Evolution of Microgrids with Converter-Interfaced Generations: Challenges and Opportunities

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Abstract: Although microgrids facilitate the increased penetration of distributed generations (DGs) and improve the security of power supplies, they have some issues that need to be better understood and addressed before realising the full potential of microgrids. This paper presents a comprehensive list of challenges and opportunities supported by a literature review on the evolution of converter-based microgrids. The discussion in this paper presented with a view to establishing microgrids as distinct from the existing distribution systems. This is accomplished by, firstly, describing the challenges and benefits of using DG units in a distribution network and then those of microgrid ones. Also, the definitions, classifications and characteristics of microgrids are revised according to their specific roles to provide a sound basis for novice researchers to undertake ongoing research on microgrids.

Keywords: Converter-based microgrids; distribution networks; renewable energy sources; definitions of microgrids; distributed generation units

1. Introduction

Currently, there is a shift in power generation from conventional energy sources to renewable ones for a number of reasons. These include mitigating the effects of climate change and the gradual depletion of energy sources (coal, gas and oil), dealing with the steadily increasing consumption of energy, satisfying the need for local economic and social development, reducing power losses over long transmission lines and decreasing the amount of investment required to construct new power transmission lines [1,2]. Figures 1a and 1b depict investments in solar and wind power, and their integration in generating power around the world [3]. Figure 1a shows that, until 2009, greater priority was given to investing in wind than solar power generation. However, since then, the trend has been reversed. These renewable energy sources (RESs) connecting to a distribution network with the help of power electronic converters (PECs) can provide alternative power sources to traditional ones. The high penetration of RESs in an existing distribution network may lead to concerns regarding the reliability and stability of the system due to the stochastic nature of their power generation and load demand [4]. These difficulties for the grid utility to control distributed resources can be minimised by logically partitioning a distribution network into zones with individual identities. When these smaller networks are capable of regulating their own regions without the help of the grid utility, which is possible because of their own control units there, they are identified as microgrids. Then, they can form clusters from the grid perspective and the management
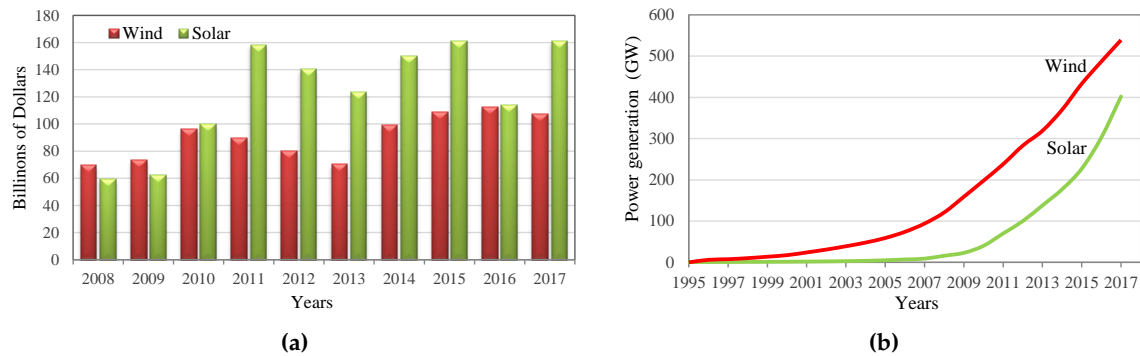
Figure 1. Wind and solar power: (a) global investment and (b) worldwide power generation.

of the entire distribution network as microgrids overcomes the challenges, limiting the integration of RESs into distribution systems. Therefore, a better understanding of how these sources interact with distribution networks and how converter-based microgrids are evolving to solve these issues is required.

There is a number of literature review on microgrids from different perspectives, including components, controls, assessments and policies. In [5], different multilevel converters with newer topologies for the application of RESs, namely wind and solar, are presented. Some recently developed control strategies (inner-loop and primary) for operating them in an effective and efficient way, together with their relative advantages and disadvantages, are documented in [4]. Adaptive and intelligent control methods for achieving microgrid stability and reliability are discussed in [6]. The stability of a microgrid based on the features of its components is assessed in [7]. In [8], a multi-agent system (MAS) for microgrid control and optimisation is reported. The basic structures of multi-microgrids with key technologies from the perspectives of voltage-grade classification as well as phase-sequence and ac/dc constitutional forms are discussed in [9]. In [10], microgrids are classified in terms of a hierarchical organisational scheme. The influence of government policy on the implementation of microgrids from the economic perspectives is presented in [11]. In [12], the parameters of typical ac and dc microgrids are described, and some of the issues involved in their implementation and development are presented for the selection of a suitable configuration of a microgrid.

While there are many research or review papers on the control, operation and management of microgrids [4–11,13,14], there is a gap in terms of identifying the definition and characteristics of converter-based microgrids and all their possible related challenges and opportunities to distinguish them from distribution networks. To bridge this gap, this paper offers the following contributions. As well as an updated review of the different issues concerning microgrids, the definitions and characteristics of state-of-the-art converter-based microgrids revised according to their specific roles are presented. The most distinguishing feature of this paper is a comprehensive analysis that differentiates a microgrid from a distribution network considering all possible issues to avoid the confusion that often arises regarding microgrid terms. Also, the very early developments of power systems and then the most advanced ones are discussed, with future possible research trends highlighted to assist novice researchers.

The rest of this paper is organised as follows. Section 2 briefly describes the development from traditional to modern power systems. In Section 3, the advantages and disadvantages of using DG units in a distribution network are discussed. Section 4 presents the evolution, classifications, characteristics and definitions of microgrids, and also discusses their future challenges and opportunities. In Section 5, future trends in microgrids for upcoming researchers to advance the field is stated. Section 6 draws the conclusion.
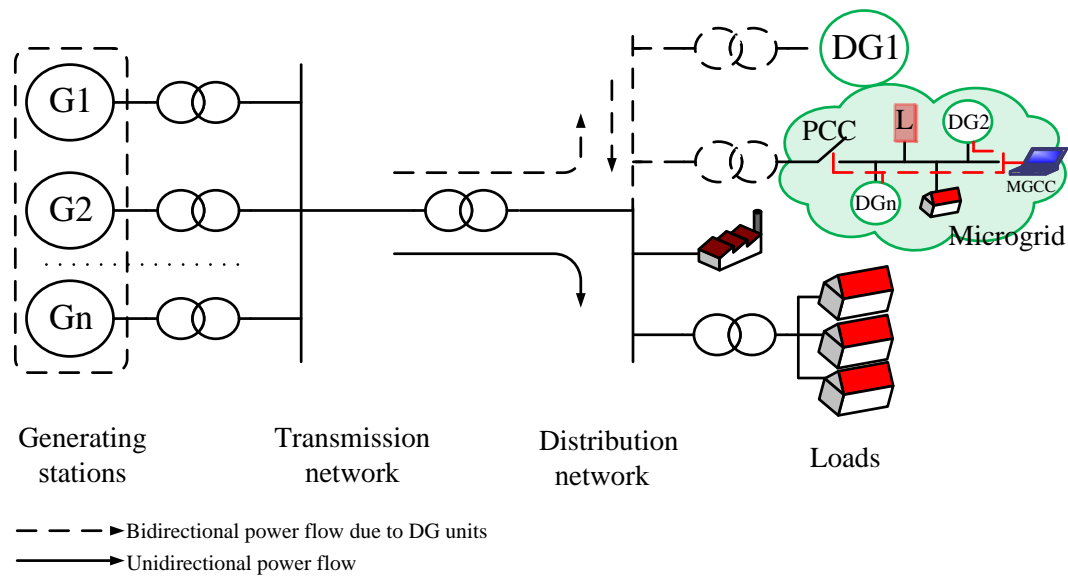
Figure 2. Evolution from traditional to modern power systems.

2. Background of modern power system

In the early stages of electricity generation, generators were placed near the premises that consumed the power produced. With the increasing demand for electricity, the disadvantages of this approach became apparent, and it led to the evolution of centralised power systems. A centralised power generation station were installed to minimise costs and improve the security of supply [15]. Prior to the 1990s, attempts to build increasingly larger power stations for financial benefits involved these stations being located either near fuel sources or in remote places for safety reasons. This indicates they were further away from the point of power consumption both electrically and geographically. Generally, in a large power station, a fossil fuel (coal, gas or oil) is burnt in a furnace to produce high-pressure steam which strikes a turbine's blades and rotates them, eventually causing a large synchronous generator to produce electricity in bulk (100 MW to 1 GW). Then, the voltage of the generated power is stepped up by a transformer to a high-voltage (HV) to send the electricity long distances through transmission networks to substations where the voltage is stepped down to a medium and/or low-voltage (MV and LV, respectively) to reach end-users through distribution networks [16], as shown in Figure 2. Therefore, the generated electricity flows through transmission lines from large generation points to distribution points, i.e., it is a unidirectional (radial) power flow.

Since the 1990s, the construction of larger power systems has been discouraged for several reasons, including their increasing CO_2 emissions, being energy deficient, lacking security of supply and incurring transportation losses [17,18]. Now, most governments provide financial incentives for the exploitation of renewable energy-based power generation, the generators for which are, by nature, smaller than conventional ones. Therefore, small-scale power generators driven by RESs are increasingly being directly connected to distribution networks whereby consumers have direct access to electricity generation. These small-scale units are defined as distributed generation (DG) units.

Incorporating DG units in a distribution network represents a fundamental change from a traditional power system as the resultant power flow is bidirectional as shown in Figure 2. Although these units are based mainly on RESs, such as solar and wind generators, they can rely on other sources, such as micro-turbines, gas turbines, fuel cells, biogas and combined heat and power (CHP) units [19–21]. DG units driven by RESs have demonstrated significantly increased electricity generation over the last two decades [22], as shown in Figure 1b. The integration of these sources in a distribution network demonstrates both merits and demerits for the existing power system.

3. Benefits and challenges of using DG units in distribution networks

3.1. Benefits of using DG units

DG units, which are small generators, offer numerous advantages compared with conventional large power plants. Some of their key features described in the following subsections emphasise the importance of current research [23–28].

Reliable electricity supply: As explained in Section 2, in a traditional power system, a generator produces bulk power (500 MW) in one place and transmits it to other places (end-users, i.e., consumers) to service a large community. On the other hand, a DG unit, the rating of which is typically low (less than 5 MW), produces electricity and services for a local small community. In the case of the failure of a 500 MW generator, the system needs to either produce an extra 500 MW of power from reserve units or shed a 500 MW load to save the system from a cascading generator shutdown. In contrast, power failures in DG units have less impact on the system and are often manageable because of the small-scale power generation [24].

Reduced transmission losses: Electrical power flows from a power station to consumer premises through transmission lines which have inherent resistance and reactance that cause them to lose power. If 142 A current flows through a line, a $0.642\,\Omega\,km^{-1}$ resistance in a line leads to a $12.95\,kW\,km^{-1}$ loss. Installing DG units near consumer premises can minimise I^2R losses which improves network efficiency [25].

Reduction in feeder capacity: The gradually increasing demand for power as a result of the desire to maintain high living standards for an increasing population necessitates changing the components of a power system used in transmission lines. The penetration of DG units in a distribution network reduces stresses on both transmission line equipment and distribution lines at times of peak demand [26]; for example, as patterns of daily office loads are more or less similar to the generation of solar power, the need to import power from the grid is avoided which places less stress on transmission lines. Therefore, using DG units, which encourage more load participation in a distribution network, can be more economical than upgrading a network's components.

Integration of RESs: The majority of DG technologies used in a network are based on RESs which have abundant input power and do not emit CO_2, i.e., they are environmentally friendly. Installing DG units around load centres provides an enhanced voltage profile and better power quality [27]. Research on DG technology is gradually reducing their production costs and increasing the power conversion efficiency of DG units, thereby leading to their being attractive choices for future power generation.

3.2. Challenges of implementing DG units

Conventional electricity structures have accommodated the installation of DG technologies in a distribution network although this can affect various quantities of a power system, such as its voltage profile and power flow. Important concerns regarding power quality, changes in a network's voltage and fault levels, system stability, modelling of networks' components and low inertia for the operation of DG units in a distribution network are briefly discussed in the following subsections.

Power quality: The power quality of a distribution network can be altered by the penetration of DG units which, if operated based on RESs, may lead to problems such as voltage fluctuations, harmonic distortions, frequency deviations and voltage flickers [29]. This is because the variable outputs of DG units cause reverse power flows, and the use of many PECs produces harmonics in the injected power. Also, the connection and disconnection of a DG unit to/from a network may cause transient currents which lead to a high-magnitude voltage [30]. Voltage flicker can be minimised by imposing constraints on how and when DG units change their outputs while a great deal of attention has been paid to increasing the power quality of a network during voltage disturbances [31,32]. The power quality of a distribution network can be improved in several ways, including by applying
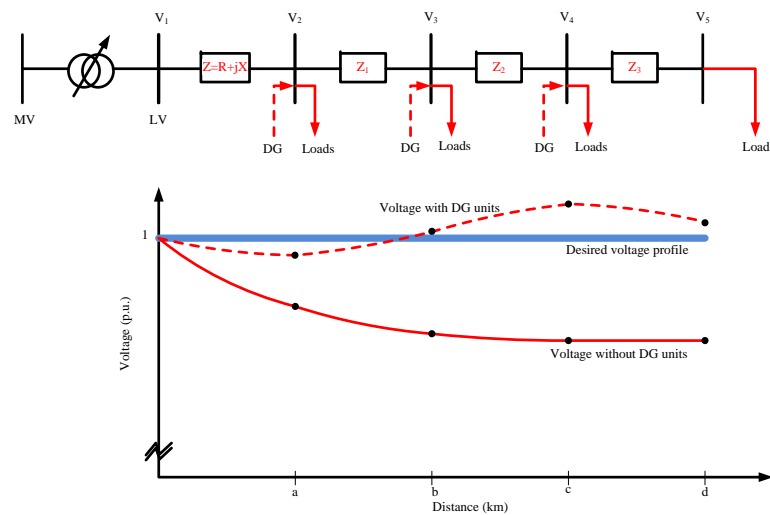
Figure 3. Impact of DG integration on voltage profile of a radial distribution network.

better control strategies for the inner-current control of converters, designing filters for interfacing converters, applying compensators and installing flexible alternating current transmission systems (FACTS) devices in networks [33,34].

