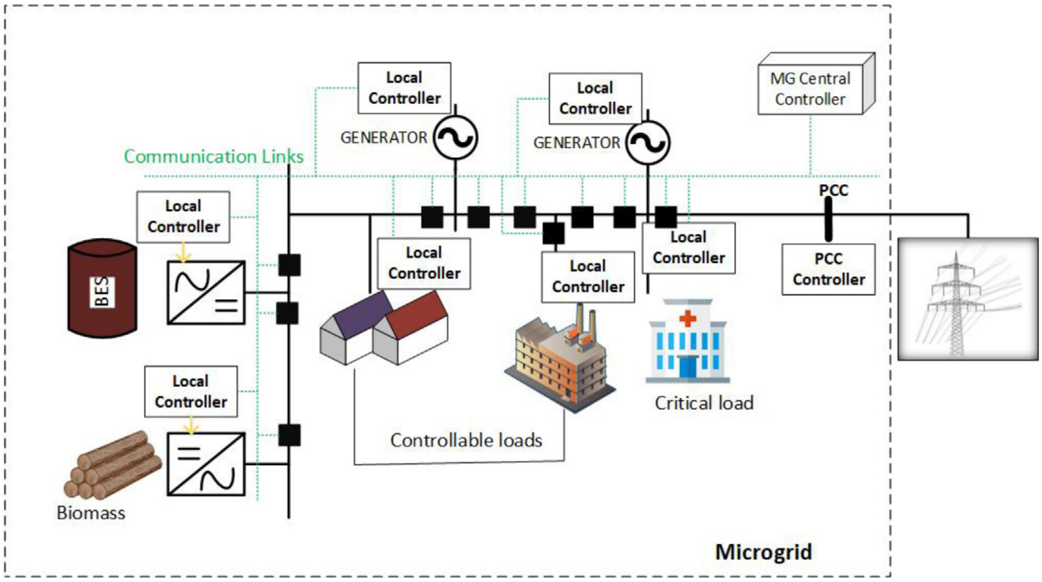

Fig. 6. Hierarchical control structure showing central and local controllers (Feng et al., 2017).

load sharing amongst different DERs, providing an optimum cost and controlling power between the main grid and MG. These functions can be classified on the basis of response time as well as their importance in controlling the MG. As shown in Fig. 6 the central controller achieves tertiary controls such as Energy management or state estimation. It can communicate with local controllers to gather information on the states and measurements of the different resources. The local controllers are responsible for the stability controls. Thus a hierarchical structure divides these different tasks into levels of significance and requirement (Bidram and Davoudi, 2012).

A hierarchical structure can be classified into primary, secondary, and tertiary levels of control. The need of standardization has been met by using hierarchical control in Guerrero et al. (2011). Guerrero et al. (2011) have utilized hierarchical control for MGs as a generalized approach which branches out from ISA-95. The ISA-95 is an international standard to decide which information and tasks should be shared by which applications such as sales, marketing or maintenance and productions (Harjunkoski et al., 2009). This view maybe beneficial for telecommunication networks operated on DC voltage. The MGs obtained through this method can work in islanded mode or as systems connected to stiff sources. The system obtained through this method can also incorporate MGs without effecting the local MGs hierarchy. However, this method ineffectively assumed an equal voltage for all converters in the MG.

Amongst the three levels of hierarchy as shown in Fig. 7, primary level has the lowest time to reach a decision whereas the tertiary level has the longest duration to gather the systems state information through communication systems and take appropriate decision (Feng et al., 2017).

3.3.1. *Primary level of control*

Primary control as mentioned before is the level that provides the fastest response in controlling MGs. It works in the absence of communication and relies on local measurements (Olivares et al., 2014). Due to this, primary control is responsible in stabilizing voltage and frequency, sharing active as well reactive powers between DERs through plug and play function, to detect islanding mode, and be able to balance out over currents by diminishing circulating current (Bidram and Davoudi, 2012). Voltage and current reference points are set up by the primary level. This level is sometimes also known as the zero level of controls and is usually used in PQ or voltage controls (Lopes et al., 2006).

3.3.2. *Secondary level controls*

The variations that occur in frequency or voltage of MGs are supposed to be kept zero and secondary control helps to keep this under control (Rajesh et al., 2017). Li et al. (2018) suggest a design which is based on two layers for controlling the MGs. The top layer is a communication based layer whereas the lower layer comprises of the MGs. The top layers agents as well as the lower layers DGs can communicate amongst them by using links between the two layers and attain information from each other. This information can be sent to different neighbors in the network. This information is managed through different controls.

The secondary controls could be initiated through optimization techniques, which are either based on the economics or power quality of the grid (Vandoorn et al., 2012). Simpson-Porco et al. (2015) control the secondary levels frequency as well as voltage by using information from local or nearby neighbors in islanded MGs. The problems between maintaining voltage and reactive power sharing side by side are solved through proposed voltage controllers. The given design does not require information of load, impedance or type of MG. The setup is applied to many experimental designs and proven to work under communication failures.

The secondary level of control can either work in centralized or distributed mode.

3.3.2.1 Distributed controls at secondary level A distributed control strategy is proposed by locally sending required control signals to the primary controllers. This method has each DG unit local controller and communication system surrounded by a decentralized secondary controller. Therefore if one of the unit fails only that unit breaks down without effecting the working of other DG units (Shafiee et al., 2014). In distributed control methods both voltage regulation as well as power sharing are controlled. Different types of distributed control techniques have been proposed in literature. Voltage at secondary level of MGs using input–output feedback linearization is implemented and shown to require scattered communication network with just one way communication. This method is more effective than centralized controllers at secondary levels (Bidram et al., 2013).

In the same way to share active as well reactive power using a robust distributed controller has been applied in Mahmud et al. (2014). The controller is designed by utilizing partial feedback linearization. The inverters, however, still require

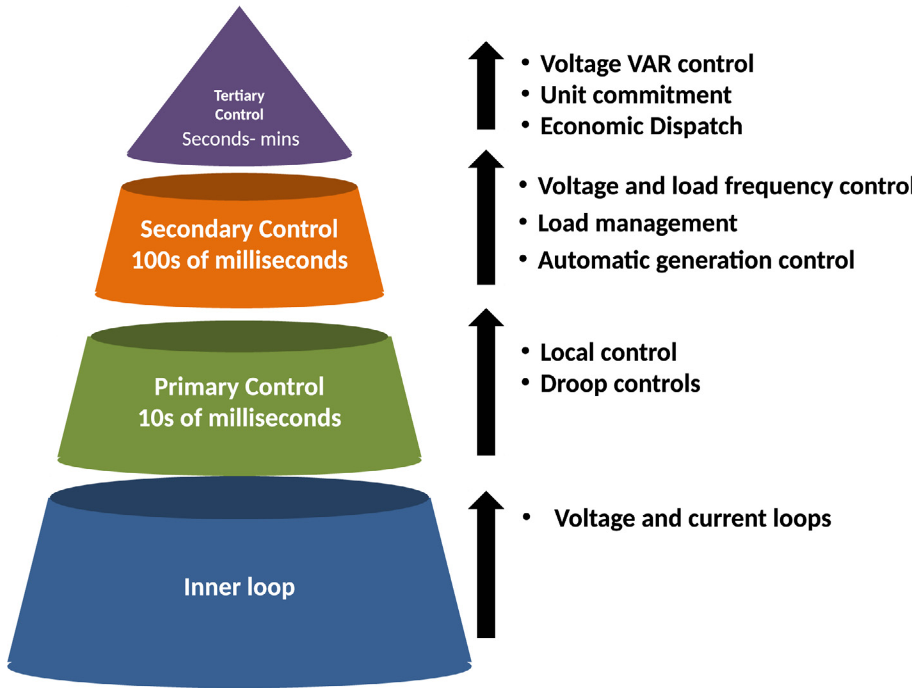

Fig. 7. Hierarchical control depicting control parameters and associated time bandwidths (Feng et al., 2017).

interconnection which as a result make the system inflexible and less redundant (Han et al., 2016). Bolognani and Zampieri (2013) have designed a distributive, leaderless and randomized algorithm solving the optimization problem of reactive power compensation. In Guo et al. (2015), voltage is compensated in an islanded MG. A completely distributive method of control which consists of information sharing as well as exchange of information is suggested which works on finite-time average consensus and newly discovered graph discovery algorithm. Xin et al. (2015) works on a two layer structure for a distributed MG. The first layer implements frequency and voltage control wheres the second layer sets the active as well as reactive power of voltage controlled voltage source inverters.

Similarly (Bidram et al., 2014) is another work based on a completely distributed MG which restores the frequency as well as the economic dispatch functionality without the need of communications links. Tuladhar et al. (2000) controls single phase inverter units operating in parallel in a distributive network. This method is able to share loads in linear as well as non linear conditions.

3.3.2.2. Centralized controls at secondary level For centralized control systems a common bus is designated for loads which are then controllable through a central secondary controller. This controller keeps the voltage around a reference value (Peyghami et al., 2017). As the communication links between the central controller and converters is not dependable, distributed methods are utilized for every converter (Nasirian et al., 2014). The voltages of certain buses are then communicated to the converters which keep the average voltage in control (Loh et al., 2016; Lu et al., 2013; Peyghami et al., 2017). Peyghami et al. (2016b,a) suggest a frequency based droop control.

3.3.3. Tertiary controls

This level of controls is also termed as the "global loop control" (Justo et al., 2013). The power flow between different MGs and the main grid as well as energy marketing is implemented at this stage (Guerrero et al., 2008). As this is the highest level of control it helps in an overall coordination between the MGs and passes on its needs to main grid like frequency or voltage regulation. Therefore, it has a longer time step to take decisions which is typically between seconds to minutes, as shown in Fig. 7. This level of control is usually taken to be part of main grid rather than the MGs (Olivares et al., 2014). Hierarchical controls majorly follow droop controls which is detailed in the next section.

Table 2
Conventional droop control vs Inverse droop control.

	Conventional droop	Inverse droop
Compatible with high voltage	Yes	No
Compatible with generators	Yes	No
Direct Voltage Control	No	Yes
Active Power Dispatch	Yes	No

4. Droop control in MGs

The primary level of control often uses the droop control method in order to make the system stable and more damped.

4.1. Significance of advance droop control over conventional droop control

$$\omega_k = \omega^\circ - m_k P_K \quad (1)$$

$$E_k = E^\circ - n_k Q_K \quad (2)$$

Eq. (1) and (2) show the well-known droop equations with w and E being the frequency and amplitude of the voltage output respectively. P and Q are the active as well as reactive powers (see Fig. 8). The droops proportional terms are represented by n and m respectively. These terms often use transfer functions to represent these gains.

