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AC-microgrids versus DC-microgrids with distributed energy resources: A review

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ABSTRACT

This paper presents the latest comprehensive literature review of AC and DC microgrid (MG) systems in connection with distributed generation (DG) units using renewable energy sources (RESs), energy storage systems (ESS) and loads. A survey on the alternative DG units' configurations in the low voltage AC (LVAC) and DC (LVDC) distribution networks with several applications of microgrid systems in the viewpoint of the current and the future consumer equipments energy market is extensively discussed. Based on the economical, technical and environmental benefits of the renewable energy related DG units, a thorough comparison between the two types of microgrid systems is provided. The paper also investigates the feasibility, control and energy management strategies of the two microgrid systems relying on the most current research works. Finally, the generalized relay tripping currents are derived and the protection strategies in microgrid systems are addressed in detail. From this literature survey, it can be revealed that the AC and DC microgrid systems with multiconverter devices are intrinsically potential for the future energy systems to achieve reliability, efficiency and quality power supply.

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1. Introduction

According to the history perspectives, AC power network has been the standard choice for commercial energy systems to power the incandescent lamps in our residences and motors in our factories since the late of 19th century. The easy to transform AC voltage into different levels for various applications, the capability to transmit power over a long distance and its inherent characteristic from the fossil energy driven rotating machine, made the AC power network to become the main choice. To this point, the AC power networks have existed for more than one century ago along with the AC loads dominated in the market [1]. However, high energy costs together with limited fund to construct new large power plants and long distance transmission lines are some of the constraints to meet the growing energy demands. Moreover, the global warming, aging of the current power system infrastructures, increased awareness of limited energy generation resources, higher energy consumption standards and the increased number of DC loads due to advance in power electronics reveal that modernization of the current energy system is inevitable [2].

In the last two decades, modern solutions such as renewable based DG units, energy storage systems (ESSs), flexible AC transmission systems (FACTS), active demand management (ADM), AC microgrids and advanced control strategies based on information and communication technologies (ICTs), have made possible for energy engineers and researchers to redesign the conventional power systems. However, not all these redesigning procedures are accomplished until now, as more researches are needed to make such advanced systems a reality. In that case, the designed and implemented AC microgrid systems utilize the existing AC power system standards such as frequency, voltage levels and principles of protection for their operations [3,4]. On the other hand, the introduction of grid control using the mercury vapor rectifier around 1903 gave rise to electronic devices application in high voltage direct current (HVDC) transmission in 1928. This was due to their remarkable ability for rectification and inversion of DC power [1,5]. Since then, the DC power systems had been restricted only to some special applications such as telecommunication systems, shipboards, tractions, HVDC transmission systems and AC power systems for control and protection [6–8]. However, the development in power electronics technology has raised a number of DC loads and more power converters for DC voltage transformation into various levels for different applications [9–11]. Today, the DC distribution systems (DC microgrid systems) are applied in avionics, automotive, marine and manufacturing industries for power distribution [12–14]. The international space station (ISS), spacecraft, modern aircraft and modern electronics loads such as computers and servers in data centers, and banks and electronics factories, require DC power supplies [15–17].

To manage our future energy demands, a more configurable, flexible, informative and physical energy system in the low voltage distribution networks if not the whole power network, is mandatory [18–20]. Due to this point of view, microgrids (MGs) are emerging and becoming more attractive structures with integration of renewable based DG units and ESSs [21,22]. So far, the DG units include several technologies such as wind turbines [23–25], photovoltaic (PV) arrays, fuel cells, and micro-turbines [27] while the ESSs are the batteries, flywheels and supercapacitors [28–30]. These components are the central ideas in the microgrid structures and are also regarded as the solution to the population without access to energy or with poor energy supply and entitled to effectively reduce the greenhouse gas (GHG) emissions [31–33]. Furthermore, the DG units provide a relief to stressed conventional power transmission and distribution infrastructures [34–36]. Besides, the liberalized electric market with demands for efficient, reliable and diversified energy resources constitutes the most important driving forces for high penetration of DG units into the energy systems.

At present time, most of renewable based DG units directly produce DC or variable frequency/voltage AC output power and hence power electronics devices (PEDs) have become the key elements in order to realize the MGs. Because of their vicinity to different types of loads (i.e. AC and DC), the DG units such as the fuel cells and the micro-turbines can be used to provide combined heat and power (CHP) generation with improved overall efficiency. With ESSs connected to the DG units such as fuel cells, a controllable output power to meet the grid codes or load transient requirements can be produced. The wind turbine and PV array based DG units are usually controlled with maximum power point tracking (MPPT) to maximize their energy generation [37–39]. Similarly, the ESSs with wind or PV based DG units can also produce controllable output power to facilitate the dispatched power generation and load demand matching [40–42]. Consequently, the MG provides an opportunity to optimize the utilization of renewable energy resources with improved overall thermal and electrical efficiencies by properly locating different DG units while considering their geographical conditions and the nature of available loads [43]. Such operating conditions require the microgrid systems to have wide-range control systems in order to perform large number of tasks [44]. For example, the guarantee to system security, optimal operation, emission reduction and a seamless transfer algorithm from grid-connected mode to islanded mode without violating system constraints and regulatory requirements are some of the main tasks [45,46]. Also, the MGs for standalone and grid-tied applications have been considered in the past as separate cases [47–49]. However, it is important nowadays to conceive flexible MGs that operate in both modes [50–52]. System protection within the microgrid components [53] and short-circuit currents limitation can be achieved through a proper coordination of the DG units [54–56].

This paper presents the latest researcher's literature review in the field of AC and DC microgrid systems integrated with renewable based DG units, ESSs and mixed (AC and DC) loads. The motivation to carry out this study is the growing interests of renewable based DG units, ESSs and the continuous changing in the type of customer's equipments from the dominated AC-type to DC-type loads. Thus, a survey on microgrid systems with various DG units configuration in low voltage AC (LVAC) and DC (LVDC) networks in regard to their current and future applications in customer equipments and energy market are included. Referring to the economical, technical and environmental advantages of renewable energy sources (RESs), a detailed overview between AC and DC microgrids is provided in relation to their feasibility, control strategies and protection approaches.

The paper is therefore structured as follows: a description of the various DG units' configurations and their interconnections with low voltage AC and DC networks in relation to the power output is provided in Section 2. Study about the feasibility of microgrid systems is discussed in Section 3 while the control and energy management strategies in microgrids are presented in Section 4. Furthermore, the discussion on microgrid system protection techniques is given in Section 5. Finally, Section 6 draws the conclusion and future trends.

2. Overview of microgrids with DG units

Distributed generation (DG) units as referred to small generators or decentralized generations can either be used as stand-alone systems at an isolated area (e.g. rural areas) or utility-connected systems [57–59]. When used as stand-alone systems, the DG units are usually operated by individuals to serve small houses such as single households to large buildings e.g. housing estate or suburb locality, an academic or public community, an industrial site or municipal region [60,61]. Larger capacity DG units are managed by the utility or an independent power producer (IPP). The utilities use DG units to help them to improve power supply flexibility, quality and expandability, system stability, optimize distribution system and reduce transmission and distribution cost. In most cases, the DG units produce incompatible AC power or DC power as a result the desired voltage magnitude, frequency and phase angle are usually obtained through the use of power electronics interfaces [62–64]. Each DG unit can be connected to the main grid by using the appropriate power electronics interface. However, using a single power electronics interface for all DG units leads to advantages of reduced losses, easier design and control with reduced cost [65,66].

So far, the DG units based on RESs are generally more sustainable (i.e. their energy sources will not perish in the long run) with little or no environmental damage than their counterparts. Solar PV arrays [37,66], geothermal and wind [25,26], tidal waves [28,31], low-head (small) hydro, biomass and biogas [38] together with hydrogen fuel cells [42] (hydrogen extracted using renewable sources) are examples of RES based DG units. These DG units can be aggregated to provide DC input voltage for the DC/AC inverter for grid-connection or strategically connected to the low voltage distribution systems (i.e. LVAC or LVDC networks) depending on their power output to form microgrid structures [67,68]. Alternatively, the microgrid concept enables high penetration of various DG units and ESSs without the need of restructuring the distribution system itself. The next Sections 2.1, 2.2 and 2.3 present the definitions and overviews of the DG units in LVAC network, LVDC network and microgrid systems with the connection possibilities of various DG units and loads.

2.1. Definition of LVAC networks

All electricity generating units (e.g. DG units) with AC power output are directly connected to an AC bus line and then to the main system via power converters for their stable coupling. Examples of the DG units that produce the AC output power include wind turbines, low-head hydro, biogas, tidal and wave turbines [4]. These are usually directly connected or may need the AC/DC/AC power converters to enable their stable coupling with the LVAC networks. In that case, the LVAC network can be interconnected with the bulk system (utility) through a power transformer. In addition, the AC loads are directly connected while the DC loads need the AC/DC power converters in order to be connected to the LVAC networks. On the other hand, the DG units which produce DC power output (e.g. solar photovoltaic arrays, fuel cells and energy storage devices) can be connected to the AC bus line of the LVAC networks using DC/AC inverters [5,8]. Fig. 1 indicates the typical configuration of the DG units with the AC power output (e.g. wind turbines) and that with the DC power output (e.g. PV systems and fuel cells) connected to the LVAC network.