Power quality is generally enhanced by the installation of devices at customers' supply points, such as a series compensator (dynamic voltage restorer (DVR)), a shunt compensator (distribution static synchronous compensator (DSTATCOM)), and hybrid series and shunt compensators (unified power quality conditioner (UPQC)). A series compensator is employed for voltage-related issues and a shunt compensator for minimising current-related ones, such as the effects of an imbalance, harmonics and the power factor. A dual-tree complex wavelet transform-based control algorithm for a DSTATCOM to enhance power quality in a distribution network is presented in [34]. The total harmonic distortion (THD) in this method is less than 5 % with the application of various load conditions under the unity power factor. A 20-pulse multiphase staggering autoconfigured transformer (MSAT), a combination of delta and zig-zag transformers, to improve power quality in MV and high power applications is discussed in [35].

Change in network voltage: The main function of a DG unit is to supply power within acceptable voltage ranges to customers. Although the standards for voltage profiles vary from country to country, their operating principles are the same as that of radial feeders which are generally arranged in such a way that the power flow is unidirectional, i.e., the power flows from the generator to the load. As a result, a poor voltage profile as shown in Figure 3 is observed at the most remote node because of the voltage drop in impedance along the radial lines. This problem can be minimised by inserting DG units directly into a network; however, this causes a bidirectional power flow along the lines that require complex protection schemes for the network [36]. If the impact of these variations in a radial network is significant, the locations, sizes and impedances of these units must be appropriately measured [36].

The insertion of DG units can also vary the voltage profile due to the intermittency of the power generated by RESs, especially on cloudy days or at times of low wind velocity, with a voltage collapse possibly leading to a complete interruption of power [37]. To inject or absorb reactive power in a network, shunt capacitor banks and static var compensators (SVCs) or FACTS devices need to be placed at optimal positions in the network [38]. Due to smaller size and faster response, a static synchronous compensator (STATCOM) is preferable to a SVC. In [39], a survey of the literature is presented on the optimal allocation of a D-STATCOM in a distribution network. The real-time control of multiple custom power devices (CPDs) using STATCOM and active power line conditioner (APLC)

Table 1. Typical line parameters.

Type	R[Ω/km]	X[Ω/km]	I_N (A)	R/X
LV	0.642	0.083	142	7.73
MV	0.161	0.190	396	0.85
HV	0.060	0.191	580	0.31

to improve voltage regulation in a distribution network are demonstrated in [37]. In this strategy, two particle swarm optimisation (PSO) algorithms are implemented to obtain the optimal sizing/siting and online control of multiple CPDs. In [40], the operational performance of a low-capacitance cascaded H-bridge STATCOM is optimised to minimise switching losses.

Change in network fault level: A distribution network containing DG units is an active network in which the power and extra current can flow in a reverse direction toward the fault side [41], with all types of DG units assisting in increasing the fault level. Although synchronous and induction generators are capable of supplying a fault current, inserting DG units can alter the fault level. Then, if all the associated protection apparatuses are upgraded to maintain the equivalent fault level, costs will increase. Although involvement of the fault level can be restricted by using an appropriate impedance, this technique augments power losses and voltage changes [42].

A robust and versatile algorithm for over-current protection considering changes in power generation and demand is described in [43]. Faults are detected by studying abrupt changes in the current's magnitude using a multi-stage morphological fault detector (MFD). In [44], a hardware-in-loop (HIL) adaptive protection scheme capable of addressing the DG effect by providing a flexible protection solution is introduced. As an adaptive protection scheme depends on communication lines to adjust the relay setting, a communication failure becomes a major threat to its security. Such a scheme that takes into account a super-capacitor's energy to improve resilience against communication failure is presented in [45]. In [46], a current limiting-approach and generalised fault model for enhancing the fault ride-through capability of droop-controlled converter-interfaced DG units are presented. A dc-link adjustable resistive type of fault current limiter for improving the fault ride-through capability of a voltage-source converter (VSC) is presented in [47,48].

System stability: An interconnected power system, which is generally large, creates complex networks in which different factors, including uncertainties in power generation and demand, can lead to instability. As power generations from RESs highly reliant on weather conditions, several transient disturbances, which are more complex and distributed than the existing ones, including a loss of power generation or system components as well as faults, increase in a distribution network.

The stability of a network is generally concerned with its transient stability, ability of a system to return back to its steady state when subjected to a large disturbance. In [49], the transient stability in Dutch 10 kV distribution network with micro-turbines, CHP plants, and wind generators is analysed. It is concluded that DG units have transient stability issues in a network which should be taken into account during their integration. A projective integration method considering a high penetration of DG units for the improvement of the transient stability of a distribution network is described in [50]. In [51], the effect of a network's transient stability on its reliability during dynamic contingencies is assessed using a direct method. A robust transient stability-constrained optimal power-flow model that takes into account uncertain variations in the model's parameters and dynamic loads is presented in [52]. A fuzzy-based damping controller that uses the frequency to control the firing angle of a thyristor-controlled series capacitor to enhance the damping of electromechanical oscillations in a distribution network is presented in [53]. The effects of a power system stabiliser and oscillation modes of a distribution network are studied in [54].

Modelling of network's components: Generally, the dynamic behaviours of a power system are analysed by using time-varying phasor models (quasi-static models), often by means of

Table 2. Comparison of different models [65].

Model	Operating point	Small-signal	High frequency	Non-symmetric network
Time-varying phasors	Yes	Yes	No	No
Dynamic phasors	Yes	Yes	–	–
abc	No	No	Yes	Yes
*dq*0	Yes	Yes	Yes	No

network power flow equations, that assume the frequency of signals is approximately constant [55]. Consequently, models are time-invariant, with a well-defined operating point that facilitates the power system study. However, due to increasing penetration of RESs into an existing distribution network, it becomes complex to observe the dynamic behaviours. This is because of the introduction of power electronics, involved with harmonics in voltage and current signals that may exhibit fast amplitude and phase variations [56]. As a result, the system may not be quasi-static in many cases. To facilitate the analysis, several alternative models, including dynamic phasors, *abc* and *dq*0 reference frame models, are developed [57]. In dynamic phasors, voltage and current signals are represented by Fourier series expansions that evaluate harmonic components over a moving time window [57,58]. It approximates the system with nearly periodic quantities [59]. Different dynamic phasor based models of a power system are demonstrated in [57]. The time-based model using the *abc* reference frame is often used in power systems for the application of unbalanced networks, where frequency is not constant. In *dq*0-based models, the symmetric electrical quantities are mapped into constant values. The assumption of quasi-static states is not required in this model, and it can work at high frequencies [60]. A number of studies are presented based on *dq*0-based models for analysing the network's dynamics [61–64]. A comparison among different models is shown in Table 2.

    Low inertia: In a conventional generator, the inertia as an energy – a form of kinetic energy stored in a rotating mass of a synchronous generator – can support regulation of the network's frequency and voltage up to 10 seconds during disturbances that lead to a generation-demand imbalance [66]. This inertia energy basically minimises the impact induced from disturbances within the time frame, whereas other controllers take initiatives after this step. However, the increasing penetration of converter-fed RESs that have non-existent or lower inertia characteristics than synchronous generators reduces the inertia of an entire network, leading to voltage or frequency fluctuations during an event [67,68]. If appropriate control measures are not applied to minimise these fluctuations within specified limits, the network may experience instability [69]. Several control strategies that realise the role of inertia in a network have been developed from different perspectives; for example, in a solar generator, the operating point of a PV voltage can be increased beyond the maximum power-point voltage to enable the reserve power to act as an inertia energy during frequency or voltage fluctuations [70]. In the case of a variable-speed wind generator, the rotor's speed and blades' pitch-angle controls can be used to reserve the inertia power to respond to any change in the network [71]. Also, the kinetic energy of rotating blades can be released using an appropriate control strategy for converters to respond in frequency deviations up to 2–6 s [72]. Although these techniques, called de-loadings, can reserve some energy at the expense of constant energy losses to emulate inertia behaviour, they may still cause reliability issues due to their reliance on the variable factors of RESs.

    To improve the reliability of a network, its low inertia can be enhanced by using batteries, capacitors and flywheels at the dc busbars of its interfacing converters. A battery can be regarded as a reserve energy source that responds to a network's requirements, i.e., it can store or release energy according to the power demand. In [73], an ESS used as an inertia energy to regulate the frequency of a microgrid has the capability to seamlessly transfer. A capacitor employed to decouple a converter's input power from the boost converter's output can be used as an inertia of the converter to control the terminal voltage [1]. In order to apply the well-established conventional control algorithms/theories to converter-interfaced generators, the concept of a synchronverter, which mimics the behaviours of

Table 3. Comparison of microgrids and modern distribution networks.

Descriptions	Microgrids	Distribution networks	Descriptions	Microgrids	Distribution networks
Central control unit	Yes	No	Power supply security	Yes	No
Specific areas	Yes	No	Monitoring system	Yes	No
Point of common coupling	Yes	No	Stability	High	Low
Categorising loads	Yes	Yes	Storage system	Yes	Yes/No
Communication with grid	Yes	Yes	Dynamic electricity prices	Yes	Yes/No
High penetration of RESs	Yes	No	Self-healing system	Yes	No
Adequate protection	Yes	Yes	Systematic structures	Yes	No
Seamless transfer	Yes	No	Flexible operation and management	Yes	No
Decentralised control system	Yes	Yes	Uninterruptible power supply	Yes	No
Systematic energy exchange	Yes	No	Controllable and coordinated mode	Yes	No
Communication facilities	Yes	Yes	Low environmental impact	Yes	Yes/No
Power outage	Low	High	Grid modernisation enabled	Yes	No
Improved power quality	High	Low	Integration enhanced	Yes	No
Reliability	High	Low	End-user needs met	Yes	Yes
Supplementary power	Yes	No	Plug-and-play	Yes	No
Optimum power management	Yes	No	Local power management	Yes	No
Resilience of power supply	Yes	No			

conventional synchronous ones over short periods of time for the integration of RESs in a distribution network, is proposed in [74]. The amount of inertia depends on the size of the virtual moment of the synchronverter's inertia with capacitors typically used to mimic it. However, to obtain a better performance that resists the intermittency of RESs, relatively large storage is preferable. An improved synchronverter that limits its voltage and frequency to within acceptable ranges is presented in [75]. In [76], algorithms for a synchronverter are modified to include the virtual field current, virtual filter inductors, (virtual) nominal active mechanical torque and virtual capacitors to enhance its performance and stability, and bring the inverter's characteristics much closer to those of synchronous machines. The hybrid use of a battery and ultracapacitor, where the latter handles high-frequency and the former low-frequency power fluctuations to implement a virtual synchronous generator, presented in [77] reduces power fluctuations. Researchers have still opportunities to improve the inertia response by the application of novel control strategies and algorithms, and the design of hybrid energy storage systems(ESSs).

4. Microgrids

4.1. Evolution of microgrid concept

To exploit the benefits of integrating DG units and overcome the issues related to the management of a network's components – DG units, loads and other equipment – from a grid utility perspective because of their multi-dimensional activities, the concept of a microgrid has evolved [78]. The word 'microgrid' is comprised of 'micro' (an extremely small attribute from the perspective of a grid utility) and 'grid' (a network of electric lines). Therefore, it is expected that microgrids will possess all the essential components of a power system in a small range, except some unnecessary equipment, such as transmission lines and substations. The core idea of a microgrid is to integrate a limited number of DG units to optimally control DG units without creating a complex network. Its major components are a hierarchical control approach, a point of common coupling (PCC), distributed controls using local information and a specific region that enable DG units to be integrated in a systematic way to ensure reliable operation of the system. As it consists of DG units, loads, energy storage elements, protection equipment and a control scheme, all of which ensure the regulation of the power flow, and voltage and frequency profiles within a defined region, it could be called a 'distribution network control' approach. However, as this description does not cover any specific region, it is not appropriate. Therefore, the integration of DG units in a distribution network to export power cannot be considered a microgrid unless it has control over the network within a defined region. The microgrid concept and distribution network are depicted in Figures 4 and 5, respectively, and their relative features presented in Table 3. One important point is that encouraging
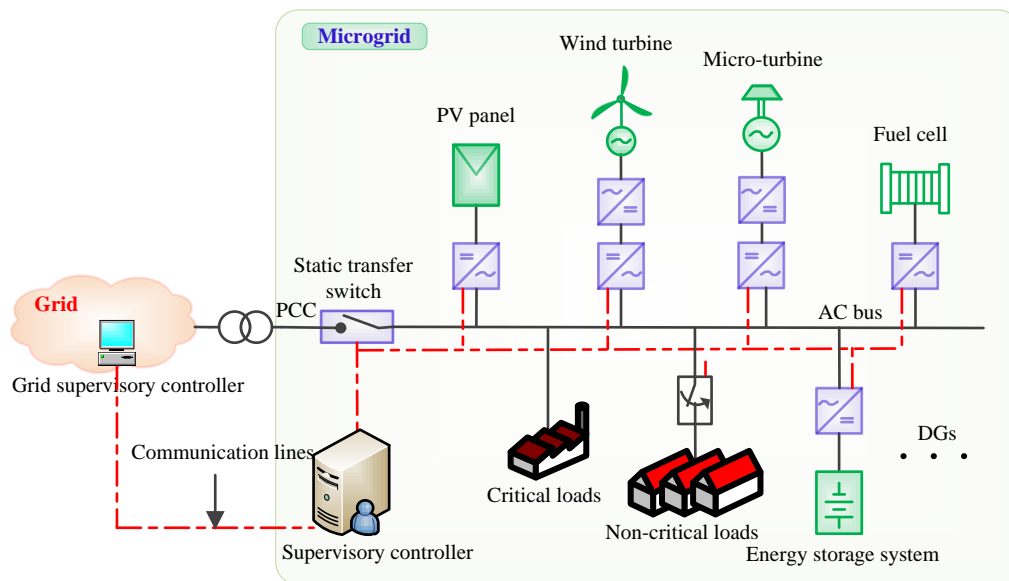
Figure 4. Concept of microgrid.

the construction of microgrids is not contrary to using a conventional power system but, rather, supplementary to a grid utility.

To obtain good services from a grid utility and DG units, microgrids are connected to the utility through a static transfer switch (STS) at the PCC. This approach provides control of the participating equipment within a defined region and enables the microgrid to be considered a single dispatchable unit from the grid perspective. An individual owner of a microgrid can both supply power to a grid utility if the microgrid has excess power and receive power if necessary. In a microgrid, generators deliver power at a certain voltage level during parallel operation with the grid utility and provide sufficient power to, at least, critical loads. Ensuring a reliable power supply for certain loads is the most important priority of a microgrid.

A microgrid can be disconnected during a period of deteriorating power quality or network contingencies without affecting the local power supply. A degradation in power quality may occur during a violation of the voltage limit of sensitive loads because, if the voltage quality hampers the equipment's operation, only local DG units can supply power to these loads. When, as an entity, a microgrid faces an unbalanced power supply, it can intentionally island itself from the grid utility to retain the power quality required for sensitive loads. This capability is effective for providing an uninterruptible power supply (UPS) to sensitive loads, not only when there is a loss of the main power supply and/or a grid failure but also during a period of the power degradation. A microgrid can be installed in any industrial area, official building, commercial centre or residential complex to receive UPS services.