The conventional droop control is taken to be inductive for connection to large systems (Rajesh et al., 2017). For a low voltage system the line voltage is almost resistive as the output impedance always relies on the type of control method used. Hence, conventional droop control equations do not work for low voltage network systems and indirect droop control methods have been applied (Palizban and Mekhilef, 2011a). Table 2 gives

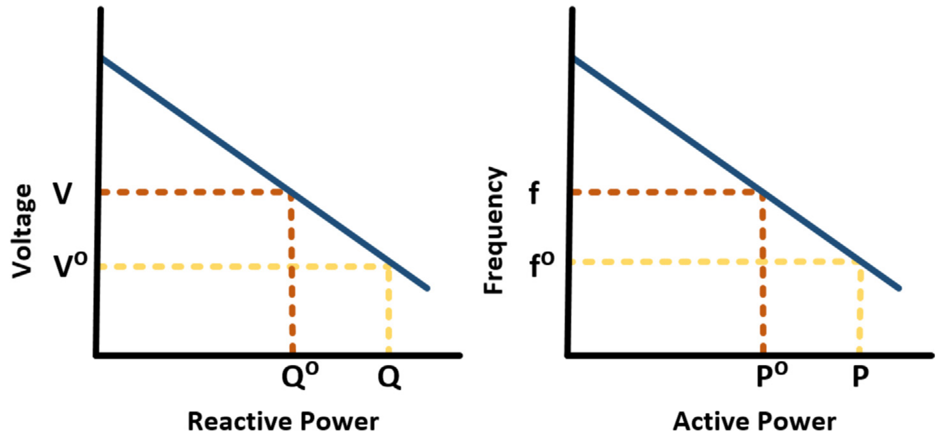

Fig. 8. Droop control characteristics showing Q Vs V and P Vs f (Avelar et al., 2012).

a brief comparison between Conventional droop control and the Inverse droop method. Palizban and Mekhilef (2011b) and Palizban and Mekhilef (2011a) have emphasized that by utilizing the indirect operation of droop controls in interconnected grids, these control methods can be used effectively at the lower voltage levels. This would in effect allow the introduction of renewable energy sources for lower voltage level systems. Q-V techniques have also been suggested for such network systems (Engler, 2005).

The need of droop control has been discussed widely. Rajesh et al. (2017) suggest that droop control is appropriate for control at the primary level especially for MGs that are of smaller capacities. For the secondary level either centralized or decentralized control techniques are proposed, whereas, the tertiary level is recommended to be used for MGs that are grid connected. New droop control techniques have many benefits as compared to conventional ones, as suggested by Agundis-Tinajero et al. (2019), which applied hierarchical control by using droop control at primary level along with a centralized extended optimal power flow control. The primary control receives references to be controlled from the centralized control. The proposed control system is then applied on two cases which show a reliable real system and is more beneficial than the conventional droop control.

Similarly, Vandoorn et al. (2012) examines the role of secondary level with the primary level being controlled through voltage droops. It demonstrates that when controllers using voltage droop control are used it is possible to incorporate secondary control in the system. The primary as well as secondary controls rely on a relation between active power and grid voltage. The advancements in droop control techniques in the past few years have explained the advantages of using modern droop control over conventional methods as shown in Table 2. As mentioned earlier, conventional droop controls do not work well for low voltage networks where the line resistance cannot be ignored and the feeder impedance cannot be taken to be inductive (Engler and Soultanis, 2005). Au-Yeung et al. (2009) perform a novel control method to be used for low voltage MGs. Resistive droop controls are used and shown to control the voltage and frequency effectively. In this context (Tayab et al., 2017) states that droop control method does not use communication links to provide reliable power as opposed to conventional droop controls. Hence, it is more flexible and redundant. These techniques, however, still require further work as they cannot solve the problems of harmonic load sharing or find a balance between frequency and active power sharing. Also, these loads do not work well for certain renewable technologies as well as complex loads. In a system with complex impedance conditions the traditional droop control is unable to share power efficiently. Therefore, a droop control method which compensates the effect of complex impedance is proposed, and circulating current is diminished alongside (Yao et al., 2011). Many researches have been carried out to balance reactive power by imitating line impedance in a faster control loop as shown in Fig. 9 (Zhang et al., 2014; Tayab et al., 2017).

5. Controls for various DERs in MGs

DG units that rely on renewable energy systems are environmental friendly as well as sustainable. Examples of renewable energy sources such as those shown in for DGs are wind, solar, geothermal, tidal waves, hydro, biogas and biomass along with hydrogen fuel cells (Justo et al., 2013). Distributed energy resources are assumed to provide power to critical loads in distribution systems in case of a voltage sag due to line faults (Basak et al., 2012). Microsources based on the use of inverters use many types of control schemes. Vandoorn et al. (2011a) proposed a balance of the MGs power by modifying its voltage set value. Similarly Sao and Lehn (2008) suggests a frequency-reactive power boost and voltage-power droop setup that allows parallel operation of voltage source converters. Dasgupta et al. (2010) have suggested control schemes based on p-q theory for series and parallel single phase inverter based DGs.

Sadabadi et al. (2018) show that the plug and play method of DGs for inverter-interfaced generators can perform as a linear time-invariant system. The system used, ensures that the needed response is obtained and is stable even when DGs are used in a plug and play manner. Also, the proposed controller uses linear matrix inequalities to gain an optimized solution to a convex optimization problem. Frequency regulation in MGs is very significant especially in unforeseen circumstances which require isolation of a certain portion of the MG. In such situations, the MG needs to stabilize its frequency in stand alone mode (Reihani et al., 2018). Mohamed and El-Saadany (2008) focus on the problem of low frequency stability issues in inverter based DG units in MGs. In order to solve this, a power sharing technique by using static droop controls along with adaptive transient droop functions is proposed (Xu et al., 2021; Sinha et al., 2021). Hence, power injection through this method is smooth at various loads

Guo et al. (2015) controls frequency through a consensus based distributed frequency control. This proposal is used on local DGs and does not require any central controller. As these controls communicate with neighboring controllers the frequency as well as voltage can be restored to their reference values and power can be shared alongside. Pahasa and Ngamroo (2016) have proposed a model predictive control in order to minimize the number of plug in hybrid electric vehicles that are needed to give sufficient frequency deviation. The model predicted control coordinates with the control method of plug in hybrid vehicles

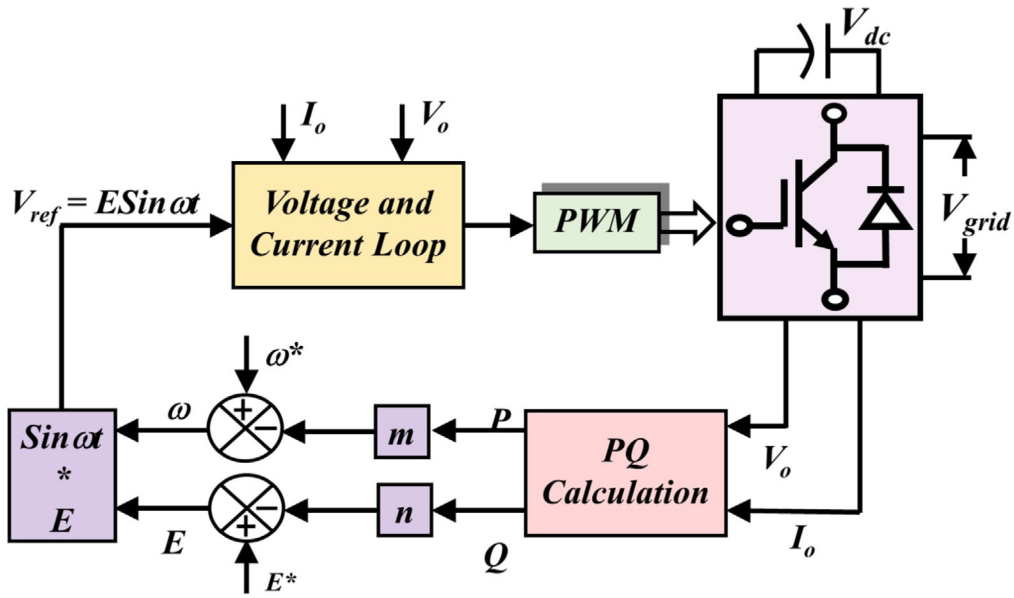

Fig. 9. P-Q control of grid connected inverters (Tayab et al., 2017).

to smoothen power production in wind energy systems by pitch angle control (Zhao et al., 2021; Hu et al., 2021a). This in turn stabilizes the system during any frequency deviations.

5.1. Photovoltaic (PV) systems

Solar panels in MGs are a source of clean and cost effective source of energy. MGs that rely solely on PV panels have the added advantage of providing electricity to a local community for extended periods of time in times of low power from the grid (Al-Shahri et al., 2021; Yan et al., 2021). Therefore PV systems can act as ideal sources of backup energy. Bawazir and Cetin (2020) provides an overview of PV siting as well as the methods used to assess PV potential as DGs.

PV systems along with wind energy are the most widely used renewable energy sources in MGs (Ramesh et al., 2021; Kumar et al., 2021). They are advantageous over conventional sources of electricity but their low energy conversion efficiency and high cost of production decreases its usage. PV panels can be installed in many locations and are easier to maintain. Solar panels can be integrated with the main grid by means of MGs so that their control is easier. Islanded MGs on the other hand are difficult to control (Elrayyah et al., 2014). The cost of PV panels can be lowered by using maximum power point tracking (MPPT) which is a method of designing PV panels to obtain optimum energy by use of power tracking (Inthamoussou et al., 2012; Messalti et al., 2017). Their increasing usage requires its optimum generation of power. Therefore, MPPT is needed to analyze the best environmental factors. Saravanan and Babu (2016) reviews many algorithms used for MPPT. Perturbation and observation (P and O) (Esram and Chapman, 2007; Femia et al., 2009) for example works by calculating dP/dV in a particular direction and then choosing an operating point where dP/dV turns out to be greater than 0 (Saravanan and Babu, 2015). This method is advantageous due to its ease of implementation. Many improvements in this method are also recommended (Kollimalla and Mishra, 2014; Abdelsalam et al., 2011). A combination of particle swarm optimization (PSO) and P and O method was used for PV system under shades (Ishaque and Salam, 2012; Lian et al., 2014). Machine Learning algorithms have also been used with PV panel controls. Artificial neural network (ANN) method, for example, is being used quite recently as it is more efficient in comparison to other techniques (Punitha et al., 2013). Its main benefit is that it can find relationships between different variables without the need of complex mathematical models (Farhat et al., 2013; Abd Kadir and Sharifah, 2014; Boumaaraf et al., 2015; Duan et al., 2015; Mahmoud et al., 2015).

5.2. Wind energy

Places with even an average supply of wind energy can benefit an off grid MG by increasing its battery life, increasing renewable energy share in MG and by decreasing fuel consumption. MGs that rely on wind energy operate in winters, during night time as well as in rainy seasons and therefore are able to supplement solar panels for energy production. Instead of extending the main grid, MGs based on wind energy can supply electricity to rural areas, small industries away from the grid and off grid farms. The main challenge with wind energy, however, is its maximum extraction of energy keeping in mind its varying speed. Wind energy is a developing area of research (Cui et al., 2017; Karakasis et al., 2018; Xu and Zhang, 2016; Kumar et al., 2018). The generated power from wind is dependent on how effectively MPPT controller is used for any type of generator in use. Due to the varying wind speeds (Yang et al., 2018a; Tiwari et al., 2018), it is important to find an optimized generator speed for which maximum amount of electricity can be generated. This is usually done by keeping the wind speed in a range of values for the MPPT algorithm (Kumar et al., 2018; Ghaffari et al., 2014). MPPT algorithms are widely researched (Heydari and Smedley, 2015; Yang et al., 2018b) and are differentiated on the basis of sensorless (Urtasun Erburu et al., 2014) or with sensors or on the basis of direct and indirect controllers (Mishra et al., 2015). Also, some evaluate wind speed for calculation whereas others do not (Alagab et al., 2015). Different generators used for conversion of wind to electricity. Doubly fed induction generator (Yan et al., 2015) and permanent magnet synchronous generators (Ghosh et al., 2015; Naidu and Singh, 2016) are some famous types (Wei et al., 2016).