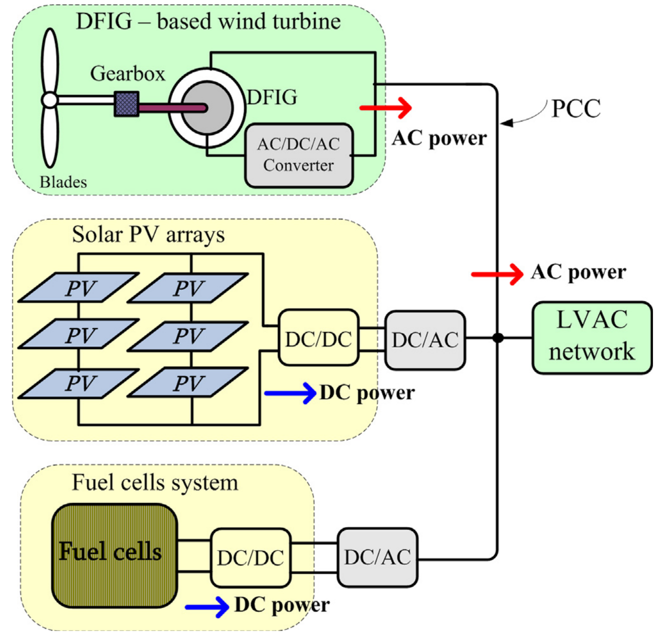


Fig. 1. Typical configuration of the DG units with LVAC network.

2.2. Definition of LVDC networks

Operation of today's consumer equipments and tomorrow's distributed renewable energy generating units needs us to ponder the alternative energy systems. With the concept of smart grid coming up, the LVDC networks such as those used for industrial power supply and commercial buildings are increasing daily [73]. In the future, the DC distribution system will become an alternative way to supply all the electrical equipments connected by a bus system and optimally controlled by an energy management system (EMS). As an example, the PV systems have a highly modular structure with many possible configurations available in which the PV inverter can be connected [5]. The emerged configurations are designated as the central inverter or string inverter. In that way, the DC based DG units and energy storage devices produce the DC power which would be easily connected to the DC bus line or LVDC network. An ESS can also be charged/discharged with the LVDC network and loads (AC and DC loads) be connected [6,7]. In this case, the AC power generating units need an AC/DC power converter for their connection to the LVDC network [8–10]. Fig. 2 depicts the LVDC network with DG units connected to it via the common bus bar at PCC. To this end, the AC based DG units (wind turbines) connection to the LVDC network requires inverters while the DC based DG units are directly connected as indicated in the figure.

2.3. Microgrid systems

In a broader and futuristic manner, microgrids (MGs) are tiny power systems which embed various components such as controlled and uncontrolled loads, DG units and storage devices operating together in a coordinated manner with controlled power electronic devices (active and reactive power flow controllers, frequency and voltage regulators) which are integrated with protective devices [1,2]. They can be operated based on the principles of the AC power systems (i.e. AC microgrids) or DC power systems (i.e. DC microgrids). Thus, the architecture of the future energy system will eventually look very different from that

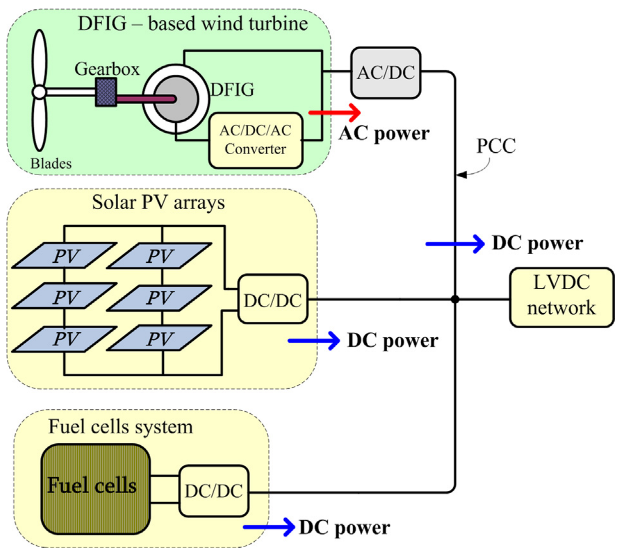


Fig. 2. Typical configuration of the DG units with LVDC network.

of the conventional energy system along with the MGs expected to be the main building blocks [66,67]. In this context, the future energy system i.e. "The smart grid" is anticipated to have the following features [68–70]:

- Energy efficiency, sustainability and RESs inputs.
- Reliability, security, ESSs and DG units (renewable based).
- Sensing, measurements and advanced control methods.
- Load usage awareness, real-time EMS and advanced load components (e.g. electric vehicles, heaters and industrial motor drives).
- Integrated information and communication infrastructures full of cyber-security.

The above features can satisfactorily be achieved through the use of the MGs and often at lower cost with greater efficiency than measures applied to the conventional AC grids. Further of this, the MGs can benefit both the utility and the customers as follows:

- *To the utility*: The MGs are treated as controllable entities that operate as a single dispatchable unit (load or generator) to provide power or ancillary services and meet the needs of the upstream networks. Moreover, the MGs involve alternative energy sources which can offer far higher efficiency and reduce environmental degradation contrary to most conventional power generation units [71]. They are also strategically installed near the loads to provide a variety of benefits such as network voltage and frequency regulation if properly operated [74].
- *To the customers*: The MGs can provide both thermal and electricity needs to meet special demands such as local reliability, and can improve power quality by supporting local voltage and frequency [72]. They not only reduce the effects of voltage sags but also offer uninterruptible power supply functions as may be needed in the areas with critical loads, such as banking systems, semiconductor industries, hospitals and data centers [73]. It is also possible for microgrids to suit the needs of an area it would be serving. That is to say, the MGs can be the fundamental power source that provides energy for lighting only as required in most of the rural areas [75,76].

Next, the MGs can be operated in a grid-connected mode or an autonomous islanding (standalone) mode, and these two operation modes of MGs can be briefly described as follows: When tied to the utility system (i.e. grid-connected mode), it is known as "*On-grid mode*". In this mode, the MG is usually connected to the main medium voltage (MV) e.g. 11–66 kV, or low voltage (LV) e.g. 110–690 V networks depending on the location and the total capacities of the installed DG units [77]. It either receives or injects some amount of power into the main system and provides power support to its local loads. Moreover, the main function of the DG units is to generate power and provide local and power support in the microgrid systems. With the interfacing power converters, controllable active and reactive powers can be produced in MGs whereby their reference values of each DG units are commanded by the microgrid operating manager (MOM) [78,79]. Also, some DG units can be controlled to track their maximum power point (MPP) as in wind turbines and PV arrays. Upon fault occurrence and its subsequent switching incidents, or preplanned switching events, the MG is disconnected from the utility as soon as possible and picks up its local loads. In this case, the MG is in islanding mode also known as "*Off-grid mode*" and it operates autonomously in a similar way to the physical islands when disconnected from the main network. The least important loads can be shed if the power capacity of the MG is insufficient to support all its local loads [80,81].

On the other hand, the future energy system is anticipated to be based on the various DG units, storage devices and controllable loads all networked with the advanced information and communication devices. In such an energy system, the MGs, DG units and ESSs can be aggregated and be used as the "virtual power plant (VPP)" main building blocks [1,82]. In contrast with the MGs, the VPPs are the new concepts which consist of aggregated DG units that are treated as a single entity. Typically, the individual resources would be small but pooled together to form a size which can provide reactive power or support peak power demand. Given their multiple locations with different generation technologies, it will be easy to see how controlling a group of small, dispersed DG units would be facilitated by ICT-assisted grid control. In that case, the power system will rely upon software systems to remotely and automatically dispatch and optimize generation, demand-side or storage resource in a single, secure web-connected system [83]. In fact the VPP will represent an "internet of energy", whereby tapping the existing grid networks to tailor electricity supply and demand services for a customer, maximizing the values for all utility participants through applications of the ICT [84]. Fig. 3 illustrates the details about the concepts of the VPP and MGs.where the abbreviations HAH—Home Area Network, BAN—Building Area Network, IAN—Industrial Area Network, FAN—Field Area Network, NAN—Neighborhood Area Network, AMI—Advanced Metering Infrastructure and CCLs—Customers with controllable loads.

3. Feasibility of AC and DC microgrid systems

Electric grid delivers electricity from the point of generation to consumers, and the electricity network functions via two primary systems, namely: (i) transmission system and (ii) distribution system. The transmission system delivers power from power plants to the distribution substations while the distribution system delivers power from distribution substations to the consumers. In that case, the centralized power stations are usually located quite far from the load centers. It is therefore difficult for the power system operators to monitor and address the disturbances occurring at the load centers. However, the DG units connected to the grid at low voltage level in the form of MGs are gradually changing the structure of the conventional grid from passive to active distribution networks [11]. Their interconnection with electric power system in the distribution level opens new

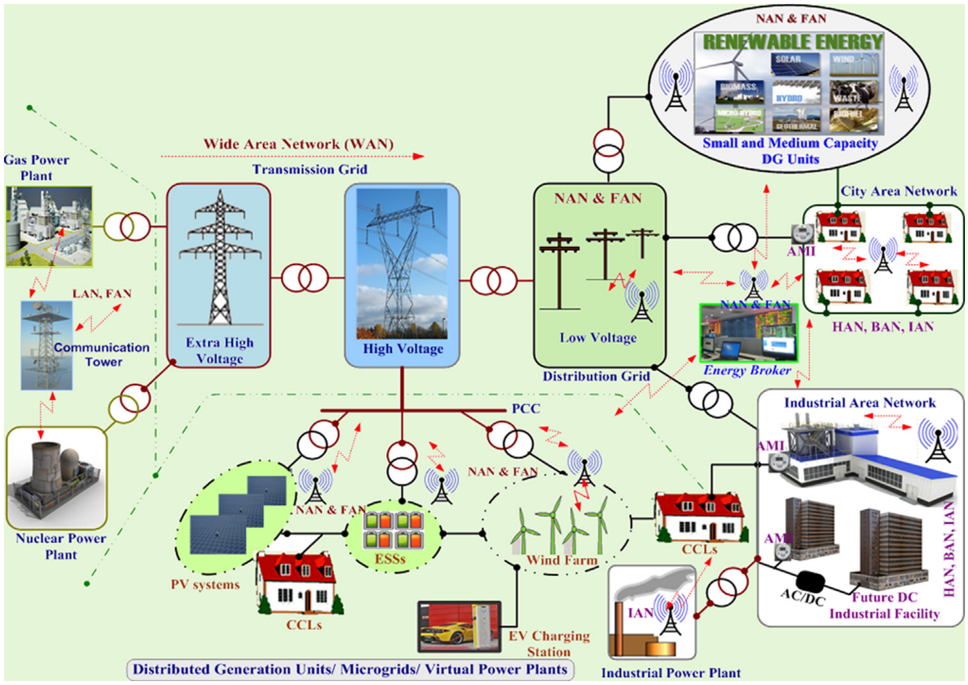


Fig. 3. Typical configuration of VPP system.