Over the last decade, microgrids have attracted the attention of industry leaders and researchers, with some research projects shown in Tables 4 and 5. Many of these were developed for test beds around the world; for example, the Consortium for Electric Reliability Technology Solutions (CERTS) in the United States of America (USA); the New Energy and Industrial Technology Development Organization (NEDO) in Japan; and The Institute for Systems and Computer Engineering, Technology and Science (INESC TEC) in Europe [79,81,82]. Some were implemented by governments to provide secure, clean and efficient energy; for example, in the USA, the Department of Energy spent 6.3 billion USD in the fiscal year 2012 on research, deployment and development activities related to clean energy [80].

Table 4. Some global projects involving converter-based microgrids [79].

Name/Place	Organisation/Institution	DG	Type	Load
Aichi/Japan	NEDO	PV, Fuel Cell and Battery	AC	Industrial and Commercial
Albuquerque/US	NEDO	PV and Battery	AC	Residential/Commercial
Benchmark Low-voltage/Greece	Microgrids Project	PV, Wind, Fuel Cell, Flywheel and Battery	AC	Residential
Barcelona/Spain	IREC	PV, Wind, EV and Battery	AC	HVAC, Air Conditioners
Borrego Springs/US	San Diego Gas & Electric	PV, EV and Battery	AC	Residential and Industrial
California/US	Santa Clara University	PV and Wind	AC	University
Chicago/US	Illinois Institute of Technology	PV, Wind, EV and Battery	AC	–
Chico Mendes/Brazil	Electrobas	PV and Battery	AC–DC	–
Continuon Holiday Park/Netherlands	More Microgrids Project	PV and Battery	AC	Residential
FIU Testbed/US	Florida International University	PV, Fuel Cell, Wind and Flywheel	DC	Residential and Motor
Fukuoka/Japan	Smart Energy Laboratory	Wind, PV and Battery	DC	–
Gazi University/Turkey	Gazi University	PV, Wind and Battery	AC	University
Hawaii Hydrogen Power Park/US	Hawaii National Energy Institute	PV, Wind and Fuel Cell	DC	Residential
Ilha da Ferradura/Brazil	–	PV and Battery	AC	–
Kyoto Eco Energy/Japan	NEDO	PV, Wind, Fuel Cell, Biogas and Battery	AC	Residential
Laboratory scale MG Testbed/US	New Jersey Government	PV and Battery	AC	Residential and Motor
Los Alamos/US	NEDO	PV and Battery	AC	Residential
Lyon/France	NEDO	PV and EV	AC	–
Manzanita Hybrid Power Plant/US	–	Wind, PV and Battery	AC	–
Nanjing University/China	Nanjing University	PV, Wind and Battery	AC	Motor
RIT Microgrid/US	Rochester Institute of Technology	PV, Fuel Cell and Wind	AC	Residential and Motor
Sino-Danish Project/China	Aalborg University/Tsinghua University	PV, Wind and Battery	AC	–
UTC/France	University of Technology of Compiègne (UTC)	PV, Fuel Cell and Battery	DC	Motor
NTUA/Greece	National Technical University of Athens (NTUA)	PV, Wind and Battery	AC	–
University of Nottingham/England	University of Nottingham	Wind and Battery	DC	Residential
University of Miami Testbed/US	University of Miami	PV, Fuel Cell and Battery	DC	University Residential
Woodstock/US	National Renewable Energy Laboratory	PV, Wind and Battery	AC	Shop and Office
Xcalak/Mexico	–	Wind and Battery	DC	Village

Table 5. Some research projects conducted on microgrids [80].

Project Title	Budget	Duration	Promoter
CERTS	12.2 M USD	from 1999	US
More Microgrids	8 M €	2006 to 2010	EU
IDE4L	8 M €	2013 to 2016	EU
Microgrids	4.5 M €	2003 to 2006	EU
Positas Microgrid	1.5 M USD	from 2015	US
Microgrid - Alstom	1.2 M USD	from 2014	US
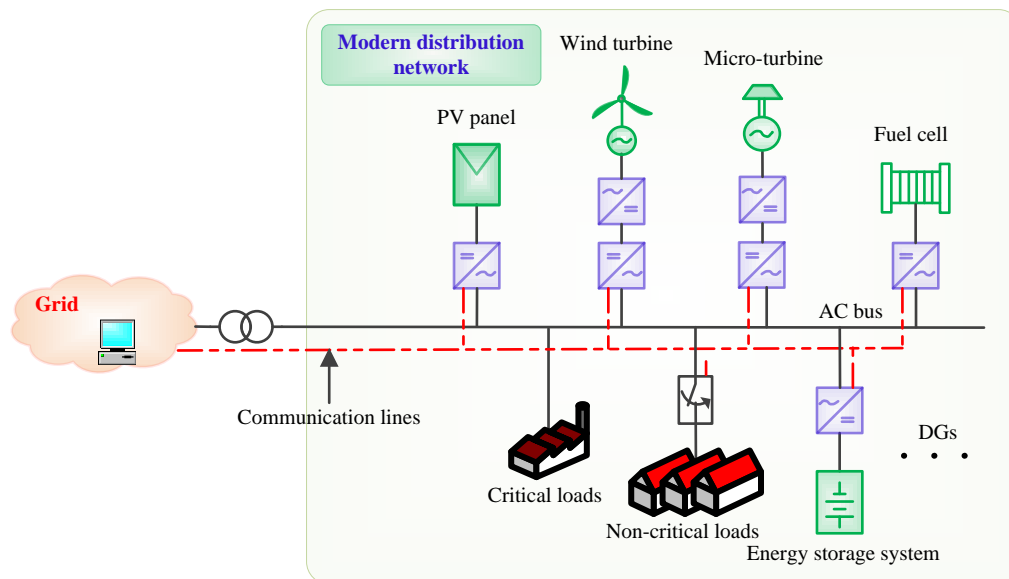
Figure 5. Modern distribution network.

4.2. Characteristics of Microgrids

A microgrid has the following characteristics which distinguish it from DG units applied in a distribution network [78,83–89].

- It supervises the electrical components, such as powers, voltages and frequencies, by means of monitors.
- It has a PCC in a distribution network for connecting and disconnecting the grid utility.
- It is a subset of LV or MV distribution networks.
- It consists of generation units, a hierarchical control approach, power consumption places and ESSs.
- It facilitates an UPS to, at least, the highest priority loads during a grid failure or power quality degradation.
- It has two operating modes: 1) grid-connected; and 2) islanded or standalone (autonomous).
- It acts as a single controllable entity from a grid perspective.
- It generates the required reference voltage and frequency in an islanded operation.
- It is constructed in a defined location which can be in a distribution network or remote area.
- It has the necessary protection schemes.
- It controls the power supply during both grid-connected and islanded operations.
- It accumulates DG units, the ratings of which are less than 100 MW.
- It displays 'plug and play' features and 'peer-to-peer' functionality.
- It adjusts to abnormal situations (unintentional islanding or faults).
- It uses local information to control the power flow of DG units.
- It can possess ac and/or dc distribution networks.
- It may provide electrical energy and thermal energy (hot and/or cold) simultaneously.

4.3. Definitions of microgrids

According to [78], a microgrid is a subsystem consisting of generation and associated loads that uses local control to facilitate its connection and disconnection to/from with the main grid in order
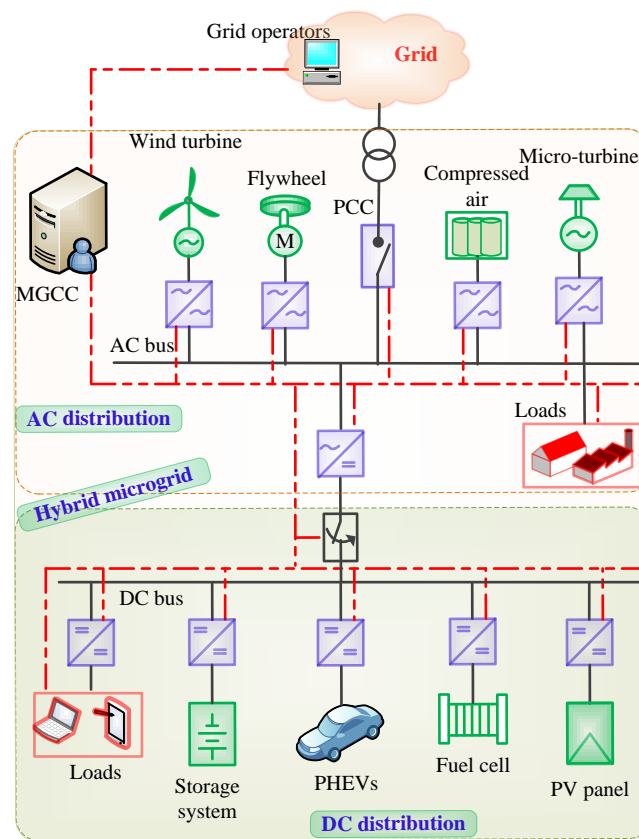
Figure 6. Hybrid microgrid.

to maintain a standard service during disturbances without harming the integrity of the transmission grid.

According to [83], a microgrid is a possible future energy system paradigm formed by the interconnection of small, modular generation units (micro-turbines, fuel cells, PV, etc.), storage devices (flywheels, energy capacitors and batteries) and controllable loads in LV distribution systems. Such systems can be operated interconnected to the power grid, or islanded, if disconnected from the grid.

In [84], a microgrid is defined as a cluster of distributed resource units and loads serviced by a distribution system which can operate in a 1) grid-connected mode, 2) islanded (autonomous) mode, and 3) a ride-through process between these two modes.

According to the U.S. Department of Energy Microgrid Exchange Group [85], a microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. It can connect to and disconnect from the grid to enable it to operate in both grid-connected and islanded modes.

CIGRÈ C6.22 Working Group in Microgrid Evolution Roadmap [86] describes microgrids as electricity distribution systems containing loads and distributed energy resources (such as distributed generators, storage devices and controllable loads) that can be operated in a controlled, coordinated way either when connected to the main power network or islanded.

All the above definitions agree on the one point that a microgrid can be operated in either a grid-connected or an islanded mode in a defined area to act as a controllable entity. However, these definitions do not mention a control unit for facilitating the system's features, such as seamless transfer, and working as a supplementary power supply during an islanded operation. Also, they
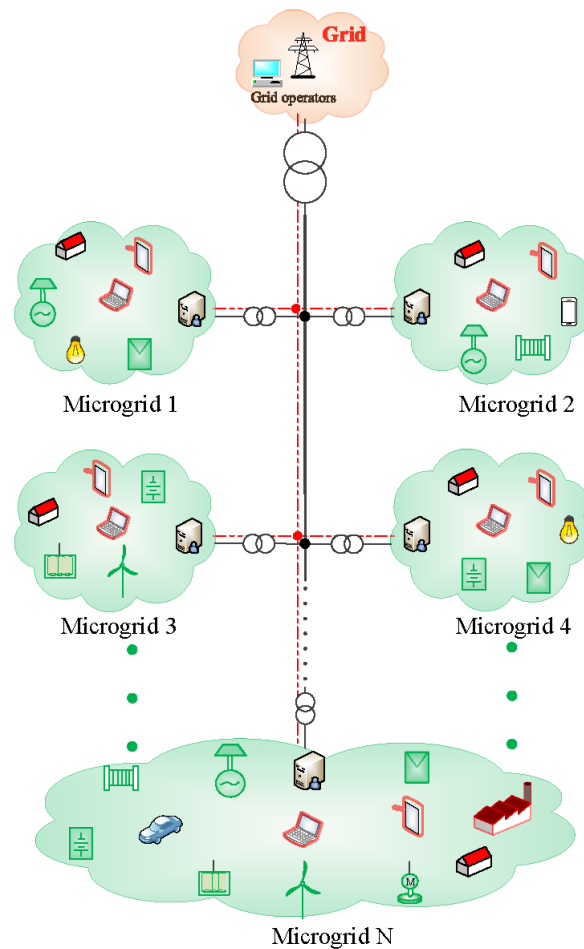
Figure 7. Concept of multi-microgrid.

may not be appropriate for an islanded microgrid with converter-interfaced generators that need a central control unit to obtain second-to-second power balancing and optimal use of these sources.

Based on the above definitions and characteristics, in this paper, a microgrid is defined as follows. *A microgrid (consisting of small-scale emerging generators, loads, energy storage elements and control units) is a controlled small-scale power system that can be operated in an islanded and/or grid-connected mode in a defined area to facilitate the provision of supplementary power and/or maintain a standard service.*

Its control unit, which is the main part of a microgrid, facilitates a systematic approach for obtaining a high penetration of RESs and reliable power supply through central regulation policies/algorithms. Although this approach basically distinguishes between a microgrid and distribution network, there are some confusing terms regarding microgrids in the literature. One of these is a hybrid microgrid, which is often used in literature to indicate a combination of different types of DGs (diesel, PV, wind and battery) [90–93]. However, this cannot be considered as a hybrid microgrid because a microgrid itself consists of these DGs by definitions. Some other incorrect terms are CCHP microgrid, standalone PV microgrid, hybrid PV—CSP-–LPG microgrid, hybrid photovoltaic-battery-hydropower microgrid, hybrid multi-microgrid and multi-bus microgrid system [94–99].

Remark 1: The term 'and/or' is added to the microgrid definition to include all types of microgrids, for example, islanded and grid-tied ones. 'And' does not cover an islanded microgrid due to its lack of grid-connection facilities whereas 'or' refers to one mode of a microgrid operation, i.e., either grid-tied or islanded.

Table 6. Comparison of ac and dc microgrids.

Factors	AC	DC
Conversion efficiency	Multiple energy conversions reduce efficiency	Less conversion processes increase efficiency
Transmission efficiency	Continuous reactive current loss reduces efficiency	Absence of reactive components increases efficiency
Stability	Affected by external disturbances	Free from external effects
Synchronisation	Synchronisation required	No synchronisation issues
Power supply reliability	Supply can be affected during seamless transfer	Power supply generally reliable
Microgrid controls	Control process complex due to frequency	Simple control approach
Protection system	Simple, cheap and mature protection schemes	Complex, costly and immature protection components
Suitability	AC loads	DC loads
Calculation methods	Complex numbers involved	Only real numbers used

4.4. Microgrid classification

4.4.1. Classification of microgrids based on power supply

Microgrids are classified in three categories based on the characteristics of power they inject into a distribution network, as shown in Figure 8, and briefly described in the following subsections.