5.3. Fuel cells

Fuel cell technology in MGs is not yet commercially available due to its cost and life span . The problems that fuel cell technology faces are reported in Choudhury et al. (2013). To step up the

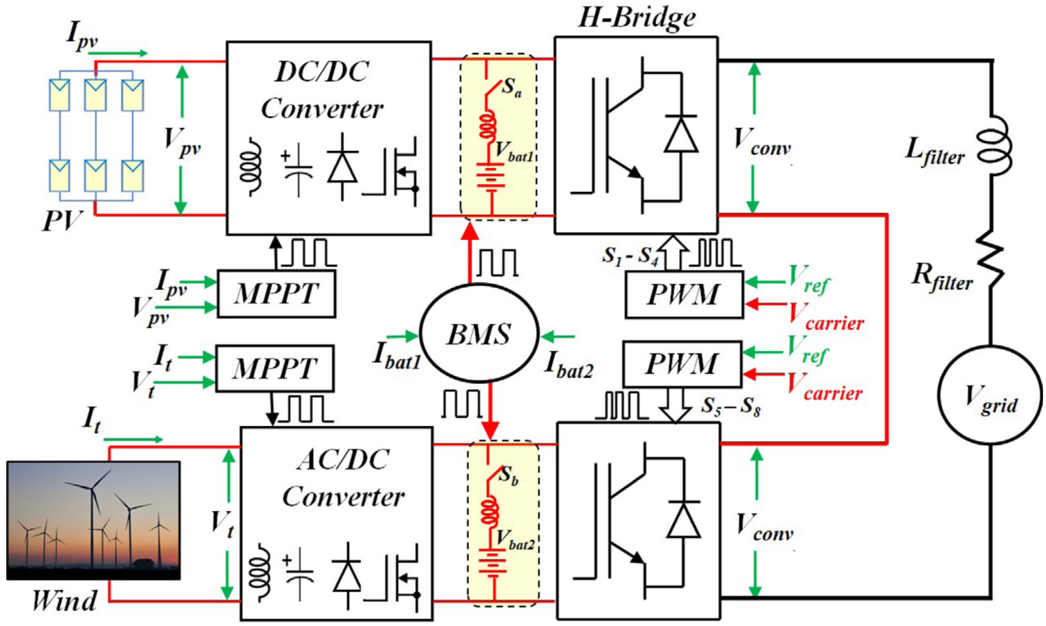

Fig. 10. Renewable energy and battery storage elements integrated to the utility grid.

output voltage of fuel cells, converters are especially developed for the task (Kirubakaran et al., 2009). Sulaiman et al. (2015) and Hatti et al. (2011) reviews some challenges faced by Electric vehicles and management of power in fuel cells (Das et al., 2017). A comparison of these RESs is shown in Table 1.

5.4. Hybrid renewable energy systems (HRES)

Due to the intermittent nature of renewables, HRES is considered an alternative approach (Denholm et al., 2015). In such a case if one RES is low the other can provide energy (Luna-Rubio et al., 2012), such as wind and solar hybrid energy systems which is a common hybrid setup (Prasad et al., 2017). Hence, generation of power and Renewable energy systems efficiency can be upgraded (Sinha and Chandel, 2015; Gupta et al., 2014). HRES optimized sizing (Upadhyay and Sharma, 2014; Neves et al., 2014; Prakash and Khatod, 2016; Siddaiah and Saini, 2016) and management strategies as well as control (Arul et al., 2015; Olatomiwa et al., 2016) has been widely reviewed. Non renewables can also be integrated in HRES to improve system reliability and to overcome the intermittent nature of renewable energy (Gupta and Purohit, 2013). Different geographical locations have specific abundance of renewable energy resource, which if chosen effectively, which can not only reduce the need of fossil fuels but also reduces heavy dependence on import of electricity (Ismail et al., 2013; Robert et al., 2019; Ishaq et al., 2014; Meyar-Naimi and Vaez-Zadeh, 2012; Mekhilef et al., 2013; Razmjoo et al., 2019). Another important advantage of HRES is its use in areas far away from the grid, such as rural areas. Mekhilef et al. (2012), Harish and Kumar (2014), Ma et al. (2013) discusses this aspect.

5.5. Battery energy storage (BES) systems

The advancements towards use of RES's for electricity production requires storage devices which can provide energy in times of need. As shown in Fig. 10 batteries provide a reliable and continuous means of electricity in grid connected mode. Many studies have been carried out on this (Whittingham, 2012; Lund et al., 2015; Juturu and Wu, 2014). In this context, BES systems have many advantages due to their controls and fast action (IRENA and Borden, 2015; Christiansen et al., 2015). There have been many reviews on the use of batteries for storage systems (Divya and Østergaard, 2009; Lawder et al., 2014), the sizing of batteries in hybrid renewables (Luna-Rubio et al., 2012; Erdinc and Uzunoglu, 2012) or on the sizing of batteries for islanded systems (Khatib et al., 2016; Belouda et al., 2016; Shaqsi et al., 2020).

In case of faults a MG needs to maintain balance by utilizing ancillary services such as contingency reserves to maintain frequency. Motalleb et al. (2016a) reviews demand response to provide contingency reserve by dividing it into faster and slower responses. This is founded on the basis of frequency deviations from the normal grid. Similarly, Motalleb et al. (2016b) uses energy storage systems in MGs as a source of ancillary services. Dynamic programming is used as an optimization tool (Mahmoud et al., 2021; Kumar and Chary). A BES system plays an important role in controlling primary frequency of a MG due to its immediate response to any imbalances between supply and load. Aghamohammadi and Abdolahinia (2014) have put forward a technique to determine the sizing of battery energy system for optimal working. Simulations are carried out in PSCAD/EMTDC softwares to check the functioning of the proposed system. In the same context, when a load change occurs (Li et al., 2008) the system utilizes a micro turbine with fuel cells and electrolyzer to increase the MGs ability to stabilize frequency. The controller is also capable of improving frequency changes caused by generation variations. Also interconnected micro-grids frequency fluctuations are investigated.

A robust control strategy to control frequency deviations of a MG is proposed in Han et al. (2015b). This method decreases the size of battery systems by using robust control algorithms and hence minimizes the cost of the entire system (due to smaller sizing of battery storage systems) while keeping the frequency deviations within an allowable range. The main problem facing renewable energy resources is their nature of intermittent sources of energy. Therefore, energy storage systems are utilized to gain optimum energy from different renewable resources by storing their excess energy (El Kafazi et al., 2020). In Kim et al. (2010b), for example the problem of frequency stability for scattered energy resources is catered by using high temperature super conducting magnetic energy storage. The technology is applied on wind energy systems by applying single as well as dual magnets. The dual magnet in superconducting magnetic energy storage is more effective but has the drawback of AC losses as compared to single magnet use. Kim et al. (2010a) applies the cooperative control strategy and the energy storage systems in islanded mode of operation. The energy storage system regulates the frequency as well as the voltage at primary level of control.

Chen et al. (2012) represents a cost effective method for the sizing of energy storage systems. BES systems tend to work better than renewable energy technologies in terms of controlling frequency. Practical applications of BES systems such as Serban and Marinescu (2014) and Serban et al. (2013) verify its frequency controlling ability. Oudalov et al. (2006) is an effective analysis of financial benefit for the use of BES systems. Oudalov et al. (2007) measure historical data of battery storage systems for primary frequency reserves. It proposes that a lead acid BES system as the optimum solution for primary reserve along with emergency resistors for use in extreme imbalance of frequency. Due to an increase in renewable energy penetration in stand alone MGs, the frequency as well as voltage deviations increase. Through comparison of synchronous generators and BES systems for frequency stability, Kim et al. (2016) propose the use of BES systems to get rid of mechanical inertia of the generator. Kerdphol et al. (2016) and Wang et al. (2021), uses particle swarm optimization based frequency control to evaluate the optimum size of the BES system and in turn minimizes the overall cost of its usage in MGs.

5.6. Recent advanced control methods in MGs

Presently, droop methods for control are utilized for power sharing in MGs. However, the main drawback of this method is its low performance during transients as it shows less precision when simultaneously sharing power and controlling deviations in voltage or frequency. To deal with this issue, researchers have assessed hierarchical control techniques to play a vital role in future MGs. Section details on the components of hierarchical controls i.e. primary, secondary and tertiary control methods. Primary, secondary, and tertiary controls work at different time frames as shown in Fig. 7. Another important time-frame of interest in the MG controls is the inertial response of MGs to a contingency event. The inertial time frame less than 10 s where control techniques are applied to support the system frequency or voltage during this time span. Various researchers use BESS and ultra capacitors as virtual inertia units in place of synchronous generators to increase the overall inertia of MGs. Recently, Model Predictive Controller (MPC) has been studied widely in control of MGs (Clarke et al., 2016). MPC works by building a prediction model on the basis of the states of the system and its forecasts. This results in using the current states of the system to compute future forecasts by using the mathematical model of the system. These future predictions can be any time varying entities in a microgrid like generation, load and electricity costs. This concept is shown in Fig. 11 . MPC is not only used in MGs with various renewable energy resources but also utilized in distributed generations connected through converters (Kouro et al., 2009; Garcia-Torres et al., 2019; Shan et al., 2020). MPC has proven to have many benefits over conventional controllers as it uses optimization techniques to incorporate constraints of the system to minimize the objective function. These constraints can be modeled according to either physical or control aspects. The challenges with the advancement of MPC is the stochastic nature of RES such as wind and solar as they are variable in nature. Particle swarm optimization on the other hand, is a stochastic machine learning based optimizer which allows online learning.

Controllers equipped with reinforcement learning algorithms are another set of advanced control procedures. Reinforcement learning is an agent-based machine learning algorithm which can perform in the absence of a model (Jordan et al., 2020; Skiparev et al., 2021).

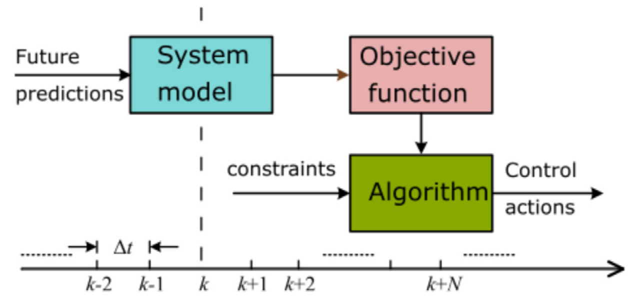

Fig. 11. Methodology of MPC (Hu et al., 2021b).

6. Optimization based control techniques in MGs

In a micro grid structure, optimization techniques may be used at any level to achieve the optimal operating conditions. Optimization methods are needed in many decision taking tasks such as in their generation scheduling, operation as well as maintenance of the MG. Given several feasible solutions, optimization algorithms work to find the optimal solution in the presence of necessary constraints. Optimization of MGs may be divided into three subgroups based on the distribution, generation, or control of MGs. Modeling a mix of generation resources in a MG requires extensive analysis to decide the optimal choice of ESS as well as generation resources (Ahmed et al., 2021, 2020). As shown in Fig. 12 optimization techniques are also categorized on the basis of the main objective according to requirements or as per the method used for achieving optimality (Topa Gavilema et al., 2021; Minchala-Avila et al., 2015). Some methods used in optimization are mixed integer linear programming (MILP) and dynamic programming. Other methods that use predictive modeling are MPC and artificial intelligence techniques. The most common objectives in MG designs are to minimize carbon dioxide emissions, demand side management (DSM) and economic dispatch.