possibilities of easily controlling any component in the network. Furthermore, in the near future, customers are expected to be able to generate, store, control and manage part of the energy they consume through the deployment of microgrids [16,70]. The future energy system is anticipated to incorporate more intelligence devices installed in the generation units, transmission lines, substations, and distribution networks and some controllable loads. It will be a combination of both power system and information and communication system networks. The two networks will be embedded to form a more advanced architecture whereby the flow of power and information will be a two-way system, allowing customers to have access to the state of the grid such as: (i) current peak power demand, (ii) the electricity tariffs at the energy market and (iii) how to minimize their bills. In so doing, customers can easily communicate and sell their excess or stored energy to the utility at the reasonable price. Again, the electricity market participation for any DG unit will be the key aspect of the microgrids and VPP concepts. Depending on the combination of the DG units, flexible loads and storage units, customer's participation in different electricity markets will be possible [85]. At the moment it is not profitable for a small DG unit to participate in the market, because most of the countries e.g. in Europe where these concepts have been widely spread, have feed-in tariffs which are more attractive. But the tariffs decrease yearly with a given percentage depending on the DG unit technology.

So, in the future the participation of the microgrids in the form of the VPP in different energy markets could be essential. One big advantage of the VPP is that the whole cluster can be managed by one broker or trader, reducing the market participation costs for a single unit significantly. In that case, the individual owner of some DG units can generate power and store the excess generated power in the ESSs. The stored energy may be discharged during peak demand to earn income [86]. Therefore, with the AC and DC microgrid systems equipped with the DG units, ESS and mixed controllable AC and DC loads, customers are expected to have information access of every unit connected to the given microgrid system. This reflects the idea of the future energy system of which the electrical and communication infrastructures expected to be embedded together [82]. Therefore, the literature survey of the AC and DC microgrid systems is provided in the Sections 3.1 and 3.2, respectively.

3.1. AC microgrid systems

A typical AC microgrid systems interconnected with MV system at the PCC is shown in Fig. 4. The main system could be an AC or DC bulk system. The DG units and ESS are connected at some points within the distribution networks. Part of the network consisting of the DG units and load circuits can form a small isolated AC electric power system i.e. an 'AC microgrid'. During normal operating conditions, the two networks are interconnected at the PCC while the loads are supplied from the local sources (e.g. the RES based DG units) and if necessary from the utility. If the load demand power is less than the power produced by DG units, excess power can be exported to the main system. Table 1(a) indicates some typical examples of the AC powered loads that are available in our homes. Meanwhile, Table 1(b) shows some typical examples of AC MG systems installed in various countries or used as testing prototype. In most cases, the AC microgrid system operations adopt the voltage and frequency standards applied in most conventional distribution systems.

In the literature, the AC microgrid systems with renewable based DG units have been researched and implemented in various countries. Their operating feasibility is discussed by a number of researchers. As per Solanki et al. [36], a smart energy management system (SEMS) to optimize the economic operation of the microgrid is presented. The SEMS consists of DG unit forecasting, ESS management and optimization modules. The characteristic of the PV output in different weather conditions is studied and then a 1-day-ahead power forecasting module is presented. As energy storage needs to be optimized across multiple-time steps, considering the influence of the energy price structures, their economics are particularly complex. Therefore, the ESS module is applied to determine the optimal operation strategies while the SEMS integrates the smart management of the ESS, economic load dispatch and operation optimization of the DG units. More about optimization of the DG units in microgrids can be found in [67–69]. An overview of the rural areas poverty and lack of access to energy, especially to electrical energy, are still significant in the rural regions across the global. Nearly 70% of the population in sub-Sahara African countries lives in rural areas and less than 10% of this population has an access to reliable electricity [71]. In that case, the MGs with local renewable energy resources such as solar PV arrays, wind turbines or biomass are proposed as an alternative isolated system to rectify the problems, and consequently support their socioeconomic development.

As per Jiayi et al. [72], a review of distributed energy resources (DERs) with several technologies and MG technology are presented. The authors describe the MG operation in both grid-connected and island mode with the market environment of the MGs being also presented. Preplanned switching and fault event leading to islanding of the distribution subsystem and formation of microgrid is presented in [73]. In that sense, the DG unit interface converter with independent real and reactive power control helps to minimize the effects of transient state and maintain both the angle of stability and voltage quality within the microgrid. Guerrero et al. [14] present the hierarchical control based on the droop control methods in the AC and DC microgrids with multilevel control schemes. More emphasis in the microgrid control strategies is also given in [39,40,43].

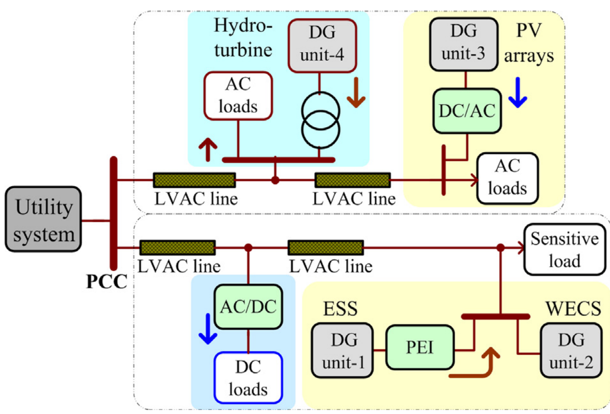


Fig. 4. AC microgrid structure with the DG units and mixed types of loads.

Moreover, Guerrero et al. [97] discuss the parallel operation of the DG unit inverters by using resistive output impedance without communication signals. Meanwhile, wind energy is being considered as the fast penetrating renewable energy source into the power system. The variable speed wind turbines e.g. doubly-fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) can be used to improve the performance of the AC MGs during islanding mode of operation. The authors in [59] report a dynamic model with DFIG to provide an additional support for primary frequency and voltage regulation within the MG network. Using DFIG control flexibility, the AC microgrid transient and dynamic behaviors during islanding and grid-connected modes are improved. Besides, synchronization of microgrids with the main system has been a hot research topic across the world. Ref. [47] presents the control of the MG with active synchronization. A review on control strategies is given together with discussion on the challenges encountered when the ESSs are included within the AC microgrids [48,49]. Furthermore, the authors in [54–56] report the study of power converter control and protection schemes for grid-connected microgrid systems integrated with renewable based DG units.

The impact of different control schemes on system stability during subsequent and fault-forced islanding conditions for microgrid systems with inverter based DG units has been analyzed. The authors in [54] present the protection techniques in the grid-connected and islanded modes of operation for the MG systems. In this case, the authors illustrate the effects of the generation to load ratio on critical clearing time and identify the factors which influence AC MGs stability. The power control strategy developed for the low-voltage microgrid is detailed in [64]. This strategy comprises a virtual inductor at the interfacing inverter output, an accurate reactive power control and sharing algorithm which consider the impedance voltage drop and the effect of the DG unit local loads. The virtual inductance can effectively prevent the coupling between real and reactive powers by presenting mainly inductive impedance even in a low-voltage network with resistive line impedances without any physical connection. On the other hand, the black-start restoration sequences to be used for MG after a blackout are solved by Moreira et al. [65]. The proposed solution is based on the communication infrastructures which automatically identify and restore the special issues for the MG services.

Table 1(a)
Typical examples of home AC powered appliances.

Sl. no.	AC powered loads	Voltage ratings (V)	Current ratings (A)	Power ratings
1	Microwave oven	240	–	8.3 kW
2	Dishwasher	120	11	–
3	Toaster	120	–	1050 W
4	Coffee pot	120	–	1100 W
5	Electric clothes drier	240	–	5600 W
6	Electric cook-top	240	–	8.8 W
7	Refrigerator	120	8.3	–
8	Washing machine	120	7	–

Table 1(b)
Typical examples of AC microgrid systems.

AC microgrid components	Voltage level	Frequency (Hz)	Capacity
PV arrays, diesel generator, battery banks—Kythnos, Greek Island [101]	1—phase LVAC	50	12 kWp from PV system, 85 kWh from battery bank
PV arrays, wind turbines, controllable digester gas engines and lead acid battery banks—Hachinohe, Japan [102]	Not specified	50	Demand = 610 kW; power generated by PV arrays and wind turbine = 150 kW, digester gas engine = 510 kW, battery = 100 kW.
PV arrays & BESS—rural areas in Senegal [66]	220 V	50 Hz	0.5–10 kW per household
Two steam turbines, two diesel generators and converter-interfaced source [69,73]	94 V (pk), 115 V_{LL} (rms)	60 Hz	3 MW
Gas engines (GEs), wind turbine (WT), EDLC and BESS, Japan [8]	110, 230, 240 V	50, 60 Hz	50 kW–2MW
Fuel cells, PV arrays, WTs, ESSs and AC utility; Porto, Portugal [77]	400 V	50 Hz	50–200 kW
More other studies are in [2,8,39,40,47,48,61,64,65,67,105,110,124]			

More about the AC MGs operation and their ongoing researches can be found in [86–89,91,95–98].