AC microgrids: AC microgrids represent the ac power supply in a distribution network. They can be easily connected to an existing grid utility without special requirements such as converters and their control approaches. Since the evolution of the microgrid concept, ac microgrids have occupied a central place in research, with several publications regarding their control and operational approaches reported in the literature [100–102]. This is because of well-established ac power networks with compatible modes of electrical and electronic devices. The distribution system of an ac microgrid can principally be classified as one of three types, single-phase or three-phase with/without neutral-point lines.

DC microgrids: The concept of a dc microgrid, which has a better short circuit protection with enhanced efficiency, has emerged due to the extensive application of modern electronic equipment and the availability of environmentally friendly dc sources (solar and fuel cells). These microgrids exhibit higher efficiency and have a lower conversion process for the application of dc loads than ac microgrids. Commercial applications (telecommunication systems, shipboard power systems and electric vehicles (EVs)) of an LV dc distributed power system are reported in [103–106]. The distribution network of a dc microgrid can be one of three types: monopolar; bipolar; or homopolar. The main difference between ac and dc microgrids is presented in Table 6.

Hybrid microgrids: Hybrid microgrids consist of both ac and dc electricity distribution networks with an MGCC as shown in Figure 6. The purposes of constructing hybrid microgrids are to minimise conversion stages, reduce interfacing devices, increase reliability and reduce energy costs, thereby improving the overall efficiency of the network. Such a structure enables both ac and dc power to be supplied to a distribution network while clients can use electricity according to their needs (ac or dc). Usually, PECs are responsible for decoupling the ac and dc parts of a microgrid [107–109].

4.4.2. Classification of microgrids based on location

Microgrids can be further classified based on their locations as urban or remote as shown in Figure 8, brief descriptions of which are given below.

Urban microgrids: These microgrids are generally connected to a grid utility and, therefore, are capable of exchanging power with the grid through PCC. These microgrids, also known as the grid-connected microgrids, are capable of operating as an islanded microgrid during unusual situations, such as degraded power quality, faults on the main grid and the undertaking of network maintenance [4,110]. In these microgrids, all the rules and regulations, including complex control approaches, for the synchronisation process are satisfied to maintain the power quality of the grid and preserve the microgrids' integrity for network stability. These types of microgrids can be constructed
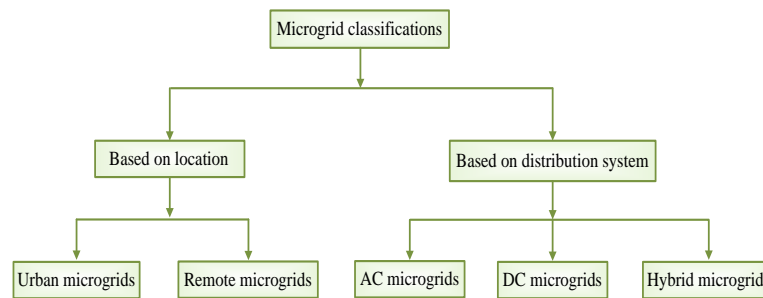
Figure 8. Classifications of microgrids.

in both residential and commercial premises, such as university campuses, hospitals, data centres, communities, industries and shopping malls.

Remote microgrids: These microgrids are constructed in remote areas where a grid utility has no access for geographical reasons, such as military installations, islands and hilly areas [1,111]. As these microgrids, also known as islanded microgrids, are not connected to the grid supply, they do not require rules and regulations like urban microgrids. They are not as common as urban microgrids due to the lack of investment in them, and economic, political and technological reasons, with remote and island communities their prime locations.

4.5. Challenges and opportunities of converter-based microgrids

In a traditional power system, output power of a large generator can be controlled according to power demand, and the rotor of it are rotated at a constant speed, thereby obtaining a fixed network frequency. However, most DG technologies generate uncontrolled power with different voltage magnitudes and frequencies. As this process is quite different from that of the conventional power generation, it is challenging to integrate DG units in a distribution network. To achieve this, PECs play a vital role by minimising harmonics and generating the required voltage, frequency and power [112–114]. Although discussing all the microgrid issues in detail is beyond the scope of this study, a few recently published articles are presented to provide a comprehensive review of the overall challenges of microgrids.

4.5.1. Challenges of microgrids

A microgrid is different from a distribution network and has both additional advantages and challenges, with a major difference its application of an energy management system or centralised control unit in a defined region. In an islanded microgrid, which is not connected to a grid utility due to the geographical area, this control unit is used to maintain a network's optimal operation. However, in a grid-connected one, it has the additional requirements to protect against islanding, synchronise with the grid utility and disconnect the microgrid.

Microgrid central controller (MGCC): An MGCC is a physical computer system consisting of a software platform in which various modules for generation and load forecasts, human machine interfaces and supervisory control and data acquisition (SCADA) are used [115]. It executes several processes for forecasting power generation, power demand and electricity market prices, and monitoring, analysing and optimising data, as shown in Figure 9, to provide the functions necessary for the effective operation of a power system by sending optimal decisions in order to ensure a power supply at the minimum cost. An MGCC can be realised for the both centralised and decentralised information processing. In a centralised processing, the central controller processes all the information of a microgrid while, in a decentralised controller, the central controller takes into account only a limited number of information with the real-time operation [116].

An MGCC is essential for coordinating a microgrid's different components in a systematic way to ensure its secure, reliable and economical operation. It enables a distribution network to integrate a high penetration of RESs and control them in an optimal way while the microgrid is either grid-connected or islanded. As its control approach is the key element of a microgrid, it needs to be designed in a way that represents the microgrid as a single entity from the grid perspective. Generally, a hierarchical control approach, in which primary, secondary and tertiary control levels are embedded, is responsible for its coordination [4,117,118]. The role of the primary control level is to ensure proper power sharing among DG units and control the terminal voltage while those of the secondary and tertiary ones enable optimal operation of the microgrid considering multiple objectives. Conventionally, these three levels, which incur a heavy computational burden and considerable costs while providing low reliability due to a single point of failure, send necessary signals through low-bandwidth communication lines to all the DG units. However, due to the development of advanced control approaches, the primary and secondary control levels can be implemented in decentralised ways, e.g., in a local DG unit controller (Figure 10), to enhance a microgrid's reliability during a single point of failure.

To avoid expensive communication lines and increase the reliability of power sharing, the primary control level generally adopts the droop control concept and the secondary one a MAS in a distributed manner to restore the voltage and frequency [119,120]. In MAS technologies, local controllers can make decisions autonomously regarding controlling their own DG units by communicating with neighbouring ones. A distributed peer-to-peer MAS for improving power sharing among DG units in a microgrid is demonstrated in [119]. An ontology-driven MAS for implementing the energy management of microgrids considering DG units and non-critical loads is presented in [121]. A review of MAS technologies used for microgrid control and optimisation is provided in [8]. Although a MAS framework can work in a grid-connected microgrid, it may not do so effectively during an islanded operation.

Although the primary and secondary control levels can be implemented in a decentralised manner to increase the reliability of a microgrid, it is important to have a centralised tertiary control level for each microgrid to coordinate it with other microgrids and the grid utility as well as provide optimal energy management of DG units in the presence of a high penetration of RESs. An MGCC detects the power quality at the PCC to determine whether to operate in an islanded or grid-connected mode and can re-synchronise an islanded microgrid with the grid utility once the grid restores the appropriate power quality [122,123]. As the different features of the energy sources in a microgrid produce fluctuating power levels which create challenges for an MGCC to balance the power in a network, various control methods for an MGCC are proposed in the literature [124–127]. Balancing the power to avoid voltage fluctuations is an essential task of a microgrid for its safe and reliable operation. An autonomous load-curtailment algorithm for disconnecting loads during peak-load hours to minimise the power difference between supply and demand is developed in [126]. An algorithm which optimises the power generation of a microgrid and its exchange of power with the grid utility is proposed in [125]. As energy storage units are responsible for regulating the voltage's amplitude and frequency in an islanded microgrid, an MGCC approach for the microgrid's safe operation within their limits to prevent its fast degradation or damage is proposed in [127]. This method avoids the overcharging of these units by curtailing their generation of active power, their deep discharging through load shedding and their uneven degradation through equalising the charge state among the units.

Microgrid stability: In a conventional power system, stability problems that define the ability of a power system to maintain synchronism during disturbances are categorised into rotor angle stability, voltage stability and frequency stability [55]. While rotor-angle stability provides information regarding the balance between the electro-magnetic and mechanical torques of a generator rotor required for it to remain in synchronism, voltage and frequency stabilities refer to the balance of a network's power supply and demand. Although the dynamic behaviour of a
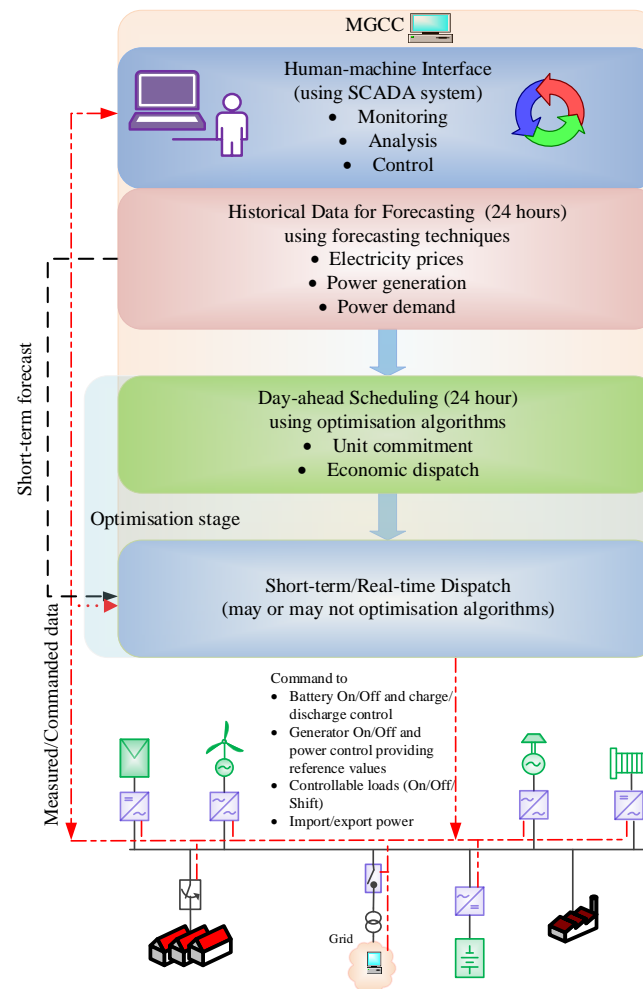
Figure 9. Typical stages of supervisory controller.

synchronous generator has a substantial role in maintaining power system stability, in a microgrid with converter-interfaced DGs, rotor angle stability is no longer an issue due to the lack of inertia of DGs that makes a significant difference in operating a microgrid from the traditional grid [1]. In addition, a microgrid also suffers from the buffer energy of an inter-connected transmission system where energy is stored in the inductance and capacitance of line parameters. Although the voltage and frequency stabilities in a microgrid are analysed in an islanded mode, only the former is controlled in a grid-tied operation due to the small effect of the frequency on the grid [7] because the voltage acts as a local variable and the frequency as a global one. Both stabilities are determined through either a small- or large-disturbance analysis, with the stability of a microgrid basically dependent on its operational modes, control topology, types of DGs and loads, and network parameters [128–130].

A small-disturbance analysis involves evaluating a microgrid's stability in terms of linearising the system around its operating points using eigenvalue analysis, Routh-Hurwitz or Nyquist stability criteria. Several small-signal analyses that deal with load fluctuations, and the influence of droop gains and variations in the line impedance on voltage and frequency characteristics are conducted in [61,62,128,129,131–133]. As droop coefficients have a direct influence on a microgrid's small-signal stability, accurate design of droop coefficients and a droop control with adjustable dynamic behaviour are recommended in [61,62,134]. A small-signal analysis of a grid-connected inverter for use in an UPS unit is first demonstrated in [135]. Then, in [61], inverter-based microgrids with linear loads are
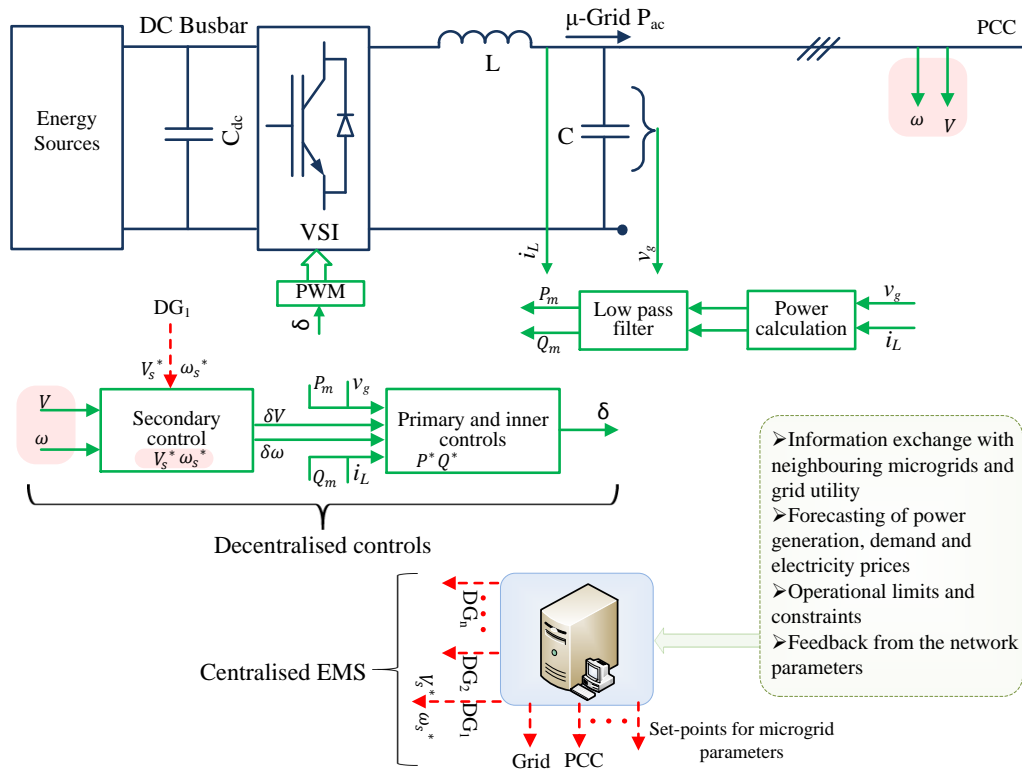
Figure 10. Centralised and decentralised controls of microgrids.

modelled to perform a small-signal analysis of the frequency and damping of oscillatory components. To demonstrate the influence of an active load in a microgrid, in [62], a network is modelled with non-linear loads and it is found that the low-frequency modes are linked to the voltage controller of the active rectifier and the large load gains cause instability in the inverter's operation. In [63], a synchronous generator is added to an inverter-based microgrid to investigate the stability margin, with a modified droop control presented. A reduced-order model using the Kron reduction method for inter-inverter oscillations is developed in [136]. In [137], inertia constant and frequency droop coefficients are tuned together by applying the knee-point-driven evolutionary algorithm (KnEA) to enhance the stability of the frequency of a microgrid. The main disadvantage of a small-signal analysis is that it is only effective around the linearised operating points and does not indicate the ranges. However, this can be overcome by implementing non-linear techniques such as Lyapunov methods. To achieve improved performances, researchers can still obtain an accurate model of a microgrid and select optimal control gains using advanced optimisation algorithms.