Optimization techniques may also be used in the choice of sizing as well as siting of RES in the MG. Sizing is defined as the kind of renewable energy resource that is employed as well as the amount of energy extracted from it. On the other hand, siting of these resources deals with their location in the distribution system. The siting must be such to minimize the losses of power and provide the best quality of power to the loads. Researchers have applied various optimization techniques in this area. Optimization techniques are also applied for the control as well as operational management of MGs (Fathima and Palanisamy, 2015). This is done to give the best power quality as well as reliable generation from various renewable energy sources. Optimal decision-making is complex in this area due to the variable nature of renewable energy resources.

As described in the previous sections MG controls are divided into primary, secondary, and tertiary controls. Tertiary controls consider decisions for energy management and exchange of power between the utility and MG. Software tools like HOMER (Hybrid Optimization Model for Electric Renewables), HYBRID 2, RETSCREEN and GAMS (General Algebraic Modeling System) are available to model renewable energy systems either in real time or offline. An optimization problem is solved by using a constrained set of inputs to find the maximum and minimum values of an objective function (Nazir et al., 2020). Usually, these problems are computationally expensive in most applications of power systems. In MGs, the problems in real time are quite complex as well as finding all possible solutions is computationally expensive.

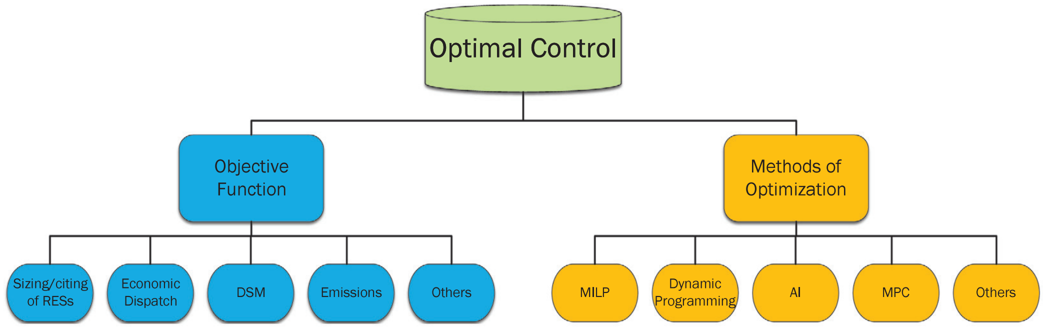

Fig. 12. Classification of Optimal Control methods (Minchala-Avila et al., 2015).

Heuristic algorithms use trial and error-based techniques to solve problems that are complex in nature. On the other hand, meta heuristic methods use algorithms inspired from nature (Fioriti et al., 2020; Tsao and Thanh, 2021; Ghavifekr, 2021). Particle swarm optimization (PSO), for example is inspired from how fish and bird swarms move in a constrained area in search of food. It solves an objective function within a constrained space iteratively. PSO was used in Saad et al. (2018) and Yazdanian and Mehrizi-Sani (2014) for tuning the parameters of PI/PID controllers to obtain the needed performance. Due to its simplicity, PSO can be used in any optimization software's. It can also be used in the sizing and control of MGs (Phommixay et al., 2020; Zhang et al., 2020; Li et al., 2020). However, if there are a lot of components to solve, genetic algorithm is a more efficient method. Ant colony is another optimization algorithm that imitates the behavior of ants to find the optimal solution for an objective function under constraints. This algorithm was used in Wu et al. (2010) to minimize losses in distribution systems and was shown to be better than genetic algorithms. "Survival of the fittest" theory is implemented in genetic algorithms. It is efficient to use in applications where the search area for optimal solution is complex and large. Genetic algorithms have been applied in hybrid renewable energy systems as well as in the economic dispatch problem of micro grids (Dougier et al., 2021; Leonori et al., 2020).

7. New developments in MG controls and optimization

Various techniques have been carried out in literature to implement controls that involve constraints related to the modes of operation, topologies, physical parameters, and structures of MGs. However, an optimal controller should consider the stochastic nature of RES as well as the variability of load in a MG system. Stochastic predictive controllers for example takes system disturbances into account and performs like the traditional MPC (Barreiro-Gomez et al., 2019; Kou et al., 2019; Chen and Hu, 2019). These controllers have the ability to forecast the future optimal control actions, and hence requires inputs based on the future values. The main challenge in these controllers is that future input parameters are required. Due to the advancement in machine learning algorithms, it is now feasible to set up sensors to gather the needed data.

7.1. Future challenges in MG development

As we are moving towards a smarter and more efficient MG setup, the need of real time control/mitigation/protection and cybersecurity of collected/processed data is rising. During the past few decades, as communication systems and machine learning algorithms have advanced a great deal, the use of predictive approaches has been enhanced. The improvement in communication technologies has also benefited the performance of controls as well as future performance predictions. The authors have identified four driving factors capable of shaping the future MGs, as summarized in Fig. 13.

7.1.1. Energy sources

MG setup consisting of both conventional and emerging distributed generators have led to a highly dynamic, intermittent, and transient power system. The stochastic nature of RESs must be considered in design, modeling, and development of MG control. Some stochastic variables are electricity price, control parameters, lifetime of equipment, initial setup cost as well as state of charge in case of BESS. In the design of optimal control algorithms, multiple cost functions and constraints should be considered so that numerous DERs can be controlled, and all the stochastic variables are weighed. Another important aspect for consideration is the development of fast-acting protection devices, such as against over currents is a challenge especially when working in islanded mode of operation in MGs. Conventional power system consists of high-inertia synchronous generators, which provide sufficient power for execution of identification, and isolation steps. Due to the increasing penetration of zero-inertia power electronics interfaced distributed generators, lack of effective control will result in extreme deviations in frequency and voltage magnitudes. To address this concern and develop stable microgrids, development of virtual inertia control of distributed generators is being developed.

7.1.2. Smart loads

Loads such as smart homes, smart buildings, and smart industry are emerging, which are really pushing the microgrid concept to be highly integrated and optimized during real-time operation. Concepts such as digital twins, internet of things, industry 4.0 focusing on automation based reliable control of various loads without relying on human intervention. Emerging MGs is a significant stakeholder in this process, which will ensure the success of this philosophy. Game changers like battery storage, and electric vehicles, which are capable of acting as source/sink, are being potentially developed as saviors of MGs. These components have also led to the wide development of smart meters, controllers, and modern data acquisition devices resulting in a more efficient and interactive framework.

7.1.3. Data processing

Tightly coupled and fast processing communication system is the lifeline of any cost-effective, and reliable MG. Data generated from all the sensors, control systems, and distribution operators must be collected, and processed for further optimization. Factors such as attenuation of signal strength, noise cancellation,

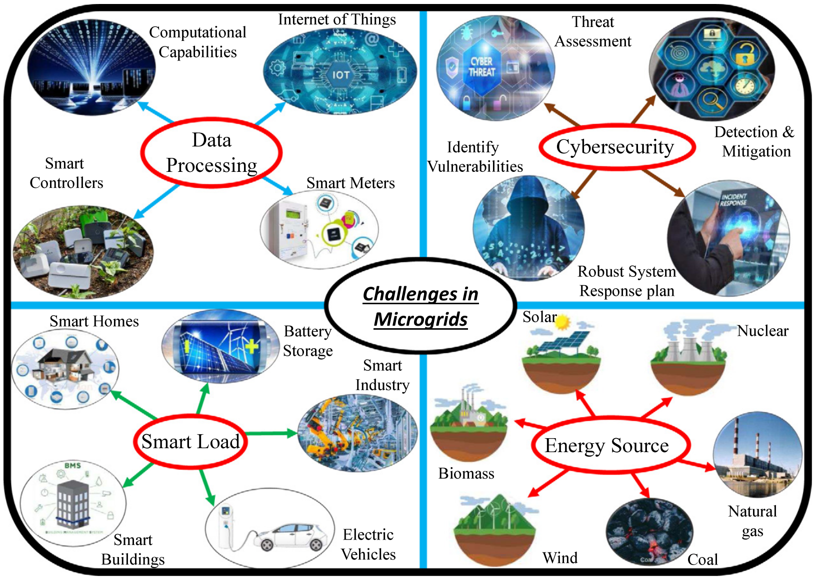

Fig. 13. Microgrids changing infrastructure.

computational burden and their potential impact on the data must be monitored to segregate corrupted data from actual data. To address this concern, local smart controlling and monitoring devices are being developed and employed in MGs. This reduces the burden on communication infrastructure as well as overall reliability of the system. Advanced super computers are also leading the cause for effective performance at the top level of MG.

7.1.4. Cybersecurity

Excess reliance on data processing have also significantly increased the threat level of cyber threats. Unlike physical attacks, the perpetrators can conveniently attack any generation plant and manufacturing plant resulting in serious damage to the world economies. Thus, there is an emerging need of identifying vulnerabilities and their potential risk to avoid any monetary or propriety loss due to cyber-attacks. In case of real-time attacks, robust detection and mitigation plans based on threat assessment and response must be developed and in-place for quick deployment. This helps in securing information or damage control in the cyberattack event.

8. Conclusion

MGs have recently drawn a lot of attention due to the many benefits they hold. From being able to choose between AC and DC transmission systems MGs also have the advantage of being operable in grid connected or stand alone mode. Not only this, but MGs also favor many types of renewable energy resources which are clean, efficient and cost effective. Hence, the control of MGs is an important area of research. In this paper, a comprehensive review of MG structure and associated control structures are presented. To understand the MG design and control, types of MG structures are investigated in detail. This helps in establishing major requirement criteria and control modes to be provided for stable operation in both grid connected and islanded mode. Also, the benefits and comparison of AC, DC, and hybrid MGs are identified. With this background, various control methodologies are reviewed. MG consists of components such as, power electronic switching components and loads, which operate at a faster time constant (1 – 10 μs). However, the objective of MG operation must be to support the main grid operation. Due to this reason, dynamics of MG is hierarchical in nature. Hierarchy consisting of primary (switching components — voltage and current), secondary (active and reactive power control) and tertiary (economic load dispatch, frequency and voltage control, mode of operation control) are investigated in detail. For effective operation, characteristics of different connected sources must be in accordance with the MG. To achieve this, droop control forms the basic structure of any control methodology in MG. Selection and design of droop characteristics is entirely dependent upon the system configuration and connected components. As renewable energy components are a crucial component of MG, detailed review of DER integration and control operation in MG is discussed. Advanced control methodologies for effective performance are also presented in detail. Also, the importance of battery storage system for filtering intermittency and variability of DERs with associated control are also explored.

Declaration of competing interest

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

Acknowledgments

This publication was made possible by Qatar University-Marubeni Concept to Prototype Development Research grant # [M-CTP-CENG-2020-2] from the Qatar University, Qatar. The statements made herein are solely the responsibility of the authors. The APC will be funded by the Qatar National Library, Qatar.

References

Abd Kadir, M., Sharifah, S., 2014. Development of artificial neural network based MPPT for photovoltaic system during shading condition. In: Appl. Mech. Mater.. 448, Trans Tech Publ, pp. 1573–1578.

Abdelsalam, A.K., Massoud, A.M., Ahmed, S., Enjeti, P.N., 2011. High-performance adaptive perturb and observe MPPT technique for photovoltaic-based microgrids. IEEE Trans. Power Electron. 26 (4), 1010–1021.

Aghamohammadi, M.R., Abdolahinia, H., 2014. A new approach for optimal sizing of battery energy storage system for primary frequency control of islanded microgrid. Int. J. Electr. Power Energy Syst. 54, 325–333.