By referring to the literature above, one can conclude that the AC MGs are feasible with both renewable and non-renewable energy sources. They are involved in many areas of applications such as in remote areas, commercial buildings and as backups for power supply and improve the efficiency and reliability of the existing power system infrastructure.

3.2. DC microgrid systems

Traditional electric power system was designed to move central station alternating current (AC) power, via high-voltage AC (HVAC) transmission lines and lower voltage distribution lines to households and businesses that use the power in incandescent lights, AC motors and other AC equipments. Meanwhile, the DC power systems have been used in industrial power distribution systems, telecommunication infrastructures and point-to-point transmissions over long distances or via sea cables and for interconnecting AC grids with different frequencies. Today's consumer equipments and tomorrow's DG units are dominated by power electronics devices. These devices (such as computers, fluorescent lights, variable speed drives, households, businesses, industrial appliances and equipments) need the DC power for their operation. However, all these DC devices require conversion of the available AC power into DC for use, and the majority of these conversion stages typically use inefficient rectifiers. Moreover, the power from DC based DG units must be converted into AC to tie with the existing AC electric network, only later to be converted to DC for many end users. These DC–AC–DC power conversion stages result in substantial energy losses. Using the positive experiences in the HVDC operation and the advance in power electronics technology, interests in pursuit for effective solutions has increased. The LVDC distribution network is a new concept which is one possibility to tackle the current power distribution problems and realize the future power system [11]. It has the features that meet the new requirements of the electrical distribution networks. Fig. 5 shows the typical DC MG systems interconnected with the main systems at PCC which can be medium voltage AC (MVAC) network from the conventional power plants or an HVDC transmission line connecting an offshore wind farm. Table 2(a) depicts some typical examples of the available home DC powered appliances while Table 2(b) shows the typical examples of the DC MG systems used as testing prototype or typically installed for most of the data centre or critical load applications. In the case of DC MG configurations, the low voltage DC links are based on bipolar configurations where the loads can be connected across the positive polarity and the ground or between the two polarities.

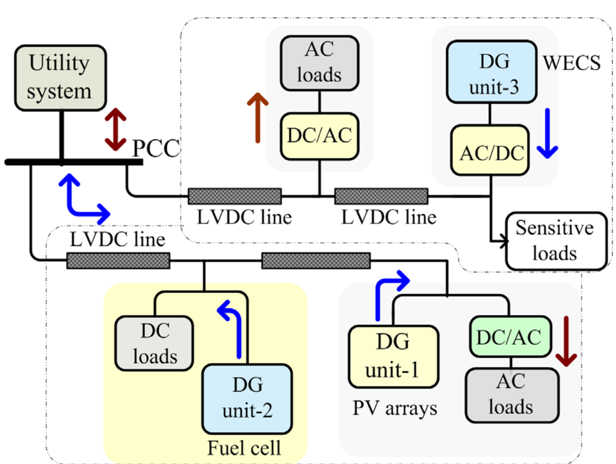


Fig. 5. Concept of a DC microgrid system with the DG units and mixed types of loads.

The LVDC distribution network can improve the efficiency of delivering power to the distribution network. It ensures a higher power quality to the customers than in the present distribution network and facilitates more DG units' connection [12]. Measuring instruments such as advanced metering infrastructures (AMIs), demand energy managements (DEMs) and protection systems can also be integrated into the power converters. To achieve all these, ongoing researches to find out the details and more emphasis on the DC MGs applications such as power supply for the critical loads in commercial buildings, electronics factories and hospitals have been presented. Results indicate a significant reduction in power quality problems, losses and downtime and protection malfunctions [73–75].

The research road map in [4] presents the opportunities and challenges associated with a DC distribution system for industrial power system. In that article, the focus is directed on the interaction between the power converters and the challenging issues of the system grounding. The DC MG for small-scale residential houses is investigated to find out the influence of current balancing, system losses together with its stability [6,7]. The authors concluded that; the DC MGs have attractive features in terms of simple structure, low system cost and the overall improved efficiency since few power converters are needed compared to the AC MGs [10–12]. An isolated DC network which comprises solar photovoltaic (PV) systems and unbalanced AC loads was investigated. In this study, the author used the LVDC cable to interlink the PV based DG units and their corresponding local loads [15,60]. Also, the DC MGs control strategies in grid-connected and islanding mode are presented by several authors [15,45,46]. For instance, the control strategy for the grid-connected DC MG with renewable based DG units and ESSs is reported by Chunhua Liu et al. [17]. Nevertheless, a detailed discussion on control strategies for the battery energy storage system during islanded and grid-connected operation to adjust the DC bus voltage is studied and presented in [45]. More details about the control strategies for grid connected and islanded DC MGs operation are available in [50].

Protection issues in the LVDC distribution system are a challenging problem addressed by few authors. In [51], the authors propose the philosophy of protecting the DC MG systems with the DG units, sensitive loads and power converters. The grounding system, protection devices, power converters and battery protection methods [53,54], and DC feeder protection approach together with their coordination are stated as the potential areas in designing any effective protection scheme in the LVDC distribution systems. More about the DC MG protection mechanism is given in [55–57]. Moreover, the dynamic behavior and stabilization of DC MG with constant power loads are also given in detail by Alexis Kwasinski and Onwuchekwa [45]. In most of the references above, the DC MG systems or LVDC networks are employed to supply power to highly sensitive electronics loads and industrial power systems in which motor drives are mostly used. In these areas of applications, the LVDC networks have shown high performance against power malfunction. The electric vehicles (i.e. PHEV and EV) charging stations are the other areas where the DC MGs are most likely to have significance to the future energy system [17,60,124]. In this perspective, with the deployment of a smart grid, the vehicle-to-grid (V2G) concept could widely become a reality. The V2G implementation would allow the EVs and PHEVs to also act as suppliers to the grid [87,88]. For example, production from the renewable based DG units such as wind power and PV system is usually intermittent. For their optimal utilization, the ESSs could be needed but often not available or limited. If the wind power production is too high during low time intervals, surplus power is

Table 2(a)
Typical examples of home DC powered appliances.

Sl. no.	DC powered loads	Voltage ratings (V)	Current ratings	Power ratings (W)
1	Laptop computer	20	4.5 A	–
2	Cell phone	5	550 mA	–
3	Wireless phones	6.5	500 mA	–
4	DVD player, home theater system	–		26, 300
5	Battery powered vacuum cleaner	10	250 mA	–
6	Cable modems	12	750 mA	–
7	Wireless internet router	5	2.5 A	–
8	Powered USB port	5	3.8 A	–
9	54″ plasma TV	–	–	465
10	PC mini-tower	–	6 A	
11	Variable speed drives for washers, dryer or air-condition	380	–	–
12	Rapid charger—PHEV or EVs	200–380	–	–

Table 2(b)
Typical examples of DC microgrid systems.

DC microgrid components	Voltage range	Capacity
Sweden UPN AB [103] for Data center IBM	24–350/380 LVDC (bipolar DC-link)	≥5 MW
Japan NTT Group [103] for data centers	380/400 LVDC (bipolar DC-link)	≥5 MW
New Zealand Telecom NZ [103] for data centers	220 LVDC (bipolar DC-link)	0.5–5 MW
US Intel Corp. [103] for data centers	400 LVDC (bipolar DC-link)	≥5 MW
For general case [75]	187.8 V—450 LVDC	600–2100 W
Two Steam turbines-Testing prototype [77]	800 V—1200 LVDC	4.8–18 kW
PV arrays, BESS & AC utility system [9]	180–210 V LVDC (system model) 360 V—420 LVDC (for experiment prototype)	150–945 W
PMSG WTs, BESS & AC utility system [10]	1200 LVDC	0.9–3.5 MW
Gas engine cogeneration, EDLC, BESS, PV arrays & AC system [12]	$\pm$ 170 V, 340 LVDC (bipolar DC-link)	700–2700 W
For general case [45] testing prototype	200, 400, 415 LVDC	5 kW, 15 kW
More studies are also reported in [11,14,16,47,48,51,60,73]		

often wasted and system security might not be compromised. However, with the V2G technology in smart grid, the surplus energy can simply be stored and later be supplied back to the grid as required.

To be more specific, a recent study on optimal planning and operation of the smart grids with the EV interconnection has shown that the EV-ESSs can be used to reduce utility-related energy costs. Also, by offering different kinds of ancillary services, it can control and manage part of the smart grid or commercial buildings following the arbitrage of energy between buildings with different tariffs [89]. Referring to more literatures regarding the EVs operation in the low voltage distribution networks, authors in [90] reported the influence of the EVs charging stations to the Polish power network and showed how the grid behaves when overloaded during peak demand. Such ongoing research studies in the DC MGs with the DG units powered by renewable and non-renewable energy sources significantly prove their feasibility. Therefore, power from substation or DG units and ESSs can be transmitted using a DC distribution line with single cable (monopolar dc link), two cables (bipolar dc link) or even three cables (homopolar dc link). The first two arrangements are normally used for HVDC long distance transmission system while the last is mainly used in low voltage distribution system (LVDC network). In this subsection, the three types of DC link configurations are briefly discussed.

3.2.1. Monopolar DC link

This type of DC link configuration uses one high voltage conductor and a ground-return or sea-return as indicated in Fig. 6(a). It is advantageous from economic point of view, but is prohibited in some countries because the ground current causes the corrosion of pipe lines and other buried metal objects. However, this type of configuration is already in operation in some European countries (e.g. Italy–Greece HVDC link) and most of them are used for submarine crossings. A metallic return can also be used where concerns for harmonic interference and/or corrosion exist. Since the corona effects in a DC line are substantially reduced with negative polarity of the conductor as compared to the positive polarity, a monopolar link is normally operated with negative polarity.