A large-disturbance stability analysis determines a system's capability to retain a network's stability after a large change, such as a fault, switching of the operating mode or loss of generators or loads, in it. Although this has been extensively used for conventional power systems, there is little information in the literature regarding that for a microgrid. The transient stability determines mainly the dynamic responses of different types of DGs, characteristics of the fault current's contribution and transient behaviour of a microgrid. In [130], the dynamic behaviour of a doubly-fed induction generator (DFIG) is analysed using a fifth-order model while, due to complications caused by the presence of several DFIGs, a simplified model is presented in [138]. A model for a grid-tied PV system for analysing the transient response under a large disturbance is implemented in [139]. In [140], a comparative study of PV systems shows that distributed PV generators have more advantages in terms of stability than solar farms. In a study of the transient stability of DG units, it is observed that the stability is greatly affected by a current limiter used to protect these units against damage [141].

In [142], a virtual power-angle instability considering an active power disturbance is analysed using the virtual power-angle curves of a converter connected to an infinity bus. In [143], as an extension of previous work, the large-disturbance stability of a droop-controlled DG unit is theoretically studied based on complicated dynamic behaviour. A 13th-order non-linear model of a dc/ac converter for gaining insights into the transient stability of converter-based microgrids is developed in [144].

The stability of microgrids can be improved in various ways, such as by using control strategies, reactive power compensations, storage systems and shedding loads [145]. Although a high droop gain can enable a proper load sharing, it may cause instability in microgrids while a microgrid's stability is improved by optimising the droop gains and using a supplementary loop [146–148]. In [149], an extra inverter is connected in parallel with DGs to inject reactive power during a voltage dip to improve the stability and LV ride through of a microgrid. An ESS can be used to support a sudden change in the mode transfer or load shedding of a microgrid to improve stability. An overview of a microgrid's stability issues and mitigation procedures is presented in Figure 11. It is worth mentioning that a microgrid's stability is divided into mainly frequency and voltage stabilities. The small- and large-disturbance stability are categorised as analysing methods not the types of stabilities reported in [7,145]. While the majority of research presented to date is based on radial networks,
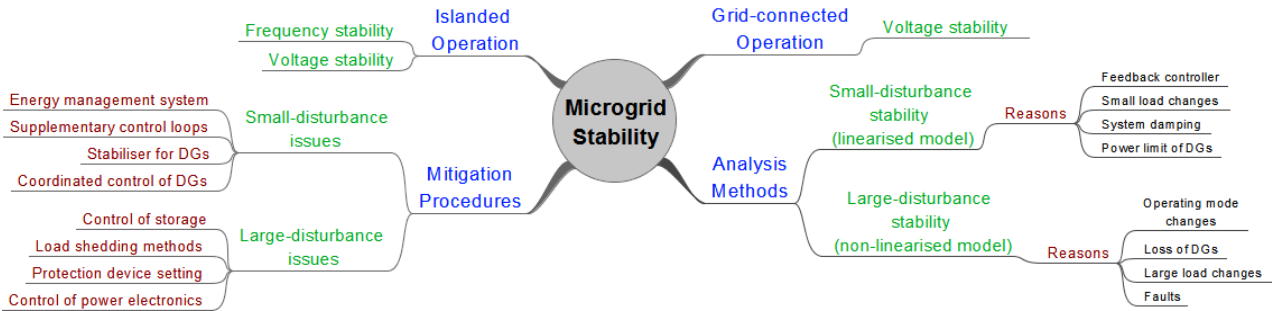
Figure 11. Pictorial overview of microgrid's stability issues and mitigation procedures.

studies of the stability of mesh ones are still needed.

Protection: A conventional distribution network, the current flow of which is unidirectional, is equipped with protection devices, such as reclosers, circuit breakers, fuses and relays, to ensure fault detection and isolation, with the former generally carried out using over-current relays. However, integrating DG units in a radial network makes the network a complicated one due to the difficulty of analysing the direction and magnitude of the bidirectional current flow [150]. In addition, DG units in a microgrid need to be protected in both grid-connected and islanded operations, where a fault current changes significantly for altering the modes. The reason is that the utility supports a huge flow current in a grid-tied microgrid, whereas converter-interfaced DG units limit the fault current during an islanded operation due to stochastic nature of power generation and power limits of electronic components [151]. This limit may be so low that conventional protection systems, such as fuses, over-current relays and reclosers, may not accurately detect faults due to their pre-set current limits and, consequently, may be inadequate for completely protecting a microgrid. A fault current is affected by the capacities, types and locations of DG units which may cause miscoordination among primary backup relays and lead to the false tripping of protection devices, unintentional islanding, failure of auto-reclosing and fault detection [152]. Therefore, it is essential to design a proper protection scheme that can be operated under different microgrid conditions.

Several protection methods for solving the above issues are proposed in the literature. One is changing the protective devices or settings by re-calculating them according to changes in the network's topology [153–156]. Its main drawback is that it does not consider an increasing penetration of DG units, uncertainties inherent in power generation and demand, and reconfiguration of the network [157]. A fault current limiter (FCL), in which a limiter (impedance) is connected in a series

with DG units, is another approach for minimising the effects of the units on the protection system [158–160]. In a normal operation, the value of impedance is almost zero but rises and limits the short-circuit current when a fault is detected. Although this method can reduce the negative impact of installing DG units, it is only applicable for specific types of microgrid topologies due to its expense and need to select the best location for the series impedance for every microgrid configuration.

To overcome the above issues, an adaptive protection scheme which changes the parameters of protective devices via communication or measurements in response to a change in a microgrid's configuration is presented in [161]. It constantly monitors the system's status using a communication channel to update the coordination of its protection devices during changes in its operations or topology. It consists of directional over-current relays with a changeable group of settings and high-speed, secure communication channels. It can be operated in both a centralised and decentralised manner whereby a microgrid's protective settings are updated either online or offline for each change in its topology [162]. In an offline process, all possible settings for different scenarios in a microgrid's grid-tied and islanded modes are first stored in a memory of a supervisory remote control unit (SRCU), then it analyses the microgrid's status to decide the settings of online relays for any change in the network's topology [163]. However, an offline method may not work for all dynamic situations and simultaneous faults due to a large number of conditions [164].

A SRCU is used in a centralised adaptive protection scheme to adjust relay settings to obtain an appropriate current level via a high-speed, secure communicative infrastructure while a decentralised one, in which a set of distribution agents of various devices is operated in a coordinated way through communication channels, has a higher speed, and greater reliability and expansibility [164,165]. Although adaptive protection is an effective approach for both the operating modes of a microgrid, outages of communication channels and cyber security threats are its major drawbacks. In [166], an adaptive protection scheme considering the existing ESSs in a network is designed to increase resiliency against communication failures. Further analysis aimed at designing a robust adaptive protection scheme that can efficiently respond in terms of uncertainty in both modes of a microgrid operation is still needed.

Island detection of microgrids: The protection scheme in a traditional power system is designed based on the assumption that, in the case of a fault or an unwanted event, the distribution system will be isolated from the network. However, for a DG-integrated network, the system remains energised in the event of a fault, with the loads supplied from local DG sources and its operation under such a condition referred to as that of an islanded microgrid [167]. The main reasons for islanding include switching operations, such as clearing faults, shedding unexpected large loads and maintaining outages [168,169].

There are two islanding operations: intentional; and unintentional. The former, which is an action conducted by grid operators, is primarily executed to either implement a power management plan or avoid cascaded failures. Due to its systematic procedure, it is generally safe and can also be implemented to improve the power quality of a microgrid [168]. In contrast, an unintentional islanding is an unexpected operation of a microgrid. If an unintentional islanding condition is not detected precisely in a timely fashion, the entire network may collapse with several negative effects, such as the introduction of safety hazards for operational personnel, damage to customers' equipment, voltage and frequency instabilities, and problems while re-closing the converters [170]. For these reasons, current standards, such as IEC 62116, IEEE 929-2000 and IEEE 1547, do not permit DG units to be operated in an islanded mode [169,171]. However, this is not economically viable as local resources may fully or only partially fulfil the power demand without interrupting a continuous power supply. In order to enable a safe microgrid operation, researchers are continuously working to develop efficient detection techniques by addressing different technical issues.

Although detecting unintentional islanding conditions is challenging, achieving this as soon as possible is essential in order to take immediate action to establish a stable microgrid operation. According to IEEE Standard 1547-2003, the maximum permissible time for detecting islanding

Table 7. Comparison of islanding detection methods [168,177].

Features	Active	Passive	Hybrid	Remote	Intelligent
Operation Principle	Injecting disturbance signal to grid	Monitoring PCC parameters	Combination of active and passive	Communication between DG	Extraction of features
NDZ	Small	Large	Very small	Zero	Negligible
Response time	Very short	Short	Longer than active methods	High	Short
Nuisance tripping percentage	Low	High	Lower than active and passive	Negligible	Low
Applicability in multiple DG system	Not preferable	Highly preferable	Not preferable	Preferable	Preferable
Implementation cost	Minimum cost	Average cost	High cost	Extremely high cost	Average cost
Effect on microgrid	Greatly decreases power quality	None	Degrades power quality	None	None

conditions is 2 seconds [172]. Several methods in the literature based on electrical quantities, such as voltage, frequency, impedance and power, for effectively detecting islanding conditions [167,170,173,174] are mainly classified as remote, local and intelligent [175].

Remote detection techniques are based on expensive communication lines between a utility and its DG units [168,176]. In them, power-line carrier communication (PLCC) and SCADA are used to execute an islanding operation [168]. Although they provide better reliability for multiple DG units than local methods, they are often criticised for the high expense involved in installing sensors and communication devices.

Local techniques widely used to detect islanding are classified based on their measurements of electrical quantities (voltage, current, frequency and harmonic distortion) at DG sites as active, passive and hybrid. The active ones deal with changes in the small signals injected into a grid to detect abnormalities in its operation while passive ones monitor the electrical quantities at the PCC to observe the transient phenomena in the network [178]. The hybrid method consists of both active and passive techniques, with the latter used first to detect islanding and then the former applied. It has lower non-detection zones (NDZs) – the zones of failure for detecting islanding situations on time – and less impact on power quality. Although passive methods are cost-effective and simple to implement, they may fail to accurately detect islanding conditions due to large NDZs. To overcome this limitation, active methods using a small NDZ are employed but require extra time to respond to perturbations [168,179].

Several approaches based on intelligence techniques, such as wavelet analysis, and neuro-fuzzy and adaptive artificial neural networks (NNs), for effectively detecting and classifying islanding conditions have recently been developed [180,181]. Their signal-processing techniques facilitate the extraction of hidden characteristics of the measured signals from which features are used as input to an artificial intelligence for further processing to identify islanding and non-islanding. Although intelligent techniques have more advantages than the previous ones, they have also some limitations that are tabulated with other methods in Table 7. There are still opportunities to improve detection procedures using modern technologies, such as smart meters, and sophistical tools like discrete fractional Fourier transforms with learning algorithms.

Seamless transfer: Microgrids can be operated in either a grid-connected or islanded mode depending on the relevant network's conditions, such as faults, power quality and maintenance, with any transfer between these modes required to be seamless and separating a microgrid when a grid fault occurs should not affect the loads. According to IEEE-1547-2003, an anti-islanding scheme must de-energise the sources within 2 seconds of an islanded operation due to concerns about stability and protection issues [182] while, according to IEEE-1547.4, a microgrid is permitted to supply continuous power to loads in an islanded mode provided that it fulfils the criteria of adequate levels of voltage and frequency stability [183]. However, when switching from a current controller mode in a grid-tied microgrid to a voltage controller mode in an islanded one, the outputs from these controllers may not be equivalent at the exchanging moment and lead to current or voltage spikes at that instant [184,185]. In contrast to the re-synchronisation of a conventional power system, where a synchroniser facilitates the process for a single machine, a microgrid is quite different due to its multiple DGs with different dynamic attributes and should restore the grid quickly and smoothly to avoid any disturbance in the power supply to loads [186]. The main difficulty for re-synchronisation is to precisely recognise the moment at which the static switch at the PCC is closed for a specific voltage, frequency and

phase of the utility grid and that of the microgrid to avoid circulating current flows in the network. An inappropriate selection of this instant can lead to a circular current, subject to the momentary voltage distinction between the grid utility and microgrid, that may conceivably harm the system's components or falsely trip its protection devices [184].

It is important to constantly monitor the voltage, frequency and phase of a grid utility for its correct operation and re-synchronisation with an islanded microgrid. However, the synchronisation criteria presented in IEEE Standard 1547-2003 may not be appropriate for a converter-based microgrid which has a low inertia, fast dynamic response and low overload capability [187]. There are two approaches for preparing a microgrid for a re-synchronisation process depending on the different dynamic sources. In the first, initially, all the sources are synchronised simultaneously to construct a microgrid bus which is then synchronised with the grid. The second is to synchronise one of the DGs with the grid first and then the others consecutively [186]. In the former approach, it is difficult to gain a grid voltage template for every DG scattered over an extensive region while, in the latter, the time required for the synchronisation process is much longer and leads to poor resource usage.

In order to minimise the transient effect of electrical parameters during mode changes, a method of seamless transfer, in which the voltage and current controllers are interchangeably used for different purposes in both operations by readjusting their reference values, is presented in [184] but the time interval during the switching process is neglected. An intelligent load-shedding scheme with an algorithm for intentional islanding and re-connection, which reduces reliability due to its load-shedding techniques, is developed in [188]. A droop-based approach, in which one DG is designed as a dispatchable unit for facilitating a smooth transition between two modes, supplies extra power immediately after the loss of the main grid for the transition and remains idle for most of the time, is implemented in [189]. A hierarchical architecture with primary and secondary control levels that considers power quality issues for achieving a seamless transitions is designed in [185]. It allows transitions to be performed without disconnecting the DGs or loads but does not consider a backup generator, apart from an ESS. The techniques discussed above are mainly applicable for UPS systems as they do not consider the dynamics of RESs.