Agundis-Tinajero, G., Aldana, N.L.D., Luna, A.C., Segundo-Ramírez, J., Visairo-Cruz, N., Guerrero, J.M., Vazquez, J.C., 2019. Extended-optimal-power-flow-based hierarchical control for islanded AC microgrids. IEEE Trans. Power Electron. 34 (1), 840–848.

Ahmed, A., Nadeem, M.F., Kiani, A.T., Khan, I., 2021. An overview on optimal planning of distributed generation in distribution system and key issues. In: 2021 IEEE Texas Power and Energy Conference (TPEC). IEEE, pp. 1–6.
Ahmed, A., Nadeem, M.F., Sajjad, I.A., Bo, R., Khan, I.A., 2020. Optimal allocation of wind dg with time varying voltage dependent loads using bio-inspired: salp swarm algorithm. In: 2020 3rd International Conference on Computing, Mathematics and Engineering Technologies (iCoMET). IEEE, pp. 1–7.
Al-Shahri, O.A., Ismail, F.B., Hannan, M., Lipu, M.H., Al-Shetwi, A.Q., Begum, R., Al-Muhsen, N.F., Soujeri, E., 2021. Solar photovoltaic energy optimization methods, challenges and issues: a comprehensive review. J. clean. Prod. 284, 125465.
Alagab, S.M., Tennakoon, S., Gould, C., 2015. Review of wind farm power collection schemes. In: 2015 50th International Universities Power Engineering Conference (UPEC). IEEE, pp. 1–5.
Arul, P., Ramachandaramurthy, V.K., Rajkumar, R., 2015. Control strategies for a hybrid renewable energy system: A review. Renew. Sustain. Energy Rev. 42, 597–608.
Asad, R., Kazemi, A., 2012. A quantitative analysis of effects of transition from ac to dc system, on storage and distribution systems. In: 2012 Asia-Pacific Power and Energy Engineering Conference. IEEE, pp. 1–5.
Au-Yeung, J., Vanalme, G.M., Myrzik, J.M., Karaliolios, P., Bongaerts, M., Bozelie, J., Kling, W.L., 2009. Development of a voltage and frequency control strategy for an autonomous LV network with distributed generators. In: 2009 44th International Universities Power Engineering Conference (UPEC). IEEE, pp. 1–5.
Avelar, H.J., Parreira, W.A., Vieira, J.B., de Freitas, L.C.G., Coelho, E.A.A., 2012. A state equation model of a single-phase grid-connected inverter using a droop control scheme with extra phase shift control action. IEEE Trans. Ind. Electron. 59 (3), 1527–1537.
Barreiro-Gomez, J., Duncan, T.E., Tembine, H., 2019. Linear-quadratic mean-field-type games-based stochastic model predictive control: A microgrid energy storage application. In: 2019 American Control Conference (ACC). pp. 3224–3229.
Basak, P., Chowdhury, S., nee Dey, S.H., Chowdhury, S., 2012. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renew. Sustain. Energy Rev. 16 (8), 5545–5556.
Bawazir, R.O., Cetin, N.S., 2020. Comprehensive overview of optimizing PV-DG allocation in power system and solar energy resource potential assessments. Energy Rep. 6, 173–208.
Belouda, M., Jaafar, A., Sareni, B., Roboam, X., Belhadj, J., 2016. Design methodologies for sizing a battery bank devoted to a stand-alone and electronically passive wind turbine system. Renew. Sustain. Energy Rev. 60, 144–154.
Bharath, K., Krishnan, M.M., Kanakasabapathy, P., 2019. A review on dc microgrid control techniques applications and trends. Int. J. Renew. Energy Res. (IJRER) 9 (3), 1328–1338.
Bidram, A., Davoudi, A., 2012. Hierarchical structure of microgrids control system. IEEE Trans. Smart Grid 3 (4), 1963–1976.
Bidram, A., Davoudi, A., Lewis, F.L., 2014. A multiobjective distributed control framework for islanded AC microgrids. IEEE Trans. ind. inform. 10 (3), 1785–1798.
Bidram, A., Davoudi, A., Lewis, F.L., Guerrero, J.M., 2013. Distributed cooperative secondary control of microgrids using feedback linearization. IEEE Trans. Power Syst. 28 (3), 3462–3470.
Bolognani, S., Zampieri, S., 2013. A distributed control strategy for reactive power compensation in smart microgrids. IEEE Trans. Autom. Control 58 (11), 2818–2833.
Boumaaraf, H., Talha, A., Bouhali, O., 2015. A three-phase NPC grid-connected inverter for photovoltaic applications using neural network mppt. Renew. Sustain. Energy Rev. 49, 1171–1179.
Chen, S., Gooi, H.B., Wang, M., 2012. Sizing of energy storage for microgrids. IEEE Trans. Smart Grid 3 (1), 142–151.
Chen, Y., Hu, M., 2019. Swarm intelligence–based distributed stochastic model predictive control for transactive operation of networked building clusters. Energy Build. 198, 207–215.
Choudhury, A., Chandra, H., Arora, A., 2013. Application of solid oxide fuel cell technology for power generation—A review. Renew. Sustain. Energy Rev. 20, 430–442.
Christiansen, C., Murray, B., Conway, G., Chambers, C., 2015. Energy storage study: funding and knowledge sharing priorities. AECOM, Sydney.
Clarke, W.C., Manzie, C., Brear, M.J., 2016. An economic mpc approach to microgrid control. In: 2016 Australian Control Conference (AuCC). pp. 276–281.
Cui, Z., Song, L., Li, S., 2017. Maximum power point tracking strategy for a new wind power system and its design details. IEEE Trans. Energy Convers. 32 (3), 1063–1071.
Das, V., Padmanaban, S., Venkitusamy, K., Selvamuthukumaran, R., Blaabjerg, F., Siano, P., 2017. Recent advances and challenges of fuel cell based power system architectures and control–A review. Renew. Sustain. Energy Rev. 73, 10–18.
Dasgupta, S., Sahoo, S.K., Panda, S.K., Amaratunga, G.A., 2010. Single-phase inverter-control techniques for interfacing renewable energy sources with microgrid—Part II: series-connected inverter topology to mitigate voltage-related problems along with active power flow control. IEEE Trans. Power Electron. 26 (3), 732–746.
Dawoud, S.M., Lin, X., Okba, M.I., 2018. Hybrid renewable microgrid optimization techniques: A review. Renew. Sustain. Energy Rev. 82, 2039–2052.
Denholm, P., O'Connell, M., Brinkman, G., Jorgenson, J., 2015. Overgeneration from Solar Energy in California. A Field Guide to the Duck Chart. Technical Report, National Renewable Energy Lab.(NREL), Golden, CO (United States).
Divya, K., Østergaard, J., 2009. Battery energy storage technology for power systems—An overview. Electr. Power Syst. Res. 79 (4), 511–520.
Dou, C.-X., Liu, B., 2013. Multi-agent based hierarchical hybrid control for smart microgrid. IEEE Trans. Smart Grid 4 (2), 771–778.
Dougier, N., Garambois, P., Gomand, J., Roucoules, L., 2021. Multi-objective non-weighted optimization to explore new efficient design of electrical microgrids. Appl. Energy 304, 117758.
Dragičević, T., Lu, X., Vasquez, J.C., Guerrero, J.M., 2015. DC microgrids—Part I: A review of control strategies and stabilization techniques. IEEE Trans. Power Electron. 31 (7), 4876–4891.
Duan, Q., Mao, M., Duan, P., Hu, B., 2015. Application of improved radial basis function neural network method in global MPPT for PV array. In: 2015 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE, pp. 3260–3264.
El Kafazi, I., Lafkih, M., Bannari, R., 2020. Pv generator and energy storage systems for laboratory building. Energy Rep. 6, 672–679.
Elrayyah, A., Sozer, Y., Elbuluk, M.E., 2014. Modeling and control design of microgrid-connected PV-based sources. IEEE J. Emerg. Sel. Top. Power Electron. 2 (4), 907–919.
Engler, A., 2005. Applicability of droops in low voltage grids. Int. J. Distributed Energy Resour. 1 (1), 1–6.
Engler, A., Soultanis, N., 2005. Droop control in LV-grids. In: 2005 International Conference on Future Power Systems. IEEE, pp. 6–pp.
Erdinc, O., Uzunoglu, M., 2012. Optimum design of hybrid renewable energy systems: overview of different approaches. Renew. Sustain. Energy Rev. 16 (3), 1412–1425.
Esram, T., Chapman, P.L., 2007. Comparison of photovoltaic array maximum power point tracking techniques. IEEE Trans. Energy Convers. 22 (2), 439–449.
Farhat, S., Alaoui, R., Kahaji, A., Bouhouch, L., 2013. Estimating the photovoltaic MPPT by artificial neural network. In: 2013 International Renewable and Sustainable Energy Conference (IRSEC). IEEE, pp. 49–53.
Fathima, A.H., Palanisamy, K., 2015. Optimization in microgrids with hybrid energy systems–A review. Renew. Sustain. Energy Rev. 45, 431–446.
Femia, N., Petrone, G., Spagnuolo, G., Vitelli, M., 2009. A technique for improving P&O MPPT performances of double-stage grid-connected photovoltaic systems. IEEE Trans. Ind. Electron. 56 (11), 4473–4482.
Feng, X., Shekhar, A., Yang, F., E. Hebner, R., Bauer, P., 2017. Comparison of hierarchical control and distributed control for microgrid. Electric Power Components and Systems 45 (10), 1043–1056.
Fiorini, L., Aiello, M., 2019. Energy management for user's thermal and power needs: A survey. Energy Rep. 5, 1048–1076.
Fioriti, D., Lutzemberger, G., Poli, D., Duenas-Martinez, P., Micangeli, A., 2020. Heuristic approaches to size microgrids: a methodology to compile multiple design options. In: 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe). IEEE, pp. 1–6.
Gaonkar, D., Guerrero, J.M., et al., 2018. Improved pf/qv and pv/qf droop controllers for parallel distributed generation inverters in ac microgrid. Sustainable cities and society 41, 421–442.
Garcia-Torres, F., Bordons, C., Ridao, M.A., 2019. Optimal economic schedule for a network of microgrids with hybrid energy storage system using distributed model predictive control. IEEE Trans. Ind. Electron. 66 (3), 1919–1929.
Ghaffari, A., Krstić, M., Seshagiri, S., 2014. Power optimization and control in wind energy conversion systems using extremum seeking. IEEE Trans. Control Syst. Technol. 22 (5), 1684–1695.
Ghavifekr, A.A., 2021. Application of heuristic techniques and evolutionary algorithms in microgrids optimization problems. Microgrids: Adv. Oper. Control Prot. 219–251.
Ghosh, S., Kamalasadan, S., Senroy, N., Enslin, J., 2015. Doubly fed induction generator (DFIG)-based wind farm control framework for primary frequency and inertial response application. IEEE Trans. Power Syst. 31 (3), 1861–1871.
Guerrero, J.M., Chandorkar, M., Lee, T.-L., Loh, P.C., 2013. Advanced control architectures for intelligent microgrids—Part I: decentralized and hierarchical control. IEEE Trans. Ind. Electron. 60 (4), 1254–1262.
Guerrero, J.M., Vasquez, J.C., Matas, J., Castilla, M., de Vicuña, L.G., 2008. Control strategy for flexible microgrid based on parallel line-interactive UPS systems. IEEE Trans. Ind. Electron. 56 (3), 726–736.
Guerrero, J.M., Vasquez, J.C., Matas, J., De Vicuña, L.G., Castilla, M., 2011. Hierarchical control of droop-controlled ac and dc microgrids—a general approach toward standardization. IEEE Trans. Ind. Electron. 58 (1), 158–172.