3.2.2. Bipolar DC link

Fig. 6(b) shows the bipolar DC-link configuration with two conductors, one operating at positive-polarity and the other operating at negative-polarity. The junction between the two power converters may be grounded at one or both ends. However, if both ends are grounded, each link can be independently operated when necessary. Each terminal has two sets of the power converters of equal rating in series on the DC side. Since both poles operate with equal currents under normal operation, there is zero ground current flowing under these conditions. Monopolar operation can also be used in the early stages of the development of the bipolar link. However, under faulty converter conditions the system can transmit half of the power in monopolar mode. In this case, one DC line may be temporarily used as metallic return with the use of suitable control strategies. Besides, the monopolar mode of operation can be maintained for a limited time only. In addition, the loads and DG units can be connected in parallel across these two lines [11,12].

3.2.3. Homopolar DC link

The homopolar link, whose configuration is shown in Fig. 6(c), has two or more conductors having the same polarity. Usually negative polarities are preferred and can be operated with ground return or metallic return. Due to undesirability of a DC link with ground return, bipolar links are mostly used. The homopolar link

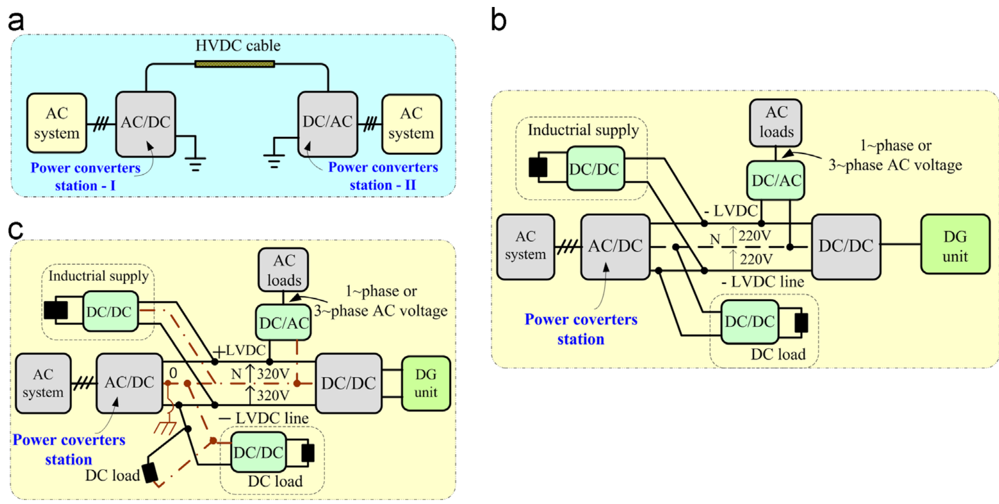


Fig. 6. Concept of the DC link configurations based on: (a) monopolar type, (b) bipolar type and (c) homopolar type.

has the advantage of reduced insulation costs. However, the disadvantage of the earth return outweighs the advantages. The three-wire system has the highest efficiency of all the three links and is mainly used for DC distribution system from substation to the actual consumers. It consists of two outer wires and a neutral wire. It has the advantage that the voltage is divided between the two sets formed by these three wires. *For example*: If the voltage between one set is 220 [V], this can be used for domestic purposes by using the neutral and one outer wire; while the voltage level of 440 [V] can be obtained by taking the voltage between the two outer wires utilized for industrial purposes [16].

Therefore, due to the importance of using the DC MG systems in the future energy systems, the paper presents their comparison with the AC MG systems. Operation and control of both microgrid systems and their protection approaches are presented in the next section.

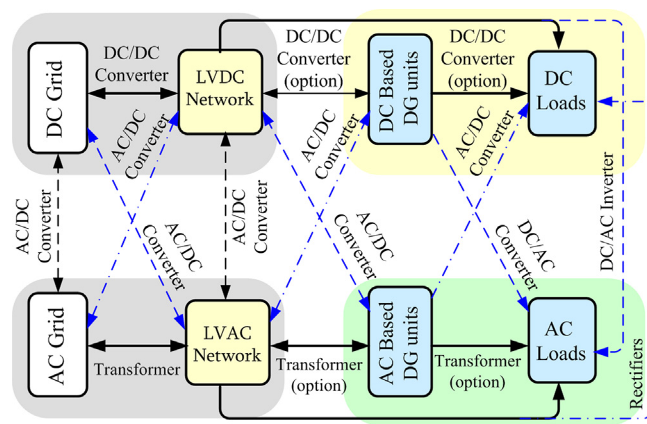


Fig. 7. Interconnection of various microgrid components.

4. Operation and control of microgrid systems

One of the elements of the future energy systems is the distribution network that measures and controls the usage [36,70]. In such energy systems, the power generation depends on the market situation (supply/demand and cost) and the power source available [66]. These structures are more realizable in the form of AC and DC MG systems. They are resurging due to the development and deployment of the RESs, advance in power electronics and their inherent advantages in various areas of applications [4]. The power electronics interfaces (PEIs) play the most important roles in interfacing various components within the MG systems and all technical issues such as power balance and power quality are resolved via the control of these devices [5–7]. The PEIs allow the MG systems to operate in both grid-connected mode and islanded mode while providing a high quality of power with minimum equipment cost [91,118]. In that manner, the PEIs are required/expected: (i) to provide the fixed power and local voltage regulation, (ii) to facilitate the DG unit to fast track the load demand using the energy storage devices, (iii) to incorporate the control methods for load sharing between the DG units, and (iv) to integrate the various key technologies for successful modern or future smart distribution systems [92–94]. So far, the DC MGs do not have demerits of the AC microgrids such as synchronization of frequency and difficulties in voltage control during islanding operation [95–97]. That is to say, the DC MGs are much simpler in operation because the frequency or phase control structure is unnecessary as compared to their counterpart.

Therefore, presented in the next subsections are the components configurations, control and power managements in both AC and DC MG systems.

4.1. Microgrid structural configurations

AC and DC microgrid systems are the central interest of this paper, as their structural configurations attract the easy deployment of the renewable based DG units and ESSs to achieve several benefits as mentioned in the previous sections. Fig. 7 shows the interaction between the two types of electrical systems and their corresponding components interlinked by the power converters. From this figure, it can be revealed that the AC MGs (or LVAC networks) can be connected to the bulk AC system via power transformers and require an AC/DC power converter to interconnect with the bulk DC system. That means, the AC based DG units together with AC loads can directly be connected to the LVAC networks. On the other hand, the DC based DG units and the DC loads require DC/AC and AC/DC power converters for their connection into the LVAC network, respectively. In the case of the DC MGs (LVDC networks), bi-directional DC/DC (boost) and DC/AC (inverter) power converters to interconnect with the bulk DC and AC systems are needed, respectively.

Furthermore, the AC based DG units and AC loads can be coupled with the DC MGs using the AC/DC power converters to facilitate their stable operation. On top of that, the DC MGs can eliminate the DC/AC and AC/DC power conversion stages required by the AC MGs to connect the DC based DG units and DC loads, respectively. In addition to the above, the power converters do not have a transformer, which contributes to overall system downsizing. This means, the DC MGs are more advantageous in terms of system efficiency, cost and system size than their counterpart.

4.2. Microgrid control and power management

The use of the power converters to interconnect various components in MGs requires proper control strategies [68]. The controllers must be able: (i) to import/export energy from/to the bulk network, (ii) to control the real and reactive power flows and manage the DG units connected to it and (iii) to operate within its prescribed specifications i.e. the system frequency and voltage must be maintained within their predefined limits. Usually the voltage and frequency variations are very small if the MG is connected to strong grids. However, large variations may occur in autonomous grids [33,46,49]. Moreover, in the grid-connected MG systems, inverters use the signal from the main grid as a reference to obtain the signal with the correct frequency (in case of AC MGs) and voltage (in case of AC and DC MGs) needed for the power factor correction and current reference computation [39,43,115]. Each DG unit and energy storage device operating in this mode can therefore be viewed as a current source, whose power flow can be controlled by varying the current reference. In both AC and DC MG systems, the grid maintains the system stability [12]. However, in islanding mode the reference from the main grid is lost and a new reference voltage must be internally generated by the individual DG unit controller to continue generation of good power quality. In this case, the DG units connected to MGs thus appear as controlled-voltage sources whose outputs should rightfully share the load demand in proportion to their ratings [119], so as not to overstress any individual unit [15,40,41]. On that note, power management strategies are vital for the MG systems operating autonomously in the presence of few small DG units, where no single dominant energy source is present to supply the power demand [42–44].

Many researchers have addressed the operational and control issues in MG systems to allow their stable operation in both grid-connected and islanding modes [78–80]. With most of the DG units widely dispersed, it is impractical to interlink every component in the microgrid systems by wires. Nevertheless, the future is in our hands with advanced information and communication technologies (ICTs) and it is clearly possible with the emerging smart grid technology to interlink every component in microgrids [43]. Currently, to avoid the unnecessary wiring, measurements are taken locally within the vicinity of each DG unit and the droop control methods are commonly used with many improved variants to allow proper sharing of real and reactive power within the MG system [77–79]. Their main functionality is to introduce some virtual inertia to the DG units. In so doing, each DG unit behaves like a synchronous generator connected to the traditional power system, whose power balancing ability can be emulated.

In opposite to the droop control methods, the master–slave MG control method is reported [80]. In this concept, the master–slave configuration avoids currents circulation among the power converters of the DG units and variation in frequency and voltage of the MG system. Unfortunately, this approach decreases the reliability of the system by placing an extra burden on the criticality of the master source and the interconnections between slave inverters and the power distribution unit. It also decreases the stability of the system. On the other hand, it is an easily-using strategy to avoid circulating currents and special steps can be applied to avoid the aforementioned limitations [47,52].