To facilitate re-synchronisation, three types of strategies are reported in [182,190]: (1) active synchronisation in which a central control technique coordinates the voltage, frequency and phase angle of an islanded microgrid with the grid using communication lines [124,191,192]; (2) passive synchronisation in which a synchroniser checks for parallel devices using a synchrocheck relay [193,194]; and (3) open-transition transfer synchronisation in which DGs and loads are de-energised before their re-connection. The third strategy has reliability issues due to its discontinuous power supply to loads during transitions, the second, although simple because of the availability of well-established synchrocheck relays in practice, may suffer from poor voltage and frequency control [190] while the first is suitable for converter-based microgrids due to its communication facilities. In [124], an active synchronisation control scheme which uses network-based control of multiple DG units to set the voltage and frequency of a microgrid is demonstrated. It permits the synchronisation of a microgrid under different working states of DGs and load changes but doesn't accomplish a quick and optimised synchronisation. This work is extended by designing a robust controller based on a μ synthesis analysis in [195]. An approach for synchronising the frequencies and phase angles of all DGs based on a combination of three distinctive phase-locked loops (PLLs) is demonstrated in [196]. In these methods, a central control unit used to make decisions sends information via communication channels that are vulnerable for a large system during communication failures. To overcome such a concern, a combination of droop control, distributed cooperation control and an active synchronisation strategy for improvimg flexibility and redundancy is developed in [195]. A bi-level distributed synchronisation control framework using minimum, sparse communication to adjust the output power of all DGs in order to regulate the voltage and frequency of a microgrid and track the grid components is presented in [197]. A linear quadratic regulator-based bumpless transfer controller for the seamless transfer of a microgrid described in [198] reduces voltage and frequency

oscillations during a transition. Control approaches based on observer and auxiliary tracking for transferring from power tracking or voltage control to voltage tracking or backup droop-based control, respectively, are developed in [199]. The research conducted to date on seamless transfers can be further extended by applying new approaches to ensure a smooth transition considering the presence of uncertainties and harmonics in a network.

Location and sizing of DG units in microgrids: Traditional distribution networks are radial in nature, whereby power flows from a distribution substation to consumers. However as, in a microgrid, DG units located in single or three phases close to the consumer end cause a bidirectional power flow, placing them in suitable places and determining their proper sizes are critical tasks [200] as inappropriate placements may lead to a microgrid being in an unbalanced condition and cause a reverse power flow and increased line losses. A greater penetration of single-phase DG units in a three-phase system increases the power loss and fault current [201] while their inappropriate placements also negatively affect the voltage quality and create harmonics in a microgrid [202]. Large DG resources alter a fault current's direction and phase angle, leading to the unwanted operation of protection devices. These issues can be overcome by the optimal planning of DG units and solving the appropriate objective functions and constraints using suitable algorithms. Most of the problems in early research studies are formulated based on a single objective, such as the minimisation of energy losses or total cost, for different perspectives of DG promoters or distribution network operators (DNO) [203,204]. Although determining a solution of a single-objective function may create conflicts of interest among agents (DG promoters, regulators and DNOs), this can be minimised using a multi-objective function that provides a compromise.

Generally, objective functions are formulated as active power losses and voltage profiles for obtaining the types, numbers, sizings and sitings of DG units [205–208]. There are also other objective functions, such as reactive power minimisation, DG capacity maximisation, environmental cost reduction, reliability improvement, imported energy minimisation and spinning reserve power [209–212]. Feasible solutions to objective functions are often limited to imposing constraints on the power balance, line current, node voltage and power factor of a DG. The constraints can be further extended to the utility limitations, such as the power exchange, short-circuit current, transformer capacity, number of DGs and maximum power production of DGs [213].

Objective functions with constraints can be solved by applying various computational methods, such as classical and artificial intelligence ones. Classical approaches, which are based on determining a mathematical solution to a problem, include linear/nonlinear programming, dynamic programming (DP) and optimal power flow, while artificial intelligence ones, which are inspired by natural behaviour, include simulated annealing, harmony search, evolutionary algorithm, ant colony and hybrid intelligence (genetic algorithm (GA) – tabu search) techniques. Although an analytical approache is typically simple and highly precise depending on the model's accuracy, it may not be suitable for a complex system's multi-objective functions [214]. In this case, an artificial intelligence algorithm can be the best option due to its flexibility regarding these functions. However, the solutions obtained by these methods may become trapped in a local minimum without reaching the global optimum. As a hybrid optimisation algorithm can overcome the difficulties of an individual one, it can be more suitable for the optimal selection of DG units as either discrete or continuous variables.

A mixed algorithm consisting of a GA and intelligent water drops (IWD) for determining the best locations and capacities of DG units, respectively, to minimise power losses, enhance voltage stability and control a microgrid is developed in [215]. In [216], a new index for calculating the optimal locations and sizes of DG units considering load variations is presented. A hybridisation of heuristic search and analytical approaches, in which the sizes of DG units are determined by analytical methods and their locations by PSO, for optimal multiple DG placements is described in [217]. A multi-objective optimisation method for determining the optimal sites and sizes of multiple DG units is presented in [218]. Further research in this area can be conducted by considering

uncertainties in loads and RESs, and the optimal power factor and reactive power limits of DG units without violating constraints.

Locations and sizes of ESSs: A battery energy system is a type of ESS that has drawn significant attention for implementation in a microgrid due to its quick response, flexible application and easy control [219]. It has a wide range of both economic and technical uses in a microgrid, such as minimising operational costs, reducing curtailed energy, minimising energy losses, improving network stability, shifting loads, supplying uninterrupted power and deferring the upgrading of transmission lines [220]. An ESS, a key element of a microgrid that helps to distinguish it from a distribution network, enables a microgrid to be operated in a stable islanded mode which is not possible for a distribution network, even with a high penetration of intermittent RESs. However, its initial cost is still a major concern that needs to be overcome before its potential advantages can be realised. Therefore, as there is a trade-off between obtaining an improved network performance and profitable investment, determining a battery's optimal size is required which is accomplished by applying computational techniques for various installation purposes, with the criteria primarily categorised as economic, technical and techno-economic [221]. The economic deals with minimising the overall cost of installing an ESS in a system while the technical concerns about improving a network's dynamics by regulating the voltage and frequency of a microgrid. The techno-economic considers both the economic and technical perspectives, where the main goal is to reduce the overall cost while taking account of technical constraints. In addition, the lifetime of a battery should be considered when deciding on its optimal size in order to prolong its storage services.

The issues regarding determining a battery's capacity can be resolved using several techniques, each of which has its own advantages and shortcomings. The common methods applied in the literature are probabilistic, analytical, mathematical optimisation, heuristic and hybrid. The key idea in a probabilistic approach is to use the stochastic behaviours of RESs to better determine the optimal battery size. Although it can provide satisfactory results with little resource data, it can only handle a limited number of performance criteria [221]. An analytical method, also known as a deterministic approach, is one of the most extensively used for determining ESS sizes. It is effective and flexible in terms of all the criteria and simulation methods in many cases but requires a large number of simulations which is problematic for limited computational resources [222,223]. Although a mathematical optimisation algorithm can improve the computational efficiency of analytical approaches, it has convergence issues in the presence of non-linear complex problems. This has led to the introduction of heuristic approaches for finding near-optimal solutions rather than accurate results. The main strength of a heuristic approach is to avoid mathematical derivatives and thereby use reasonable amounts of memory and time [224]. However, as there is a possibility of a heuristic method becoming stuck in a local optimum rather than a global one, using a combination of the above methods which overcomes their individual limitations could guarantee convergence toward global optimisation.

In [225], a cost-benefit analysis of the optimal sizes of ESSs for both grid-connected and islanded modes is demonstrated by applying a mixed linear integer problem (MLIP). An improved bat algorithm for determining the optimal ESS size of an LV grid-connected microgrid considering some constraints, such as the amount of DG power, ESSs' energy capacities, the operating reserve and load demand, is applied in [226]. An effective battery size for regulating the voltage and peak load under a high level of PV penetration is determined in [227]. This study conducts a cost-benefit analysis that considers a battery's influence on the work stress of voltage regulation devices, load shifting and peak power generation, and the cost for its estimated lifetime. In [228], a probabilistic model for obtaining the optimal sizing and siting of a battery system in a distribution system is developed considering both the operating modes of a microgrid for minimising the amounts of energy storage, energy losses and expected energy not supplied. A multi-objective sensitivity algorithm for optimising the capacities of PV and storage systems is presented in [229]. As a power-flow algorithm is used to control the reactive power flow of a solar system, voltage variations are minimised, energy savings

maximised and peak loads reduced. Different architectures, sizing methods, design criteria and control techniques for ESSs in microgrids considering relevant constraints are discussed in [230]. Taking different objective functions with constraints into account, the work can still be advanced by the application of novel optimisation algorithms.

Power sharing: A basic control approach for converter-based DG units is adopted from the control for an UPS unit which is similar to an islanded microgrid. As a microgrid consists of multiple generators, unlike a stand-alone UPS that generally uses a single storage or generating unit, special control strategies are needed for accurate sharing of the generated power (active and reactive) among its DG units. This can ensure the stability, reliability and economical operation of a microgrid during load changes and depends greatly on the types of energy sources, i.e., PV, wind, micro-turbine and fuel cells, distribution lines and non-linear loads. As power sharing is challenging due to the uncertainties inherent in the power generated by RESs and the resistive nature of distribution lines [231], proper strategies for load distribution need to be improved to increase a microgrid's reliability. Power sharing can generally be performed in one of two ways, communication-based or communication-less.

Communication-based power control achieves effective power sharing and voltage regulation at the expense of a high investment cost for the communication's infrastructure. These methods include centralised, master-slave, average load sharing, peak value-based current sharing, circular chain and distributed forms of control [4] and, of them, a master-slave control approach is widely used in practice [232,233]. In it, the master converter that is in charge of a microgrid control works as a VSC by producing a controlled voltage and frequency while slave converters act as CSCs by obeying the current pattern ordered by the master inverter in order to achieve effective power sharing among DG units [234]. Although a master-slave method can achieve good power sharing with the benefit of easy installation, its expensive communication lines reduce the reliability of a microgrid during communication failures or delays as well as limit any increase in the number of DG units [4].

Communication-less power sharing based on droop characteristics that avoids expensive communication infrastructures and increases a system's reliability and redundancy requirements is proposed in the literature. It is particularly helpful for connecting remote DG units and can be easily expanded due to its plug-and-play features that permit one unit to be replaced without stopping the entire system [4,235]. A drop in the voltage and frequency at a DG's terminal during any disturbance is the key concept of droop control which facilitates the plug-and-play feature without depending on central commands. The main advantages of droop control methods are their better flexibility and reliability than other techniques. However, their disadvantages are their coupling of power control, dependence on network impedance, issues with non-linear loads, and voltage and frequency deviations [4]. To overcome these problems, different control approaches together with their relative strengths and weaknesses are discussed in the literature.

In [236], a virtual flux method for improving frequency deviations by reducing the multi-feedback loops of an inverter control is presented. A voltage/current (V/I) droop-based control approach for enhancing the reactive power sharing, dynamics and stability of a microgrid is proposed in [237]. Voltage-based droop control, which includes the characteristics of RESs in the power-sharing strategies of a microgrid, is described in [238]. To minimise power-coupling issues due to the near-unity ratio of R/X, modified droop control, virtual inertia and universal droop control methods are presented in [239–242]. Different methods for the power sharing of DG units is discussed in [4,243], with their relative benefits and drawbacks shown in Table 8. Researchers can still improve the power sharing strategies by employing new control strategies and optimisation algorithms that can tune the co-efficiency of the controllers for better performance.

Table 8. Benefits and drawbacks of power sharing strategies.

Control Methods	Advantages	Disadvantages
Communication-based methods	Accurate power sharing and voltage regulation Improved transient response Elimination of circulation currents	Expensive communication lines Microgrid reliability issues DG expansion and flexibility issues
P/f droop	Suitable for high and medium voltage line Not dependable on communication line Easy implementation and flexible expansion	Sluggish dynamic response Poor reactive power regulation Sensitive to physical components
P/V droop	Suitable for low voltage distribution line Not dependent on communication line Easy implementation and flexible expansion	Sluggish dynamic response Poor active power regulation Sensitive to physical components
Adaptive derivation	Enhanced power sharing Eliminates voltage and frequency distortions Improves dynamic stability of power sharing	Not suitable for complex network Difficult to implement multiple DGs
Frequency based signal injection	Suitable for different types of load application Robustness in system parameter variations	Harmonic issues in voltage control Complex implementation
Voltage based droop	Suitable for highly resistive network Suitable for renewable energy control Easy power balancing	Difficult practical implementation Voltage varies during load changes
Virtual flux control	Improved frequency control Simple control structure	Difficult to implement in a large system Slow dynamic performance
V/I droop control	Improved faster dynamic response Ensures accurate real and reactive power sharing Suitable for small-inertia DG units	Oscillation issue for small droop coefficients Voltage issue under heavy load conditions

Microgrid planning: The problem of a microgrid planning, which involves determining the economic viability and optimal selection of a microgrid's parameters before its practical implementation, is a challenging task because of the involvement of uncertain data, such as forecasting errors in loads, renewable generations and market prices, during assessments of the microgrid's deployments [244,245]. Therefore, because of a microgrid's high cost, efficient planning techniques need to be developed to ensure a profit and justify further investment based on cost analyses of unpredictable situations. In [245], an economical model that considers uncertainties in physical and financial information is developed for efficient and viable microgrid planning. A theoretical framework, including a long-term investment and short-term cost, for studying the cooperative planning of RESs in a multi-microgrid operation is presented in [246]. It is observed that, compared with non-cooperative microgrids, these cooperative ones obtain a 35.9% reduction in a system's overall cost. Two-stage stochastic programming for minimising the risk and expected cost of an investment that considers different scenarios of uncertainty over the data is described in [247]. It is concluded that risk-averse stochastic programming obtains better results in terms of economic benefits than deterministic approaches while still satisfying environmental objectives. In [248], the optimal planning of a multi-microgrid considering different factors, such as network- and resource-based uncertainties, to increase reliability and operate economically is investigated using a probabilistic minimal cut-set-based iterative methodology. A robust optimisation approach considering economic, technical and reliability aspects for the optimum design of a microgrid and employment of DG units with a section switch and tie switch allocation is presented in [244]. In [249], a tool for the long-term planning (up to 20 years) of an industrial microgrid taking into account the objectives of all the stakeholders (prosumers, consumers and the microgrid's energy manager) is developed using a game theoretical framework.