Guo, F., Wen, C., Mao, J., Song, Y.-D., 2015. Distributed secondary voltage and frequency restoration control of droop-controlled inverter-based microgrids. IEEE Trans. Ind. Electron. 62 (7), 4355–4364.
Gupta, A., Doolla, S., Chatterjee, K., 2018. Hybrid ac–dc microgrid: systematic evaluation of control strategies. IEEE Trans. Smart Grid 9 (4), 3830–3843.
Gupta, P., Pandit, M., Kothari, D., 2014. A review on optimal sizing and siting of distributed generation system: integrating distributed generation into the grid. In: 2014 6th IEEE Power India International Conference (PIICON). IEEE, pp. 1–6.
Gupta, S.K., Purohit, P., 2013. Renewable energy certificate mechanism in india: A preliminary assessment. Renew. Sustain. Energy Rev. 22, 380–392.
Han, H., Hou, X., Yang, J., Wu, J., Su, M., Guerrero, J.M., 2016. Review of power sharing control strategies for islanding operation of AC microgrids. IEEE Trans. Smart Grid 7 (1), 200–215.
Han, H., Liu, Y., Sun, Y., Su, M., Guerrero, J.M., 2015a. An improved droop control strategy for reactive power sharing in islanded microgrid. IEEE Trans. Power Electron. 30 (6), 3133–3141.
Han, Y., Young, P.M., Jain, A., Zimmerle, D., 2015b. Robust control for microgrid frequency deviation reduction with attached storage system. IEEE Trans. Smart Grid 6 (2), 557–565.
Harish, V., Kumar, A., 2014. Demand side management in India: action plan, policies and regulations. Renew. Sustain. Energy Rev. 33, 613–624.
Harjunkoski, I., Nyström, R., Horch, A., 2009. Integration of scheduling and control—theory or practice?. Computers & Chemical Engineering 33 (12), 1909–1918.
Hatti, M., Meharrar, A., Tioursi, M., 2011. Power management strategy in the alternative energy photovoltaic/PEM fuel cell hybrid system. Renew. Sustain. Energy Rev. 15 (9), 5104–5110.
Hatziargyriou, N., 2014. Microgrids: Architectures and Control. John Wiley & Sons.
Heydari, M., Smedley, K., 2015. Comparison of maximum power point tracking methods for medium to high power wind energy systems. In: 2015 20th Conference on Electrical Power Distribution Networks Conference (EPDC). IEEE, pp. 184–189.
Hu, Q., Amini, M.R., Kolmanovsky, I., Sun, J., Wiese, A., Seeds, J.B., 2021a. Multihorizon model predictive control: An application to integrated power and thermal management of connected hybrid electric vehicles. IEEE Trans. Control Syst. Technol..
Hu, J., Shan, Y., Guerrero, J.M., Ioinovici, A., Chan, K.W., Rodriguez, J., 2021b. Model predictive control of microgrids–An overview. Renew. Sustain. Energy Rev. 136, 110422.
Inthamoussou, F.A., De Battista, H., Mantz, R.J., 2012. New concept in maximum power tracking for the control of a photovoltaic/hydrogen system. Int. J. Hydrog. Energy 37 (19), 14951–14958.
IRENA, R.K., Borden, E., 2015. Battery storage for renewables: market status and technology outlook. Abu Dabi.
Ishaq, S., et al., 2014. Techno-economic analysis of a hybrid grid-connected/PV/wind system in Pakistan (Ph.D. thesis). Bahria University Islamabad Campus.
Ishaque, K., Salam, Z., 2012. A deterministic particle swarm optimization maximum power point tracker for photovoltaic system under partial shading condition. IEEE Trans. Ind. Electron. 60 (8), 3195–3206.
Ismail, M.S., Moghavvemi, M., Mahlia, T., 2013. Energy trends in palestinian territories of west bank and gaza strip: possibilities for reducing the reliance on external energy sources. Renew. Sustain. Energy Rev. 28, 117–129.
Jena, D., Rajendran, S., 2015. A review of estimation of effective wind speed based control of wind turbines. Renew. Sustain. Energy Rev. 43, 1046–1062.
Jian, Z., He, Z., Jia, J., Xie, Y., 2013. A review of control strategies for dc micro-grid. In: 2013 Fourth International Conference on Intelligent Control and Information Processing (ICICIP). IEEE, pp. 666–671.
Jiang, Z., Dougal, R.A., 2008. Hierarchical microgrid paradigm for integration of distributed energy resources. In: 2008 IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century. IEEE, pp. 1–8.
Jiang, Z., Yu, X., 2009. Power electronics interfaces for hybrid dc and ac-linked microgrids. In: 2009 IEEE 6th International Power Electronics and Motion Control Conference. IEEE, pp. 730–736.
Jin, G., Li, L., Li, G., Wang, Z., 2017. Accurate proportional load sharing among paralleled inverters based on improved pv droop coefficient. Electr. Power Syst. Res. 143, 312–320.
Jordan, S., Chandak, Y., Cohen, D., Zhang, M., Thomas, P., 2020. Evaluating the performance of reinforcement learning algorithms. In: International Conference on Machine Learning. PMLR, pp. 4962–4973.
Jordehi, A.R., 2016. Maximum power point tracking in photovoltaic (PV) systems: A review of different approaches. Renew. Sustain. Energy Rev. 65, 1127–1138.
Justo, J.J., Mwasilu, F., Lee, J., Jung, J.-W., 2013. AC-microgrids versus dc-microgrids with distributed energy resources: A review. Renew. Sustain. Energy Rev. 24, 387–405.
Juturu, V., Wu, J.C., 2014. Microbial cellulases: engineering, production and applications. Renew. Sustain. Energy Rev. 33, 188–203.
Kakigano, H., Nishino, A., Ise, T., 2011. Distribution voltage control for dc microgrid with fuzzy control and gain-scheduling control. In: 8th International Conference on Power Electronics-ECCE Asia. IEEE, pp. 256–263.
Karakasis, N., Tsioumas, E., Jabbour, N., Bazzi, A.M., Mademlis, C., 2018. Optimal efficiency control in a wind system with doubly fed induction generator. IEEE Trans. Power Electron. 34 (1), 356–368.
Kaviri, S.M., Pahlevani, M., Jain, P., Bakhshai, A., 2017. A review of ac microgrid control methods. In: 2017 IEEE 8th International Symposium on Power Electronics for Distributed Generation Systems (PEDG). IEEE, pp. 1–8.
Kerdphol, T., Fuji, K., Mitani, Y., Watanabe, M., Qudaih, Y., 2016. Optimization of a battery energy storage system using particle swarm optimization for stand-alone microgrids. Int. J. Electr. Power Energy Syst. 81, 32–39.
Khan, I., Li, Z., Xu, Y., Gu, W., 2016. Distributed control algorithm for optimal reactive power control in power grids. Int. J. Electr. Power Energy Syst. 83, 505–513.
Khan, I., Xu, Y., Sun, H., Bhattacharjee, V., 2017. Distributed optimal reactive power control of power systems. IEEE Access 6, 7100–7111.
Khan, I., Zhang, Y., Xue, H., Nasir, M., 2019. A distributed coordination framework for smart microgrids. In: Smart Microgrids. Springer, pp. 119–136.
Khatib, T., Ibrahim, I.A., Mohamed, A., 2016. A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system. Energy Convers. Manage. 120, 430–448.
Kim, J.-Y., Jeon, J.-H., Kim, S.-K., Cho, C., Park, J.H., Kim, H.-M., Nam, K.-Y., 2010a. Cooperative control strategy of energy storage system and microsources for stabilizing the microgrid during islanded operation. IEEE Trans. Power Electron. 25 (12), 3037–3048.
Kim, Y.-S., Kim, E.-S., Moon, S.-I., 2016. Frequency and voltage control strategy of standalone microgrids with high penetration of intermittent renewable generation systems. IEEE Trans. Power Syst. 31 (1), 718–728.
Kim, A.-R., Seo, H.-R., Kim, G.-H., Park, M., Yu, I.-K., Otsuki, Y., Tamura, J., Kim, S.-H., Sim, K., Seong, K.-C., 2010b. Operating characteristic analysis of HTS SMES for frequency stabilization of dispersed power generation system. IEEE Trans. Appl. Supercond. 20 (3), 1334–1338.
Kirubakaran, A., Jain, S., Nema, R., 2009. A review on fuel cell technologies and power electronic interface. Renew. Sustain. Energy Rev. 13 (9), 2430–2440.
Kollimalla, S.K., Mishra, M.K., 2014. A novel adaptive P&O MPPT algorithm considering sudden changes in the irradiance. IEEE Trans. Energy Convers. 29 (3), 602–610.
Kou, P., Feng, Y., Liang, D., Gao, L., 2019. A model predictive control approach for matching uncertain wind generation with PEV charging demand in a microgrid. Int. J. Electr. Power Energy Syst. 105, 488–499.
Kouro, S., Cortes, P., Vargas, R., Ammann, U., Rodriguez, J., 2009. Model predictive control—A simple and powerful method to control power converters. IEEE Trans. Ind. Electron. 56 (6), 1826–1838.
Kumar, N.S., Chary, P.H., Cooperative optimal control strategy for microgrid under grid-connected mode.
Kumar, M.B.H., Saravanan, B., Sanjeevikumar, P., Blaabjerg, F., 2018. Review on control techniques and methodologies for maximum power extraction from wind energy systems. IET Renew. Power Gener. 12 (14), 1609–1622.
Kumar, G., et al., 2021. Optimal power point tracking of solar and wind energy in a hybrid wind solar energy system. Int. J. Energy Environ. Eng. 1–27.
Lawder, M.T., Suthar, B., Northrop, P.W., De, S., Hoff, C.M., Leitermann, O., Crow, M.L., Santhanagopalan, S., Subramanian, V.R., 2014. Battery energy storage system (BESS) and battery management system (BMS) for grid-scale applications. Proc. IEEE 102 (6), 1014–1030.
Leonori, S., Paschero, M., Mascioli, F.M.F., Rizzi, A., 2020. Optimization strategies for microgrid energy management systems by genetic algorithms. Appl. Soft Comput. 86, 105903.
Li, C., Jia, X., Zhou, Y., Li, X., 2020. A microgrids energy management model based on multi-agent system using adaptive weight and chaotic search particle swarm optimization considering demand response. J. clean. Prod. 262, 121247.
Li, Q., Peng, C., Wang, M., Chen, M., Guerrero, J.M., Abbott, D., 2018. Distributed secondary control and management of islanded microgrids via dynamic weights. IEEE Trans. Smart Grid.
Li, X., Song, Y.-J., Han, S.-B., 2008. Frequency control in micro-grid power system combined with electrolyzer system and fuzzy PI controller. J. Power Sources 180 (1), 468–475.
Lian, K., Jhang, J., Tian, I., 2014. A maximum power point tracking method based on perturb-and-observe combined with particle swarm optimization. IEEE J. Photovolt. 4 (2), 626–633.
Loh, P.C., Blaabjerg, F., Peyghami-Akhuleh, S., Mokhtari, H., 2016. Distributed secondary control in DC microgrids with low-bandwidth communication link. In: 2016 7th Power Electronics and Drive Systems Technologies Conference (PEDSTC). IEEE, pp. 641–645.
Loh, P.C., Li, D., Chai, Y.K., Blaabjerg, F., 2013. Autonomous operation of hybrid microgrid with ac and dc subgrids. IEEE Trans. Power Electron. 28 (5), 2214–2223.
Londero, R.R., Affonso, C.M., Nunes, M.V., Freitas, W., 2010. Planned islanding for Brazilian system reliability. In: IEEE PES T&D 2010. IEEE, pp. 1–6.