Most of the recent research interests have largely focused on the droop control strategies to allow the MGs to operate interchangeably between the two modes of operation. For instance, the ISA-95 [15] is adopted in the MG systems control with the zero to three control levels usually implemented in a structural form depicted by Fig. 8(a). The challenge with the MG controllers remain to be the need for operating each individual DG unit at its optimal state and to coordinate different advanced technologies with mixed loads and ESSs [97,98]. In addition, the islanding detection algorithm is another challenge which is necessary to guarantee the MGs to operate interchangeably while attaining a seamless transition between the two modes [99,100,106].

Traditionally, the MG controllers ensure the system security, optimal operation, emission reduction and smooth transfer from one operating mode to the other without violating system constraints and regulatory requirements [63,116]. These objectives can be achieved through three kinds of controllers, namely: (i) a DG unit controller (DGC) connected to each unit and energy storage device, (ii) a microgrid central controller (MGCC), and (iii) a Load controller (LC). Each DG unit can produce its output frequency and voltage amplitude tuned in proportion to the amount of active and reactive power drawn so as to achieve a proper load demand sharing [64,96,97]. Based on these requirements, the control in microgrid systems is therefore divided into four levels which are:

Level 0 (*inner control loop*): This is a power controller loop that determines the operating state of the DG units and storage devices and it is known as low level voltage and current controllers [40,44,48]. Fig. 8(b) illustrates the configuration of this control level in which the regulation issues such as the driving signal of each module are integrated. It also includes the feedback and feed-forward compensators together with the linear and non-linear control loops. Maintaining the system

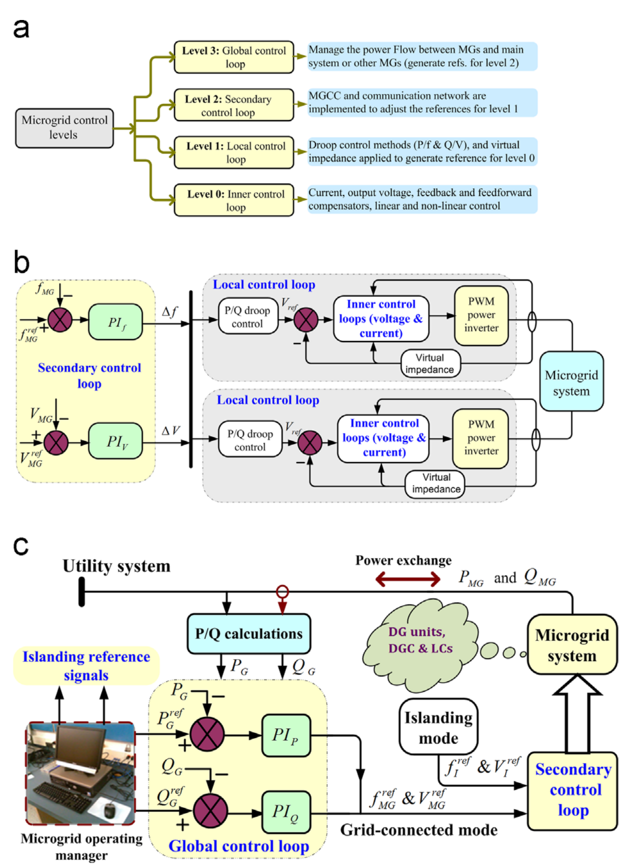


Fig. 8. Detail configurations of microgrid system control levels: (a) hierarchical control levels in microgrid systems; (b) configuration of the secondary, local and inner control loops in microgrid systems; and (c) configurations of the global and secondary control structures.

stability with high bandwidth and performance, a fast response under any operating condition is usually guaranteed in this level.

Level 1 (*local control loop*): It is also known as the primary control or decentralized control (they do not require any commutations between the power converters) [32,46]. The droop control equations are often used in this level to emulate physical behaviors that make the system stable and more damped [8,12,14]. For example, it includes the active power/voltage droop for the DC microgrids [13], and active power/frequency and reactive power/voltage droop characteristics [77,78] for the AC MG systems.

Level 2 (*secondary control loop*): It is located in microgrid central controller (MGCC) and responsible for measuring frequency and voltage [44,55,64]. The output of this control unit is sent through communications to adjust the reference of the local controllers (e.g. *P*/*Q* droops) as indicated in Fig. 8(b). In addition, it can include a synchronization control loop to seamlessly connect or disconnect the MG to or from the MVAC or MVDC networks [46].

Level 3 (*global control loop*): It is also called a tertiary control loop in which the energy-production or energy-market stage which controls the power flows between the MGs and the grid is implemented [14,49]. In this level, once the MG is connected to the main system the power flow can be controlled by changing the voltage inside the MG. Fig. 8(c) illustrates that the frequency and voltage references for the secondary control are generated through a MG operating manager (MOM) or the transmission system operator (TSO). It also organizes the relation between a given MG and distribution network as well as other connected MGs and forecasts the short-term load changes, storage capabilities together with marginal generation cost of each DG unit [97]. The global or emergency control, and to some extent the secondary control are termed as the centralized control systems, since they both require communication for their operation [33,48].

Fig. 9 indicates a typical configuration of the MG system with the centralized control based on MGCC, DG units and controllable loads. The DG units and energy storage devices are fitted with the DGCs that execute smooth and flexible operation to meet customer and utility requirements. The DGCs may operate with or without any intervention of the MGCC [48,64]. The objective of the DGCs is to take care of the local control functions (levels 0 and 1) which greatly depend on power electronic interfaces provided at each DG unit and storage device.

In summary, the DGCs ensure: (i) new microsources can be added to the system without modification in the existing AC or DC MG configuration, (ii) MG can connect/disconnect itself to/from the utility in a rapid and detectless style, (iii) active and reactive power can be independently controlled, (iv) voltage sag and system unbalances can be corrected, (v) faults can be handled

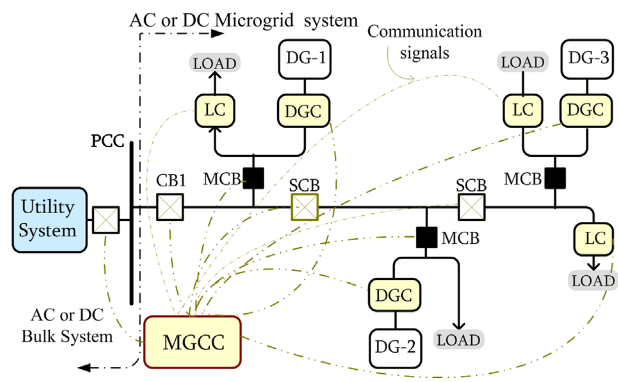


Fig. 9. Centralized control of microgrid system with MGCC, DGCs and LCs.

Table 3
Comparison between AC microgrids and DC microgrids control strategies.

Operating mode	AC microgrids	DC microgrids
Grid-connected mode		
MGCC	• Monitoring system diagnosis by collecting information from the LVAC network, DG units and loads (AC & DC). • Performing state estimation and security assessments, evaluate economic generation scheduling, active and reactive power control of the DGs units and demand side management functions using the available information. • Ensuring synchronized operation with the main grid, maintaining the power exchange at prior contract points.	• The main function of the MGCC is to independently control the power flow and load-end voltage profile of the DG units in response to any disturbance and load changes. • Participating in economic generation scheduling, Load tracking or management and Demand side management (DSM) by controlling the storage devices.
DGCs	• Ensuring that each DG unit rapidly picks up its generation to supply its share of the load in stand-alone mode and comes back to the grid-connected mode automatically with the help of the MGCC.	• Ensuring that each DG unit quickly picks up its generation to supply its share of the load in stand-alone mode and comes back to the grid-connected mode automatically with the help of MGCC.
Islanding mode		
MGCC	• Performing active and reactive power control of the DGs in order to maintain stable voltage and frequency at the load ends. • Managing load interruption/shedding strategies using demand side management (DSM) with ESS support for maintaining power balance and voltage. • Initializing local black start to ensure reliability and continuity of the service. • Switching the microgrid to grid-connected mode after the main grid supply is restored without hampering the stability of either grid.	• Independently control the power flow and load-end voltage profile of the DG units in response to any disturbance and load changes. • Ensuring the DG units rapidly picks up its generation to supply its local load in islanding mode and automatically reconnect to grid with the help of the MGCC.
DGCs	• Commanding each DG unit to rapidly pick up its generation to supply its corresponding local loads in the stand-alone mode and automatically resynchronize to grid with the help of the MGCC.	• Ensuring that each DG unit rapidly picks up its generation to supply its share of the loads in stand-alone mode and comes back to the grid-connected mode automatically with the help of the MGCC.

without the loss of stability and (vi) MGs can meet the requirements of the load dynamics of the power utility. The built-in control features of the DGCs comprise: (a) active and reactive power control, (b) voltage and current control, (c) storage requirement for fast load tracking and (d) load sharing through *P–f* control. The function of the MGCC is to execute the overall control of microgrid operation and protection through the DGCs and load controllers (LCs).

More importantly, the MGCC maintains the power quality and reliability via active power-frequency, reactive power-voltage control loops in the AC MGs and active power-voltage control loop in the DC MGs. It also executes economic generation scheduling of the DG units, energy storage devices and helps to maintain the power exchange between the main utility grid and MG system at mutually agreed contract points. The MGCC also provides the power dispatch and voltage set points for all DGCs to meet the needs of the customers. Moreover, the MGCC ensures energy optimization for the microgrid and maintains the specified frequency and voltage profile for the electrical loads. This controller is usually designed to operate in automatic mode with provision for manual intervention when required. Table 3 presents the comparison between the AC and DC MG systems control strategies during grid-connected mode and islanded mode with centralized control system.