Forecasting data: The intermittent nature of RESs together with the unpredictable participation of loads poses great difficulties for balancing power generation and demand. To address these challenges, a spinning reserve becomes an essential part of a microgrid as an energy buffer to relieve fluctuations. However, it increases the monetary and related administration costs which lead to less motivation for investing in a microgrid-related infrastructure [250]. Therefore, to obtain precise estimations of the levels of power generation and demand, from a few minutes to a few days, a forecasting method for scheduling a microgrid's devices, as shown in Figure 9, is essential for achieving a cost-effective and reliable operation. This is a challenging task because of the uncertainties

in RESs, loads and real-time electricity prices. Prediction periods can be divided into various time horizons, such as very short-term (1 min – 1 h), short-term (1 h – 1 week), medium-term (1 month – 1 year), and long-term (1 year and above) [251]. Very short-term forecasting is used for real-time power dispatch, optimal reserves and power smoothing while short-term forecasting ensures the unit commitment and economic power dispatch/scheduling. Medium-term forecasting methods are used to plan and maintain a power system by estimating its future available power supply and long-term ones in the planning phase of power generation, transmission and distribution systems to determine the appropriateness of the investment [252].

Forecasting techniques can be generally categorised as statistical, machine learning, physical/numerical and hybrid. Statistical ones depend on analysing historical data in a time series of the variables, where input data are decomposed into time series, a regression of which is used to estimate future specific variables. Common statistical methods include linear regression, autoregressive moving average (ARMA), autoregression with exogenous inputs (ARX), sparse vector autoregression (sVAR) and Grey models [250,251]. Although a statistical method is computationally efficient, a machine-learning technique, such as a neural network (NN), is suitable for the interpretation and prediction of non-linear relationships related to historical data. In it, a NN is first trained using approximately 70% of the total amount of data with the help of a back-propagation algorithm, and then tested using the remaining 30%. The main drawbacks of a NN are its requirement for a large amount of data and its over-fitting issues during the training phase. Common machine-learning algorithms are NNs, support vector machines, and fuzzy and recurrent negative correlation learners. Physical forecasting techniques predict the future states of variables based on mathematical models of physical processes and they include numerical weather prediction (NWP), engineering white and grey box, spatial averaging temporal interpolation and physical weather forecasting methods using external inputs. In these methods, the historical data are not generally needed and therefore avoid guessing the input-output relationship like NN. However, the parameterisation of the physical system sometimes has to be made by the accessibility of data sources that create complexity. As each method has its own weaknesses and strengths, hybrid ones, such as PSO-NN, NWP-NN and ARMA-NN, which take the strengths of each method, are applied in the literature [253,254].

A large-scale spatial technique for providing very short-term probabilistic forecasting for different wind firms in Australia is demonstrated in [255], with a logit-normal transformation associated with a spatio-temporal model. The sVAR technique outperforms the conventional VAR and autoregressive models in terms of both the deterministic and probabilistic scores. A NWP and Gaussian process regression model considering the impact of atmospheric stability on the accuracy of short-term wind predictions, where the Gaussian model enhances the prediction accuracy over that of the original NWP data, are presented in [256]. A hybrid forecasting method consisting of a NN and metaheuristic algorithm, in which the latter is used to efficiently train the NN to avoid the trapping of local optima and over-fitting, is described in [257]. It is shown that this method obtains better prediction accuracy than nine others. In [258], a comparative study of forecasting methods for thirty-two solar plants of various sizes and technologies is presented. It also analyses the effects of the weather conditions and forecasts on the prediction of solar power generation. A hybrid method consisting of a generalised extreme learning machine, wavelet pre-processing and bootstrapping for improving the accuracy of load forecasting which considers the uncertainties of the forecasting model and noise data is discussed in [259]. In [260], four different deep-learning models for forecasting electricity prices are presented and it is concluded that they generally provide better accuracy than statistical models. However, there are various influential parameters in these estimating models in which improper parameter settings have an impact on the construction of these forecasting models in different ways, such as over- or under-fitting problems. For these reasons, parameters should be precisely chosen in which several optimisation techniques can be applied.

There are still opportunities for researchers to construct a suitable forecasting model with higher accuracy, and minimum computational cost and complexity.

Energy management: Energy management involves the optimal use of energy for generated power and load demands taking into account some constraints, such as power, voltage, battery and logistics, in order to facilitate the economical, sustainable and reliable operation of a microgrid [261]. Due to the penetration of RESs, EVs and ESSs into existing networks, the general task of an energy management system has been diversified from the unit commitment and economical dispatch of generators. Therefore, the energy management of a microgrid can be performed from either the generation or load side, as shown in Figure 12. Although, conventionally, it involves the former, it is a challenging task due to the second-to-second power balancing required for stochastic power generation from RESs and fluctuating power demands. Energy management is the essential task in optimal scheduling for managing generation dispatch, saving energy, reducing system losses, supporting reactive power, mitigating GHG emissions, decreasing operational costs, and increasing reliability and efficiency of a microgrid. It also takes into account the operation, maintenance and degradation costs of a battery, and the penalty cost of the load shedding [116]. In an energy management unit shown in Figure 9, firstly, a day-ahead scheduling based on the electricity price and forecasted data of power generation and demand is determined to obtain a cost-effective operation. Then, the short-term/real-time dispatch module receives the set-points from the scheduling program for sending them to the resources as commanded, compensating forecasted errors using short-term forecasting and real-time measurement of the data after each time step in the prediction horizon. Several computational algorithms, such as linear/non-linear programming, DP, GAs, fuzzy logic and NNs, are applied to reduce computational complexity and improve the convergence of energy management strategies for the efficient and reliable operation of a microgrid.
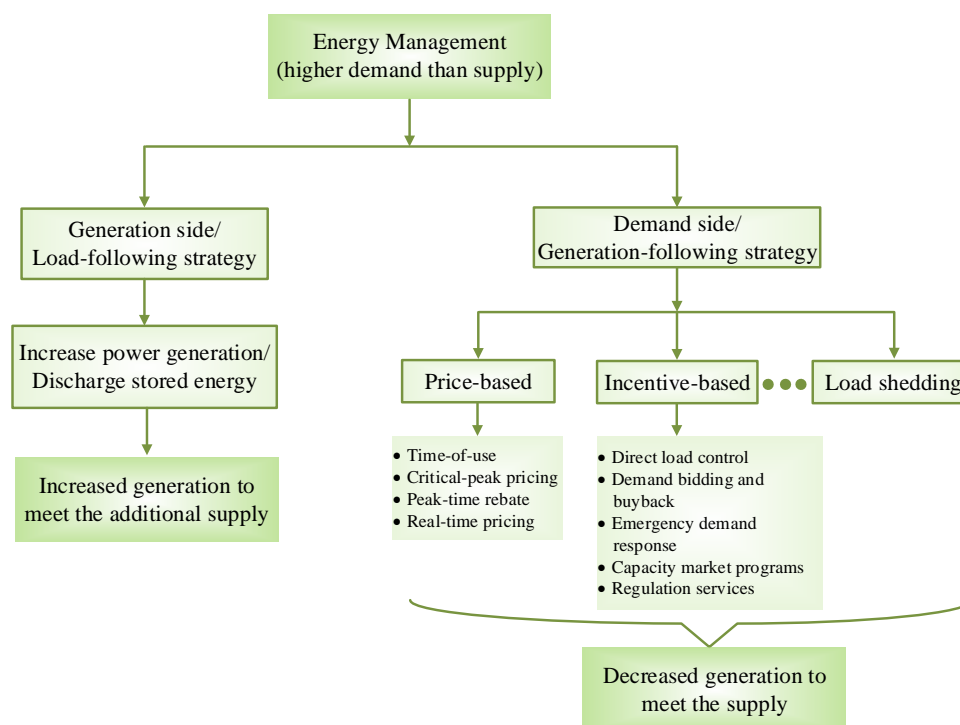
Figure 12. Energy management of microgrid including demand responses.

The linear programming model for minimising load consumption which balances the power supply and demand presented in [262] demonstrates that demand fluctuations can be reduced by up to 19%. A cost-minimisation model for the optimal energy management of a grid-connected

microgrid is described in [263]. It incorporates a charging spot for vehicle-to-grid systems, energy trading costs, the wearing costs of EVs' batteries and penalty costs of load shedding. In [264], a power management mechanism that includes PV systems with storage that allows the massive penetration of PV power into a grid network using a peak-shaving service is discussed. In it, a predictive control system based on a DP approach is applied to optimise the power flow of a grid-connected PV system with storage. An operational scheme for optimising RESs and the energy management of a battery considering solar, wind, battery and utility powers is developed in [265]. In [266], adaptive DP (ADP) is employed in an office building for the optimal control of battery energy management. In [267], a comparative study of various methods for implementing residential energy scheduling with respect to a battery model, charging/discharging rate and capacity is conducted. An intelligent dynamic energy management system (I-DEMS) for optimally using RESs and an ESS for maintaining a continuous electricity supply to critical loads by applying ADP is developed in [268]. In [269], a hybrid swarm intelligence-based algorithm considering operational costs and reliability as a multi-objective approach for the optimal operation of a microgrid is presented. Real-time distributed algorithms – consensus and optimal control ones – that depend on local computation and sparse communication networks to optimise the overall social welfare are discussed in [52]. An online energy management strategy considering the power flow and operational constraints in a network for the real-time operation of a microgrid is implemented in [270]. Research in the field of energy management can be further conducted by the application of novel optimisation algorithms with the incorporation of different objective functions to find optimal operational points with reduced computational time and complexity.

Demand response: The increasing integration of RESs in a microgrid leads to difficulty in balancing its power supply and demand. Although this can be achieved using spinning reserves or ESSs, it incurs a significant investment cost. Therefore, energy operators emphasise a demand response that balances the power supply and demand based on customers' participation. This is because of its involvement in generation-following strategies that respond to the availability of power generation rather than load-following ones, as shown in Figure 12. As, traditionally, energy providers do not provide incentives for consumers to change their load patterns, clients are unaware of ways to efficiently use energy [271]. However, those who exhibit a demand response by changing their power consumption in relation to the market's electricity prices are currently encouraged by the provision of different types of programs, such as direct load control, the emergency demand response program (EDRP), demand bidding, capacity market programs, interruptible rates, time-of-use (TOU), real-time pricing (RTP) and critical-peak pricing (CPP) [272–277]. These programs have their own unique features that determine their suitability for a particular community and basically offer financial incentives or impose penalties to encourage customers to use their loads flexibly. Some loads that a customer can reschedule according to the response of a program are those of air-conditioning systems, water heaters, EVs, washing machines and pumps. A demand response can help to achieve peak-load shaving, improve energy efficiency, decrease generation capacity, manage electricity costs, ensure network security, save energy and increase grid reliability. Also, it can maximise the capacity of a network by deferring the need for new investment in constructing the lines required by increased power demand [278,279]. Load-shaping techniques using demand responses are shown in Figure 13.

Economic operations based on the demand responses of a microgrid are investigated in [281–283] and various price-based offers aimed at encouraging customers to participate in programs discussed in [281]. In [282], interruptible load-based programs available for a variety of consumers are demonstrated while a real-time load-scheduling algorithm for the short-term power management of RESs at a minimum reserve cost is presented in [283]. An optimal economic dispatch of grid-connected microgrids considering the demand response which aims to minimise the effect of intermittent RESs and provide incentives to consumers is discussed in [275]. In [276], the effects of irrational incentive values and consumers' participation in an EDRP in the presence of various uncertainties are analysed, and it is concluded that the optimum operational cost is related to the
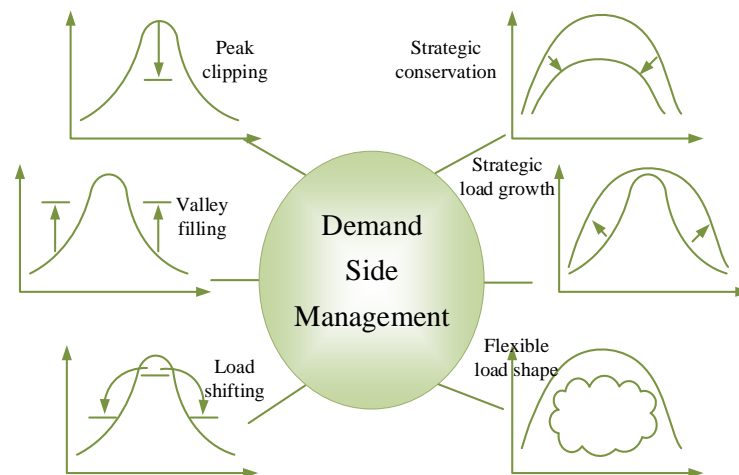
Figure 13. Demand-side management for load-shaping techniques [280].

accurate selection of incentive values. A robust optimisation approach that considers an uncertainty model of upstream grid prices to obtain the optimal strategy for a microgrid to bid in a day-ahead market is proposed in [277].

A financial-based demand response still suffers from promoting its rapid acceptance by electricity clients [284] while the demand response to a real-time price requires modifying the hardware on both the utility and consumer sides. As a result, both ageing utility workers and customers are unwilling to accept any quick changes in terms of technological infrastructures, e.g., the installation of communication lines and smart meters, which are perceived as intrusive [285]. Therefore, educating the society about recent advance in technologies is essential to realise a large scale implementation of the demand response, otherwise it may take longer than expected to observe its widespread effectiveness.

In future, the demand response will be able to be realised in ways other than program-based ones as the number of prosumers (**pro**ducer+con**sumers**) is gradually increasing. Then, peer-to-peer (P2P) energy trading with the help of smart devices that facilitate each prosumer to take part in energy trading with one another will become an easy option for reducing electricity costs and energy storage losses, and optimising the output from RESs. Thus, the energy operators should take into account the rules and regulations about their power exchanging trades [286]. In addition, as the energy trading deals with the decision-making process of participants with their own interests, the process needs to be modelled based on mathematical and signal processing tools to guarantee an efficient operation. The main challenges of the P2P energy trading is to model user behaviour, ensure the users' privacy, design pricing schemes and maintain trust between users [287]. There are a lot of opportunity to improve the P2P energy trading in the future smart grid.

Coordination among microgrids: A distribution network can contain a large-scale integration of RESs through clusters of microgrids, called a multi-microgrid, that can be operated as a reliable power supply in the network during major external events. The formation of a multi-microgrid can enhance the economic and operational performance of each individual microgrid by reducing its energy exchange with the main grid. However, achieving the optimal operation of different microgrids is a challenging task, particularly under the influences of irregular RESs [288] because of the number of energy exchanges among the microgrids; for example, every microgrid firstly satisfies its internal power balance and then the amount of surplus power it supplies depends on the operations of the other microgrids in finding suitable energy trades within the multi-microgrid. Subsequently, a multi-microgrid is required to check whether it needs further energy exchanges with

the grid to comply with the energy balance constraints. Also, each microgrid has its own profit-driven goals (local optima) that may contradict the objectives of the system operator (the global optimum).