Lopes, J.P., Moreira, C., Madureira, A., 2006. Defining control strategies for microgrids islanded operation. IEEE Trans. Power Syst. 21 (2), 916–924.
Lu, X., Guerrero, J.M., Sun, K., Vasquez, J.C., 2013. An improved droop control method for dc microgrids based on low bandwidth communication with dc bus voltage restoration and enhanced current sharing accuracy. IEEE Trans. Power Electron. 29 (4), 1800–1812.
Lu, X., Guerrero, J.M., Sun, K., Vasquez, J.C., 2014. An improved droop control method for dc microgrids based on low bandwidth communication with dc bus voltage restoration and enhanced current sharing accuracy. IEEE Trans. Power Electron. 29 (4), 1800–1812.
Luna-Rubio, R., Trejo-Perea, M., Vargas-Vázquez, D., Ríos-Moreno, G., 2012. Optimal sizing of renewable hybrids energy systems: A review of methodologies. Sol. Energy 86 (4), 1077–1088.
Lund, P.D., Lindgren, J., Mikkola, J., Salpakari, J., 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew. Sustain. Energy Rev. 45, 785–807.
Ma, T., Cintuglu, M.H., Mohammed, O., 2015. Control of hybrid ac/dc microgrid involving energy storage, renewable energy and pulsed loads. In: 2015 IEEE Industry Applications Society Annual Meeting. IEEE, pp. 1–8.
Ma, T., Yang, H., Lu, L., 2013. Performance evaluation of a stand-alone photovoltaic system on an isolated island in Hong Kong. Appl. Energy 112, 663–672.
Mahmoud, Y., Abdelwahed, M., El-Saadany, E.F., 2015. An enhanced MPPT method combining model-based and heuristic techniques. IEEE Trans. Sustain. Energy 7 (2), 576–585.
Mahmoud, M., Abouheaf, M., Sharaf, A., 2021. Reinforcement learning control approach for autonomous microgrids. Int. J. Modelling Simul. 41 (1), 1–10.
Mahmud, M., Hossain, M., Pota, H., Oo, A., 2014. Robust nonlinear distributed controller design for active and reactive power sharing in islanded microgrids. IEEE Trans. Energy Convers. 29 (4), 893–903.
Manas, M., et al., 2015. Renewable energy management through microgrid central controller design: An approach to integrate solar, wind and biomass with battery. Energy Rep. 1, 156–163.
Mekhilef, S., Faramarzi, S., Saidur, R., Salam, Z., 2013. The application of solar technologies for sustainable development of agricultural sector. Renew. Sustain. Energy Rev. 18, 583–594.
Mekhilef, S., Saidur, R., Kamalisarvestani, M., 2012. Effect of dust, humidity and air velocity on efficiency of photovoltaic cells. Renew. Sustain. Energy Rev. 16 (5), 2920–2925.
Menezes, E.J.N., Araújo, A.M., da Silva, N.S.B., 2018. A review on wind turbine control and its associated methods. J. clean. Prod. 174, 945–953.
Meng, L., Savaghebi, M., Andrade, F., Vasquez, J.C., Guerrero, J.M., Graells, M., 2015. Microgrid central controller development and hierarchical control implementation in the intelligent microgrid lab of aalborg university. In: 2015 IEEE Applied Power Electronics Conference and Exposition (APEC). IEEE, pp. 2585–2592.
Meng, L., Shafiee, Q., Trecate, G.F., Karimi, H., Fulwani, D., Lu, X., Guerrero, J.M., 2017. Review on control of DC microgrids and multiple microgrid clusters. IEEE J. Emerg. Sel. Top. Power Electron. 5 (3), 928–948.
Messalti, S., Harrag, A., Loukriz, A., 2017. A new variable step size neural networks MPPT controller: review, simulation and hardware implementation. Renew. Sustain. Energy Rev. 68, 221–233.
Meyar-Naimi, H., Vaez-Zadeh, S., 2012. Sustainable development based energy policy making frameworks, A critical review. Energy Policy 43, 351–361.
Minchala-Avila, L.I., Garza-Castañón, L.E., Vargas-Martínez, A., Zhang, Y., 2015. A review of optimal control techniques applied to the energy management and control of microgrids. Procedia Comput. Sci. 52, 780–787.
Mishra, S., Shukla, S., Verma, N., et al., 2015. Comprehensive review on maximum power point tracking techniques: wind energy. In: 2015 Communication, Control and Intelligent Systems (CCIS). IEEE, pp. 464–469.
Mohamed, Y.A.-R.I., El-Saadany, E.F., 2008. Adaptive decentralized droop controller to preserve power sharing stability of paralleled inverters in distributed generation microgrids. IEEE Trans. Power Electron. 23 (6), 2806–2816.
Mohammed, A., Refaat, S.S., Bayhan, S., Abu-Rub, H., 2019. Ac microgrid control and management strategies: evaluation and review. IEEE Power Electron. Mag. 6 (2), 18–31.
Motalleb, M., Thornton, M., Reihani, E., Ghorbani, R., 2016a. A nascent market for contingency reserve services using demand response. Appl. Energy 179, 985–995.
Motalleb, M., Thornton, M., Reihani, E., Ghorbani, R., 2016b. Providing frequency regulation reserve services using demand response scheduling. Energy Convers. Manage. 124, 439–452.
Naidu, N.S., Singh, B., 2016. Grid-interfaced DFIG-based variable speed wind energy conversion system with power smoothening. IEEE Trans. Sustain. Energy 8 (1), 51–58.
Nasir, M., Jin, Z., Khan, H.A., Zaffar, N.A., Vasquez, J.C., Guerrero, J.M., 2019. A decentralized control architecture applied to dc nanogrid clusters for rural electrification in developing regions. IEEE Trans. Power Electron. 34 (2), 1773–1785.
Nasirian, V., Davoudi, A., Lewis, F.L., Guerrero, J.M., 2014. Distributed adaptive droop control for DC distribution systems. IEEE Trans. Energy Convers. 29 (4), 944–956.
Nazir, M.S., Abdalla, A.N., Wang, Y., Chu, Z., Jie, J., Tian, P., Jiang, M., Khan, I., Sanjeevikumar, P., Tang, Y., 2020. Optimization configuration of energy storage capacity based on the microgrid reliable output power. J. Energy Storage 32, 101866.
Neves, D., Silva, C.A., Connors, S., 2014. Design and implementation of hybrid renewable energy systems on micro-communities: A review on case studies. Renew. Sustain. Energy Rev. 31, 935–946.
Olatomiwa, L., Mekhilef, S., Ismail, M.S., Moghavvemi, M., 2016. Energy management strategies in hybrid renewable energy systems: A review. Renew. Sustain. Energy Rev. 62, 821–835.
Olivares, D.E., Mehrizi-Sani, A., Etemadi, A.H., Cañizares, C.A., Iravani, R., Kazerani, M., Hajimiragha, A.H., Gomis-Bellmunt, O., Saeedifard, M., Palma-Behnke, R., et al., 2014. Trends in microgrid control. IEEE Trans. Smart Grid 5 (4), 1905–1919.
Opiyo, N.N., 2019. A comparison of DC-versus AC-based minigrids for cost-effective electrification of rural developing communities. Energy Rep. 5, 398–408.
Oudalov, A., Chartouni, D., Ohler, C., 2007. Optimizing a battery energy storage system for primary frequency control. IEEE Trans. Power Syst. 22 (3), 1259–1266.
Oudalov, A., Chartouni, D., Ohler, C., Linhofer, G., 2006. Value analysis of battery energy storage applications in power systems. In: 2006 IEEE PES Power Systems Conference and Exposition. IEEE, pp. 2206–2211.
Pahasa, J., Ngamroo, I., 2016. Coordinated control of wind turbine blade pitch angle and PHEVs using MPCs for load frequency control of microgrid. IEEE Syst. J. 10 (1), 97–105.
Palizban, O., Mekhilef, S., 2011a. Modeling and control of photovoltaic panels base perturbation and observation mppt method. In: 2011 IEEE International Conference on Control System, Computing and Engineering. IEEE, pp. 393–398.
Palizban, O., Mekhilef, S., 2011b. Power optimization and static performance investigation of an island-mode doubly-fed induction generator (DFIG). In: 2011 IEEE International Conference on Control System, Computing and Engineering. IEEE, pp. 399–403.
Papadimitriou, C., Zountouridou, E., Hatziargyriou, N., 2015. Review of hierarchical control in DC microgrids. Electr. Power Syst. Res. 122, 159–167.
Peyghami, S., Davari, P., Mokhtari, H., Loh, P.C., Blaabjerg, F., 2016a. Synchronverter-enabled DC power sharing approach for LVDC microgrids. IEEE Trans. Power Electron. 32 (10), 8089–8099.
Peyghami, S., Mokhtari, H., Blaabjerg, F., 2017. Hierarchical power sharing control in DC microgrids. In: Microgrid. Elsevier, pp. 63–100.
Peyghami, S., Mokhtari, H., Loh, P.C., Davari, P., Blaabjerg, F., 2016b. Distributed primary and secondary power sharing in a droop-controlled LVDC microgrid with merged AC and DC characteristics. IEEE Trans. Smart Grid 9 (3), 2284–2294.
Phommixay, S., Doumbia, M.L., St-Pierre, D.L., 2020. Review on the cost optimization of microgrids via particle swarm optimization. Int. J. Energy Environ. Eng. 11 (1), 73–89.
Prakash, P., Khatod, D.K., 2016. Optimal sizing and siting techniques for distributed generation in distribution systems: A review. Renew. Sustain. Energy Rev. 57, 111–130.
Prasad, A.A., Taylor, R.A., Kay, M., 2017. Assessment of solar and wind resource synergy in Australia. Appl. Energy 190, 354–367.
Punitha, K., Devaraj, D., Sakthivel, S., 2013. Artificial neural network based modified incremental conductance algorithm for maximum power point tracking in photovoltaic system under partial shading conditions. Energy 62, 330–340.
Rajesh, K., Dash, S., Rajagopal, R., Sridhar, R., 2017. A review on control of ac microgrid. Renew. Sustain. Energy Rev. 71, 814–819.
Ramesh, M., Yadav, A.K., Pathak, P.K., 2021. An extensive review on load frequency control of solar-wind based hybrid renewable energy systems. Energy Sources, Part A: Recovery, Utilization, Environ. Eff. 1–25.
Razmjoo, A., Shirmohammadi, R., Davarpanah, A., Pourfayaz, F., Aslani, A., 2019. Stand-alone hybrid energy systems for remote area power generation. Energy Rep. 5, 231–241.
Reihani, E., Eshraghi, A., Motalleb, M., Jafarzadeh, S., 2018. Frquency regulation of microgrid with battery droop control. In: 2018 IEEE/PES Transmission and Distribution Conference and Exposition (T&D). IEEE, pp. 1–5.
Rezaei, N., Mazidi, M., Gholami, M., Mohiti, M., 2020. A new stochastic gain adaptive energy management system for smart microgrids considering frequency responsive loads. Energy Rep. 6, 914–932.
Robert, F.C., Sisodia, G.S., Gopalan, S., 2019. Sustainable trade-off between reliability and electricity prices for geographically isolated communities. Energy Rep. 5, 1399–1407.
Saad, N.H., El-Sattar, A.A., Mansour, A.E.-A.M., 2018. A novel control strategy for grid connected hybrid renewable energy systems using improved particle swarm optimization. Ain Shams Eng. J. 9 (4), 2195–2214.