Presented in Sections 4.2.1 and 4.2.2 is the detail of commonly used AC MGs and DC MGs control strategies based on droop control methods.

4.2.1. AC microgrids control strategy

AC microgrids are now in the cutting edge of the state of art whereby their control and energy management still require more investigation. In the grid-connected mode, the AC microgrid power-frequency (*P–f*) droop control has been adopted for the DG units power sharing methods [96–98]. This control approach uses the grid frequency as a common signal among the DG units to dynamically balance the active power generation of the system [101,114,117]. The relationship between the frequency and the active power output of the given two DG units (DG_1 and DG_2) can be expressed by *P–f* droop characteristics (1) and illustrated by Fig. 10(a).

$$f_{mi} = f^{*} - K_{pi}P_i \tag{1}$$

where f_{mi}, and f^* are the measured and rated frequency, K_{pi} and P are the droop-coefficient and the DG unit output active power difference between the setpoint and the measured actual active powers, respectively while $i = 1,2,\ldots,\lambda$, with λ being the total number of DG units.

The differences in the droop coefficients allow the sharing of the total load power requirement among the DG units according to a predefined ratio. For example, the total load power requirement of the MG can be shared in proportion to the rated real power output of each DG unit [112,120]. The voltage and frequency regulations are necessary for the local reliability and stability [46]. Without local voltage control, the systems with high penetrations of the DG units could experience over-voltage and/or reactive power oscillations [48,49,108]. Small errors in the voltage set points cause circulating currents which can exceed the ratings of the DG-unit [65,75]. This situation requires a voltage-reactive power droop controller so that as the reactive power generated by the DG units becomes more capacitive or inductive the power converter reference voltage amplitude, V^* from the measured reactive power follows its *Q–V* droop characteristics depicted in Fig. 10(b) and represented by (2). This has also been reported by the authors in [95,97,104].

$$V_{mi} = V^{*} - K_{vi}Q_i \tag{2}$$

with V_{mi} and V^* being the measured and nominal voltage, K_{vi} and Q_i are the droop-coefficient and reactive power difference between the setpoint and its measured values, respectively while $i = 1, 2,\ldots,\lambda$, with λ being the total number of DG units.

In the islanding mode, the problems from slight errors in frequency generation at each coupling inverter and the need to change power-operating points to match the load demand lead to restructuring of the control strategies [61]. The active power-frequency droop characteristics in each DG unit can effectively solve such problems without any communication network. To keep the voltage and frequency variation within the defined range, the gradients/droop-coefficients in (1) and (2) above automatically adjust to be less gradual [63,110]. However, this process compromises the load sharing accuracy between the DG units [98]. Alternatively, the droop characteristics in (1) and (2) which are

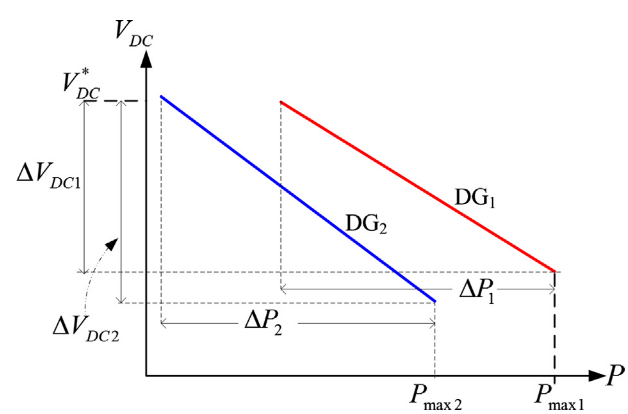


Fig. 11. Droop-characteristics for the DC microgrid system control.

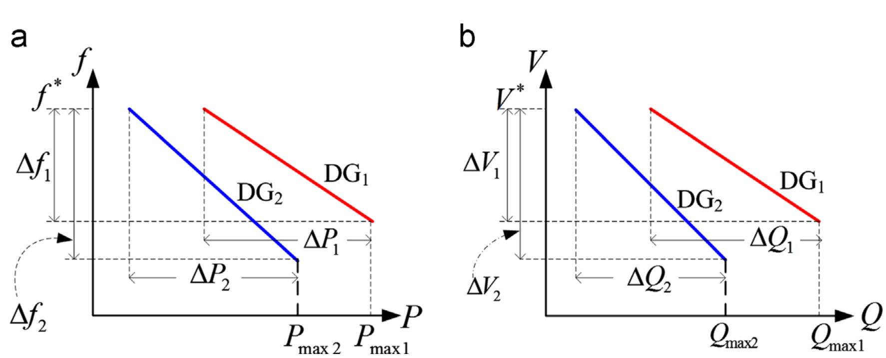


Fig. 10. Control methods for AC microgrid system: (a) *P–f* droop characteristics and (b) *Q–V* droop characteristics.

indicated by Fig. 10(a) and (b) can further be enhanced by adding attractive features such as improved dynamics, additional damping and line impedance effect minimization, as per [75,111].

4.2.2. DC microgrid control strategy

There are several problems associated with the AC MGs, such as the need for synchronization of the distributed generations, the inrush currents due to transformers, reactive power flow, harmonic currents and three-phase unbalances [74–76]. Also, the increase in interest to integrate the DC based DG units such as solar PV arrays, fuel cells and energy storage systems (e.g. batteries, super-capacitor modules or hydrolysers) makes a possibility for the DC microgrids [14,42]. The control strategy in the DC MGs is usually for (i) soft-start control approach, (ii) external common controller to restore the voltage deviation inside the DC system and (iii) regulation of the current/power flow from/to an external stiff DC source which can be a medium voltage DC (MVDC) system or a DC/AC power converter connected to the AC grid [97,107,110]. Algorithms for the DC MGs are also necessary to ensure a smooth transition between the grid-connected and islanding modes [44] meanwhile, the power sharing between the DG units in islanded DC MG system can vary from centralized to decentralized control system [123,124,117].

Unlike the AC MG systems, the DC MG systems are much simpler in the sense that they do not have reactive power, and only the voltage quantity available for control is its amplitude. In this case, the active power is no longer dependent on the system frequency but the voltage difference [97]. The active power sharing among the DG units within the DC microgrid can be obtained through the droop-characteristics (3) as illustrated below.

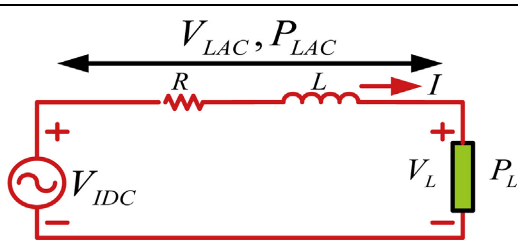
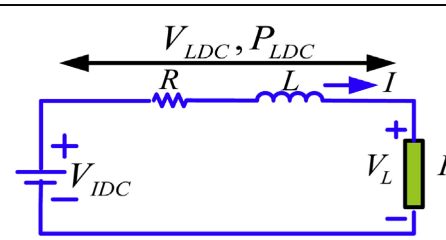
$$V_{DCi} = V^*_{DC} - \beta_{vi} P_i \tag{3}$$

where β_{vi} is the droop-coefficient introduced to represent the drooping gradient drawn in Fig. 11, while P is the difference in active power between the setpoint active power and its

Table 4
Comparison between AC distribution lines and DC distribution lines.

Influence parameters	AC distribution line	DC distribution line
Power transmitted	Less efficiency due to high line loss, hence less power transmission	More efficiency and more power transmission
	Require more conductors	Require few conductors
System stability	Less stable due to easily affected by external disturbances	More stable and can also increase the stability of the AC microgrid systems
Reluctance	Have reactance in the line	No reactance in the line and hence more power transmitted
Frequency (50 Hz or 60 Hz)	Frequency monitoring is mandatory	Frequency is zero, so no need of
	Transient stability due line clearance and	frequency monitoring
	Switching are problems	No transient stability problems
	Electromagnetic interference must be taken into consideration	No electromagnetic interference
Resistance	High line resistance and hence high losses	Have low line resistance and hence low line losses
Susceptance	Charging current and over-voltage problem lead to high cost and low power transmission	Do not exist, and hence effect of overvoltage and over-charging leading low cost and high power transmission
Analysis	Involve complex numbers and hence difficult to analyze	Involve only real numbers i.e. more simple

Table 5
Analysis between AC and DC circuits.

AC circuit analysis		DC circuit analysis	
(i)		(i)	
(ii)	$P_{LDC} = P_{LAC} = P_L$	(ii)	$P_{LDC} = P_{LAC} = P_L$
(iii)	$V_{LDC} = V_{LAC} = V_L$	(iii)	$V_{LDC} = V_{LAC} = V_L$
(iv)	$P_{LAC} = V_L I_{AC} \cos\varphi$ $\rightarrow I_{AC} = \frac{P_2}{V_{LAC}\cos\varphi}$	(iv)	$P_{L,DC} = V_L I_{DC}$ $\rightarrow I_{DC} = \frac{P_2}{V_{LDC}}$
(v)	$V_{L,DC} = V_{I,AC} - V_L$ $= \sqrt{\left[\frac{P_2}{V_2}R + \frac{Q_2}{V_2}X\right]^2 + \left[\frac{P_2}{V_2}X - \frac{Q_2}{V_2}R\right]^2}$	(v)	$V_{LDC} = V_{I,AC} - V_L = I_{DC}R$ $= \frac{P_L}{V_L}R$
(vi)	$P_{LAC} = I_{AC}^2 R = \left(\frac{P_2}{V_2}\right)^2 \frac{R}{\cos^2\varphi}$	(vi)	$P_{LDC} = P_{IDC} - P_L$ $= V_{IDC}I_{DC} - V_L I_{DC}$ $= I_{DC}^2 R = \left(\frac{P_2}{V_2}\right)^2 R$

NB: $\cos\varphi$ = power factor.

instantaneous shared powers, V_{DCi} and V^{*}_{DC} are the measured DC voltage and its reference value, respectively while $i=1,2,\ldots,\lambda$; with λ being the number of DG units.