The multi-microgrid concept was first introduced in [289] in which its technical feasibilities and complexities for providing primary reserves are investigated. In [290], a hierarchical control method for dealing with the frequency issues of a multi-microgrid is presented. A framework for operating microgrids at various frequencies, in which each microgrid is connected to a common dc line through an interlinking inverter controlled using a droop frequency to reduce the number of interlinking converters, is demonstrated in [291]. It is also shown that the frequency control can be improved using the energy reserve of neighbouring microgrids which enable a high level of integration of RESs without the need for a large energy reserve. A coordinated management strategy for voltage and frequency controls that allows for a large number of RESs in a multi-microgrid and uses a meta-heuristic algorithm to support the voltage and a hierarchical structure to regulate the frequency during a transition is presented in [292].

There are several publications in the literature that deal with the interactions in a multi-microgrid. A scheme for energy trading with scheduling using the Nash bargaining theory to encourage proactive energy trading and benefit sharing is developed in [293]. A multi-objective approach for developing a fair scheme among microgrids, the power grid and the independent system operator to avoid conventional utility maximisation is presented in [294]. An optimised strategy that considers DG units, storage systems, EVs and demand responses to assess the energy management of microgrids is described in [295]. In [296], a distributed energy management technique for minimising a multi-microgrid's operating cost through exchanging power with neighbouring microgrids and the grid utility in a real-time market is developed. An analytical target-cascading theory for decoupling the dynamic economic dispatch between a multi-microgrid and grid utility to improve the power dispatch's efficiency is discussed in [297]. In [288], a two-stage robust optimisation algorithm that considers discrete aggregates of the energy transactions among microgrids to reduce the operating cost is demonstrated. The first stage is used to buy/sell decisions and the second to optimise the power to be bought/sold under the worst-case energy scenarios. A study of cooperative game theory for achieving a highly energy-efficient operation of a multi-microgrid is presented in [298]. It considers the potential conflicts of interest when maximising profits between microgrids' owners and system operators to obtain a trade-off solution, and concludes that power exchanges among microgrids can decrease the cost of power generation. A contingency-based energy management scheme for preventing a network from incurring economic loss is developed in [299]. It formulates the probability of contingencies in the energy management system for a multi-microgrid to avoid their effects in terms of economic losses. An energy trading using a game theory to balance the power generation and consumption of a multi-microgrid is designed in [300] and the basic structures of those networks from various sides can be found in [9]. The work of a multi-microgrid can be further extended to enhance the energy efficiency and reliability by mathematically modelling different scenarios and uncertainties.

Smart meters and cyber attacks: Demand-side management can be facilitated by employing smart devices, such as smart meters and communication links, at consumers' premises to obtain the necessary data using advanced measurements and acting accordingly. Their communication links can assist in controlling the power demand by sending hourly electricity prices, which are usually high at times of peak load demands, from the utility to customers to shift flexible loads, such as washing machines, dishwashers and water heaters [301]. As the electricity price depends on the power demands on a network, it is essential to access all the data on those of consumers, with an explicit-duration hidden Markov model with differential observations that receive these data from home appliances developed in [302]. An energy management scheme with smart meters is demonstrated in [303] using a SCADA system that monitors a network of programmable logic controllers (PLCs) to collect various types of information from modern buildings.

There are some challenges related to implementing and operating an advanced metering infrastructure (AMI) due to the precision required for data reading and transmission, and its use of a high frequency that introduces privacy issues regarding consumers' data [304] because, as data are transmitted through WLAN/HAN/NAN networks, cyber-attacks by external controllers may steal information. A load-hiding approach that conceals the actual consumption of loads using storage systems is designed in [304]. In [305], information leakage from a smart meter is studied using a RES and battery to partially hide customer details, and it is concluded that larger batteries can help to enhance privacy by exploiting the available energy. To determine malicious meters, a fraud detection system (FDS) is developed in [306] while detectors in both centralised and distributed settings for the online detection of false data injection (FDI) and denial of service (DoS) attacks are proposed in [307] using a CUSUM algorithm. As exposure to radio frequencies from smart meters during wireless communication is another concern, various countries have taken action to limit its bad effects [308]. A state-of-the-art survey of cyber security in [309] demonstrates its risks and offers solutions to the problem of increasing the security of power systems. New detection methods to protect information from cyber-attack need to be continuously developed with the advanced of technologies.

Regulatory policies: Regulatory policies are the principal motivation for customers and investor-owned electricity utilities to construct microgrids in order to obtain an effective and economical energy supply. The implementation of a microgrid can be facilitated through policies that prescribe guidelines for integrating DG units in it and connecting it to the grid utility. The current regulatory process is complex due to the amalgamation of different existing rules and regulations that are not particularly suitable for microgrids [310]. Although they are designed to maintain standard operations during a disturbance in a microgrid [311], the high connection fees are the main burden for microgrid operators [312]. Also, the islanding operation, one of the most-cited features of microgrids, creates conflict with existing rules and regulations as it has a large effect on the power supply of a grid utility. Furthermore, bidirectional meters that need to be installed at the PCC to record energy exchanges between a microgrid and grid utility are another important issue. More research is still needed to realise the full benefits and thereby perceive politicians or lawmakers to amend the current laws in favour of constructing a microgrid.
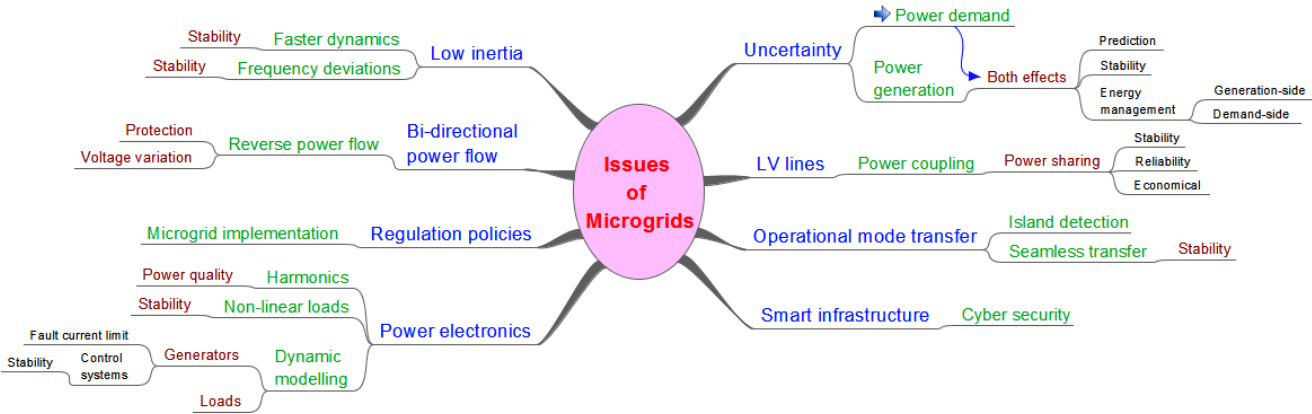
Figure 14. Pictorial elaboration of key issues for microgrids.

Remark 2: Numerous challenges that are barriers to fully exploiting the benefits of a microgrid can be identified from the above discussion. Of them, the key issues that lead to other difficulties are shown in Figure 14 and summarised as follows.

- Uncertainty: The stochastic nature of a RES, together with its non-dispatchable power generation, which leads to a generation-following strategy, is the greatest challenge for managing the second-to-second power balance of a microgrid for its economic, reliable and

efficient operation. In addition, the uncertainty in power demand, which is much greater in a microgrid than bulk power system because of the limited number of load participants, is another challenge.

- Low inertia: The dynamics of converter-interfaced DG units are almost neglected, except for those of the filters of an inverter and the capacitor at the dc-bus, compared with those of synchronous generators. Therefore, any change in a network prompts its DG units to respond quickly which may lead to instability because of the severe frequency deviations of an islanded microgrid.

- LV distribution lines: The LV lines, in which RESs are integrated, are dominated mainly by resistance rather than inductance. Therefore, conventional control theories need to be revised as there is a strong coupling in both the active and reactive powers which leads to power-sharing issues.

- Bi-directional power flow: The installation of DG units on distribution lines designed for a unidirectional power flow causes a reverse power flow along the lines which leads to a voltage rise, unexpected power patterns and an abrupt fault current.

- Power electronics: The participation of a large number of power electronic devices in the process from power generation to demand may cause harmonics in a network. Although this can be controlled by adequate control designs, it may lead to issues regarding power quality and stability in microgrids.

- Operational mode transfer: As one of the main features of a microgrid is its capability to be operated in both grid-tied and islanded modes, it is essential to precisely detect any unintentional islanding and then re-synchronise the microgrid with the grid utility.

- Smart infrastructure: Microgrids are building blocks of a smart grid that is equipped with modern technologies and communication systems which an intruder may use to hack into particular information or an entire system.

- Regulatory policies: As the rules and regulations in energy policies can encourage investors to build microgrids to receive financial benefits, governments should initiate the formulation of rules in favour of implementing microgrids.

4.5.2. Benefits of microgrids

A microgrid established in a defined region with a centralised control unit has several advantages, including offering all the benefits of using DG units in a distribution network as well as providing extra facilities to the locality due to its control over the entire area.

More reliable power supply: The power generated by DG units in a microgrid is supplied to end-users in a specific region with high-priority power needs, with the electricity demand divided into two categories, critical and non-critical. In this way, a microgrid is capable of maintaining a continuous power supply to critical loads during a scarcity of power while providing the remainder to non-critical loads, thereby improving the overall power supply.

Smart electricity management: In a microgrid's operation, its central control unit facilitates dynamic demand responses in the network. Therefore, consumers are able to tailor their demands according to the electricity price which balances the power demand and generation, whereby consumers can enjoy low electricity prices and a microgrid operator can manage the demand responses.

Economic benefits: If a microgrid is constructed on an island for geographical reasons, the community can benefit by operating small-scale factories and irrigation to improve its lifestyle and economy. Also, business activity is increased due to access to electricity for freezing and heating systems, and other modern amenities. Moreover, the RESs used in a microgrid are environmentally friendly and can provide an island with sustainable development.

Improved stability of grid network: Microgrids are self-controlled entities from the grid utility perspective due to their own operating capabilities during any undesirable situation, such as a major

storm or fault on the main grid. These features enable them to simultaneously improve their stability and that of the grid utility because they can detect any malfunction within their regions and act accordingly to protect themselves and the grid utility against cascaded failures.

High integration of RESs: RESs are stochastic in nature due to their high dependence on the weather; for example, solar energy is produced from solar irradiation and wind power from the wind's speed. Although integrating them in a distribution network poses challenges, these can be overcome by using a central control approach for a microgrid. Most importantly, a high penetration of RESs in a microgrid reduces carbon emissions, thereby providing socio-economic and environmental benefits.

5. Future work

As a microgrid has evolved from a distribution network and can be viewed as a building block of a smart grid supported by modern communication architectures, microgrid research is likely to continue until smart grids are fully established everywhere. Although there are different projects on converter-based microgrids, most are implemented as test beds and there are still several challenges that need to be addressed before realising the full potential of microgrids. Different approaches developed with the aim of applying a particular solution method have some limitations. As extensive research on microgrids has been conducted during the last decade, some issues, such as their inner control and power sharing, have been resolved to some extent. However, as it is still possible to develop better techniques for improving a microgrid's performance, future work is likely to be conducted in the following areas.

• Advanced control techniques (such as artificial intelligence, predictive control and MASs) considering high penetrations of RESs with different power ratings need to be designed/implemented to resolve issues regarding power quality and power sharing. However, proper power sharing for RESs, which is in a practical field, is often overlooked as it is assumed that the voltage source at the inputs to a converter is ideal.

• As an effective control application depends on the accuracy of the model of a system, the uncertainties in a microgrid, for example, those of catastrophes, power and loads, should also be modelled when designing an advanced controller, the complexity of which can be reduced for implementation in practical systems.

• The low inertia of DG units may experience severe voltage and/or frequency changes during abrupt disturbances. Although there is some previous research that increases the response times of DG units by applying a flywheel and/or mimicking synchronous generators, there are still opportunities for researchers to develop a microgrid with improved inertia.

• Maintaining the stable operation of a microgrid is challenging due to the increased participation of non-linear loads and high penetration of DG units. Although the stabilities of microgrids with linear loads in a radial network have been extensively studied recently, determining the stability margins of a mesh network for DG units and synchronous generators with non-linear loads, such as induction motors, constant power loads and electrical vehicles, has not been thoroughly investigated.

• Power management of the generation side of a conventional power system using several optimisation algorithms is being extensively studied, with algorithms taking into account the effect of RESs now applied to microgrids. However, as they often do not analyse the objective functions, they obtain only slight improvements in outcomes compared with those of other algorithms. Also, optimal energy management considering multiple energy providers or multiple users can also be explored in future research.

• A new set of rules and regulations for incorporating DG units with an advanced metering infrastructure in microgrids is required to efficiently implement demand-side management as there are no appropriate policies in many countries.

● As, in recent papers, the control strategies for a converter are generally not integrated with an energy source, the dynamics of an integrated system have not been developed. However, this is necessary for a detailed analysis of the stability of a microgrid.

● There are few research studies that deal with the management of a multi-microgrid or peer-to-peer energy trading which is a promising field for future research as RESs are increasingly being integrated in distribution networks to improve a system's overall efficiency and provide a smooth transition between its grid-tied and islanded operations.

● Although the optimum operation of battery energy is a key subject for an islanded microgrid, there is little research that considers the cost of a battery's lifetime when it is applied to improve a network's voltage profile and stability, and minimise operational costs.

● As cyber hackers invent new ways of attacking power networks, advanced protection methods need to be continually developed.

6. Conclusions

The paper clarifies the concept of a microgrid and a modern distribution network in a broad perspective. In a modern distribution network, a high penetration of RESs is restricted due to severe issues regarding the grid utility whereas a microgrid is capable of overcoming these problems because of its unique regulation features, such as having a specific area controlled by an MGCC. Although the microgrid concept was introduced back in 2002, there is a no clear distinction between a microgrid and a distribution network due to their very similar functionality. In this paper, the features of these two terms are distinguished based on their components, characteristics, advantages and disadvantages. In addition, this study establishes a definition for a converter-based microgrid after analysing the well-known microgrid definitions. The relative technical challenges and solutions of microgrids are analysed to show current progress. It is expected that this paper will help researchers to focus on the fundamental ideas of a microgrid, and its challenges and opportunities.

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