Sadabadi, M.S., Shafiee, Q., Karimi, A., 2018. Plug-and-play robust voltage control of DC microgrids. IEEE Trans. Smart Grid 9 (6), 6886–6896.

Sao, C.K., Lehn, P.W., 2008. Control and power management of converter fed microgrids. IEEE Trans. Power Syst. 23 (3), 1088–1098.

Saravanan, S., Babu, N.R., 2015. Performance analysis of boost & cuk converter in mppt based pv system. In: 2015 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2015]. IEEE, pp. 1–6.

Saravanan, S., Babu, N.R., 2016. Maximum power point tracking algorithms for photovoltaic system–A review. Renew. Sustain. Energy Rev. 57, 192–204.

Schiffer, J., Seel, T., Raisch, J., Sezi, T., 2016. Voltage stability and reactive power sharing in inverter-based microgrids with consensus-based distributed voltage control. IEEE Trans. Control Syst. Technol. 24 (1), 96–109.

Serban, I., Marinescu, C., 2014. Control strategy of three-phase battery energy storage systems for frequency support in microgrids and with uninterrupted supply of local loads. IEEE Trans. Power Electron. 29 (9), 5010–5020.

Serban, I., Teodorescu, R., Marinescu, C., 2013. Energy storage systems impact on the short-term frequency stability of distributed autonomous microgrids, an analysis using aggregate models. IET Renew. Power Gener. 7 (5), 531–539.

Shafiee, Q., Guerrero, J.M., Vasquez, J.C., 2014. Distributed secondary control for islanded microgrids—a novel approach. IEEE Trans. Power Electron. 29 (2), 1018–1031.

Shan, Y., Hu, J., Guerrero, J.M., 2020. A model predictive power control method for PV and energy storage systems with voltage support capability. IEEE Trans. Smart Grid 11 (2), 1018–1029.

Shaqsi, A.Z.A., Sopian, K., Al-Hinai, A., 2020. Review of energy storage services, applications, limitations, and benefits. Energy Rep..

Shoeiby, B., Davoodnezhad, R., Holmes, D., McGrath, B., 2014. A resonant current regulator based microgrid control strategy with smooth transition between islanded and grid-connected modes. In: 2014 IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems (PEDG). IEEE, pp. 1–8.

Siddaiah, R., Saini, R., 2016. A review on planning, configurations, modeling and optimization techniques of hybrid renewable energy systems for off grid applications. Renew. Sustain. Energy Rev. 58, 376–396.

Simpson-Porco, J.W., Shafiee, Q., Dörfler, F., Vasquez, J.C., Guerrero, J.M., Bullo, F., 2015. Secondary frequency and voltage control of islanded microgrids via distributed averaging. IEEE Trans. Ind. Electron. 62 (11), 7025–7038.

Sinha, S., Chandel, S., 2015. Review of recent trends in optimization techniques for solar photovoltaic–wind based hybrid energy systems. Renew. Sustain. Energy Rev. 50, 755–769.

Sinha, S., Ghosh, S., Bajpai, P., 2021. Power sharing through interlinking converters in adaptive droop controlled multiple microgrid system. Int. J. Electr. Power Energy Syst. 128, 106649.

Siraj, K., Khan, H.A., 2020. DC distribution for residential power networks—A framework to analyze the impact of voltage levels on energy efficiency. Energy Rep. 6, 944–951.

Skiparev, V., Machlev, R., Chowdhury, N., Levron, Y., Petlenkov, E., Belikov, J., 2021. Virtual inertia control methods in islanded microgrids. Energies 14, 1562.

Sulaiman, N., Hannan, M., Mohamed, A., Majlan, E., Daud, W.W., 2015. A review on energy management system for fuel cell hybrid electric vehicle: issues and challenges. Renew. Sustain. Energy Rev. 52, 802–814.

Tayab, U.B., Roslan, M.A.B., Hwai, L.J., Kashif, M., 2017. A review of droop control techniques for microgrid. Renew. Sustain. Energy Rev. 76, 717–727.

Tiwari, S.K., Singh, B., Goel, P.K., 2018. Design and control of microgrid fed by renewable energy generating sources. IEEE Trans. Ind. Appl. 54 (3), 2041–2050.

Topa Gavilema, Á.O., Álvarez, J.D., Torres Moreno, J.L., García, M.P., 2021. Towards optimal management in microgrids: An overview. Energies 14 (16), 5202.

Trinh, Q.N., Wang, P., Tang, Y., Choo, F.H., 2018. Mitigation of DC and harmonic currents generated by voltage measurement errors and grid voltage distortions in transformerless grid-connected inverters. IEEE Trans. Energy Convers. 33 (2), 801–813.

Tsao, Y.-C., Thanh, V.-V., 2021. Toward sustainable microgrids with blockchain technology-based peer-to-peer energy trading mechanism: A fuzzy meta-heuristic approach. Renew. Sustain. Energy Rev. 136, 110452.

Tuladhar, A., Jin, H., Unger, T., Mauch, K., 2000. Control of parallel inverters in distributed AC power systems with consideration of line impedance effect. IEEE Trans. Ind. Appl. 36 (1), 131–138.

Upadhyay, S., Sharma, M., 2014. A review on configurations, control and sizing methodologies of hybrid energy systems. Renew. Sustain. Energy Rev. 38, 47–63.

Urtasun Erburu, A., Sanchis Gúrpide, P., Marroyo Palomo, L., 2014. Small wind turbines sensorless mppt: robustness analysis and lossless approach. IEEE Trans. Ind. Appl. 50 (6), 4113–4121.

Vandoorn, T.L., De Kooning, J.D., Meersman, B., Vandevelde, L., 2012. Communication-based secondary control in microgrids with voltage-based droop control. In: PES T&D 2012. IEEE, pp. 1–6.

Vandoorn, T., De Kooning, J., Meersman, B., Vandevelde, L., 2013a. Review of primary control strategies for islanded microgrids with power-electronic interfaces. Renew. Sustain. Energy Rev. 19, 613–628.

Vandoorn, T.L., Meersman, B., De Kooning, J.D., Vandevelde, L., 2013b. Transition from islanded to grid-connected mode of microgrids with voltage-based droop control. IEEE Trans. Power Syst. 28 (3), 2545–2553.

Vandoorn, T.L., Meersman, B., Degroote, L., Renders, B., Vandevelde, L., 2011a. A control strategy for islanded microgrids with dc-link voltage control. IEEE Transactions on Power Delivery 26 (2), 703–713.

Vandoorn, T.L., Renders, B., Degroote, L., Meersman, B., Vandevelde, L., 2011b. Active load control in islanded microgrids based on the grid voltage. IEEE Trans. Smart Grid 2 (1), 139–151.

Vandoorn, T.L., Vasquez, J.C., De Kooning, J., Guerrero, J.M., Vandevelde, L., 2013c. Microgrids: hierarchical control and an overview of the control and reserve management strategies. IEEE Ind. Electron. Mag. 7 (4), 42–55.

Wan, Q., Zhang, W., Xu, Y., Khan, I., 2016. Distributed control for energy management in a microgrid. In: 2016 IEEE/PES transmission and distribution conference and exposition (T&D). IEEE, pp. 1–5.

Wang, F., Zhang, H., Zhou, A., 2021. A particle swarm optimization algorithm for mixed-variable optimization problems. Swarm Evol. Comput. 60, 100808.

Wei, C., Zhang, Z., Qiao, W., Qu, L., 2016. An adaptive network-based reinforcement learning method for MPPT control of PMSG wind energy conversion systems. IEEE Trans. Power Electron. 31 (11), 7837–7848.

Whittingham, M.S., 2012. History, evolution, and future status of energy storage. Proc. IEEE 100 (Special Centennial Issue), 1518–1534.

Wu, T., Bao, G., Chen, Y., Shang, J., 2018. A review for control strategies in microgrid. In: 2018 37th Chinese Control Conference (CCC). IEEE, pp. 30–35.

Wu, Y.-K., Lee, C.-Y., Liu, L.-C., Tsai, S.-H., 2010. Study of reconfiguration for the distribution system with distributed generators. IEEE Trans. Power Deliv. 25 (3), 1678–1685.

Xin, H., Zhang, L., Wang, Z., Gan, D., Wong, K.P., 2015. Control of island AC microgrids using a fully distributed approach. IEEE Trans. Smart Grid 6 (2), 943–945.

Xu, T., Zhang, N., 2016. Coordinated operation of concentrated solar power and wind resources for the provision of energy and reserve services. IEEE Trans. Power Syst. 32 (2), 1260–1271.

Xu, T., Zhou, J., Liang, L., Wu, Y., Cai, S., Liu, Z., Li, P., Yu, L., 2021. Consensus active power sharing for islanded microgrids based on distributed angle droop control. IET Renew. Power Gener..

Yamashita, D.Y., Vechiu, I., Gaubert, J.-P., 2020. A review of hierarchical control for building microgrids. Renew. Sustain. Energy Rev. 118, 109523.

Yan, H.W., Farivar, G.G., Beniwal, N., Gorla, N.B.Y., Tafti, H.D., Ceballos, S., Pou, J., Konstantinou, G., 2021. Control strategy for effective battery utilization in a stand-alone dc microgrid with solar energy. In: 2021 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE, pp. 1046–1051.

Yan, R., Saha, T.K., et al., 2015. A new tool to estimate maximum wind power penetration level: in perspective of frequency response adequacy. Appl. Energy 154, 209–220.

Yang, B., Yu, T., Shu, H., Dong, J., Jiang, L., 2018a. Robust sliding-mode control of wind energy conversion systems for optimal power extraction via nonlinear perturbation observers. Appl. Energy 210, 711–723.

Yang, B., Yu, T., Shu, H., Zhang, X., Qu, K., Jiang, L., 2018b. Democratic joint operations algorithm for optimal power extraction of PMSG based wind energy conversion system. Energy Convers. Manage. 159, 312–326.

Yao, W., Chen, M., Matas, J., Guerrero, J.M., Qian, Z.-M., 2011. Design and analysis of the droop control method for parallel inverters considering the impact of the complex impedance on the power sharing. IEEE Trans. Ind. Electron. 58 (2), 576–588.

Yazdanian, M., Mehrizi-Sani, A., 2014. Distributed control techniques in microgrids. IEEE Trans. Smart Grid 5 (6), 2901–2909.

Zhang, Q., Ding, J., Shen, W., Ma, J., Li, G., 2020. Multiobjective particle swarm optimization for microgrids pareto optimization dispatch. Math. Probl. Eng. 2020.

Zhang, G., Jin, Z., Li, N., Hu, X., Tang, X., 2014. A novel control strategy for parallel-connected converters in low voltage microgrid. In: 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific). IEEE, pp. 1–6.

Zhang, J., Wang, Q., Hu, C., Rui, T., 2017. A new control strategy of seamless transfer between grid-connected and islanding operation for micro-grid. In: 2017 12th IEEE Conference on Industrial Electronics and Applications (ICIEA). IEEE, pp. 1729–1732.

Zhao, Z., Xun, J., Wan, X., Yu, R., 2021. Mpc based hybrid electric vehicles energy management strategy. IFAC-PapersOnLine 54 (10), 370–375.

Zhong, Q.-C., 2013. Robust droop controller for accurate proportional load sharing among inverters operated in parallel. IEEE Trans. Ind. Electron. 60 (4), 1281–1290.