This coefficient β_{vi} must be tuned appropriately according to the given DG unit ratings and operating conditions since a steeper slope would give a better power sharing. However, wider voltage variations may lead to unacceptable predefined limits [31]. Alternatively, the improved droop characteristics have been researched and presented in the various publications to produce a better response [109,120].

4.3. LVAC distribution versus LVDC distribution lines

Low voltage distribution lines are characterized by a number of parameters such as power transmission capability, system stability, reluctance, line resistance, frequency and susceptances. Table 4 shows the comparison between the two LV distribution lines. Operation of the AC and DC microgrids can also be expressed in terms of the voltage, flow of current and power transport in their distribution lines and circuits as indicated in Table 5. To demonstrate the influence of the line parameters, the AC and DC circuits are considered with only the type of source that differentiates the two circuits. The load has a power factor cos φ with the same voltage magnitude applied to both AC and DC loads. where R_C and L_C represent the conductor resistance and inductance, V_{IDC} and V_{IAC} are the DC and AC source voltages, V_L and $P_L=P_2$ are the load terminal voltage and active power consumed by the load while Q_2 stand for the reactive power consumed by the AC load. V_{LDC} and P_{LDC} signify the voltage drop and power loss in the DC circuit, and V_{LAC} and P_{LAC} are the voltage drop and power losses in the AC circuit, respectively.

5. Microgrid protection systems

One of the major challenges in MG operations is the protection system to properly respond to both modes of operations [91]. Protection relays must be designed to operate in a grid-connected mode as well as in an islanded mode. From the literatures, the fault currents in the grid-connected and islanded MG systems are significantly different [121,122]. In that case, the protection of the MG systems cannot be achieved with same approaches that have been used in the conventional distribution systems. In the grid-connected mode, the protection relays isolate the MG from the main grid as soon as possible to protect the DG units and loads. In the islanding mode, the protection relays operate to isolate the smallest part of the MG system during fault clearing. Likewise, the fault currents are limited by the ratings of the power electronics converters (PECs) to around 2–3 p.u. of their rated currents [50,51]. As stated in the previous sections, the modern MG systems consist of different distributed generation (DG) units connected to it or to the utility grid. So a proper coordination between the DG units, protective equipments and loads is required to ensure a safe operation of MGs. The protection equipments setting should always be updated while considering the mode of operation [53–55]. The MGCC communicates with all the relays and DGCs to record their status as ON/OFF, their rated current and fault current contribution. Communication with the relays is required to update the operating current, detect the direction of the fault currents and thus properly mitigate the fault [57]. The details of the generalized relay tripping current that can be used in designing the MG protection scheme are given in Section 5.1, and the AC and DC MG protection techniques are explained in Sections 5.2 and 5.3, respectively.

5.1. General protection technique in microgrid systems

In designing a protection scheme, safety and fault analysis is very important. Proper safety model provides appropriate level of confidence in protection system [54]. In both AC and DC MG systems safety design, some parameters need to be considered. For example, sensitivity—in which the nominal threshold values are set considering all the safety levels of the equipments within the MG [53]. In many cases, the protection scheme must therefore be able to identify any abnormal condition. It is worth noting that, the protection scheme has a role to determine and identify a fault zone. On that note, selectivity is another important parameter used to serve this purpose in which a fault is detected in a system based on voltage magnitude, current and power direction. In order to minimize fault consequences, the protection system acts to disconnect only the faulted part. To avoid damage to equipments and maintain system stability, the protective relays should respond in the least possible time in any abnormal conditions i.e. 'the speed of response' is another important parameter. Security level is another factor which must be high so that the protection system should operate only when required to operate and reject all the abnormal conditions and transients which are not faults [55–57].

Basically, there are two main issues that must be carefully investigated in order to derive a generalized MG protective scheme. The first is related to the number of installed DG units within the MG system. Second, the availability of a sufficient level of short-circuit current in an islanded operating mode of the MG is very important since this level may substantially drop down after the isolation from the main grid [55]. Fig. 12 demonstrates the fault current contributed by each component in a grid-connected microgrid system. When the MG is operating as a self-contained power island, any fault currents will have to be supplied by those DG units which are still connected to it. In this case, their fault

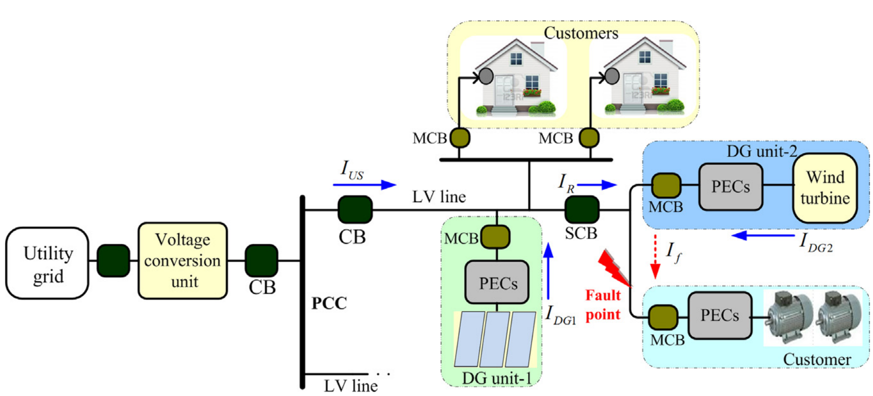


Fig. 12. Fault current contribution in microgrid system with DG units.

current contributions are relatively low values. The difficulty caused by using the generator units that rely on the power converters is that these units are designed to limit their output current to protect their power converter devices [57].

Considering Fig. 12, let the fault current contributed by the bulk source be I_{US}, and λ be the total number of the DG units installed within the given microgrid system, and then the total fault current contributed by the DG units is given by $I_{DG}=I_{DG1}+I_{DG2}+\cdots+I_{DG\lambda}$. Let also the current rating across the sectionalizers circuit breaker (SCB) be I_R, and then the total fault current at the fault point without the DG units is given by:

$$I_f = I_{US} = I_R \tag{4}$$

When the DG units are included in the distribution system (microgrid system), the total fault current at the fault point for the grid-connected microgrid system is given as

$$I_f = I_{US} = I_R + \sum_{i=1}^{\lambda} I_{(DG)i} \tag{5}$$

For the MG operating in the stand-alone mode (i.e. off-grid mode), the total fault current at fault point is given by

$$I_f = \sum_{i=1}^{\lambda} I_{(DG)i} \tag{6}$$

where I_f is the total fault current at the fault point. So far, the communication between the central control unit and the protection relays is necessary to update their operating currents and to detect the direction of fault currents so as to properly isolate the faulted region. To generalize this analysis: The relay tripping current depends on: (i) the operating mode of the microgrid and (ii) the status of the DG units. Based on (4)–(6) above, the generalized equation for the relay tripping current is given by (7) as in [50,55,113].

$$I_{relay} = (I_{US}\,\mu) + \sum_{i=1}^{\lambda} (\gamma_i\, I_{(DG)\,i}\chi_i) \tag{7}$$

where μ is the operating mode of the microgrid which takes a value of one for grid-connected mode and zero for an islanding mode, γ_i is the impact factor depending on the distance between the fault location and the DG unit, and χ_i is the status of the DG unit introduced to account for the fault current contribution e.g. solar PV arrays may have a value of one during the daytime, and a value of zero at night [56].

5.2. AC microgrid system protection strategy

Several methods of protecting the AC MGs have been proposed with a wide variety of equipments that are used in the conventional AC distribution networks protection [55]. These particular types of protection devices depend on the system element being protected and voltage level even though there are no specific standards for the overall protection. The devices which are mostly used for the AC distribution network protection are: (i) overcurrent relays, (ii) reclosers, (iii) sectionalizers (SCB), (iv) miniature circuit breakers (MCB) and (v) fuses. So far, the low voltage distribution protection schemes or coordination philosophies vary from utility to utility such as (i) fuse saving schemes, (ii) fuse blowing schemes, (iii) instantaneous reclose and (iv) delayed reclose.

One scheme which is applied in the AC MGs protection is to configure each DG unit to have its own relay and operate in the decentralized mode. This approach is more efficient for the single line-to-ground and line-to-line faults. However, the method is limited to faults with low impedance. Another approach is to use a voltage protection scheme which is a centralized method. In this case, the phase voltages are transformed into the *d-q*-0 axes and then compared with a reference voltage via the MGCC equipped with central protection unit [50]. When a change in voltage occurs beyond acceptable range, the tripping device (e.g. miniature circuit breakers, MCBs or sectionalizers, SCBs) is activated to appropriately isolate the faulted section by sending the signal to the appropriate relay or switching device as indicated in Fig. 13. The protection issues and the essential requirements in the future-protection concept for LV-microgrid or the smart grid can be found in [52,56]. Based on these papers, the details for microgrid zones such as MG PCC protection zone with CBs and static switch transfer (SST), feeder protection with CBs and SCBs, service connection for customers with MCB and the DG units with MCBs are reported. Since the realization of the future smart grids with different modes of operation requires all the technical issues including protection mechanisms to be resolved, applications of high speed protection devices such as the standards IEC 61850-based communication for fast response, selective and reliable operating scheme, are mandatory [50].

5.3. DC microgrid system protection strategy

In the case of the DC MG system protection, the limits of the standard SFS 6000 about electrical safety must be fulfilled. Currently, the main challenges in the DC MGs protection design

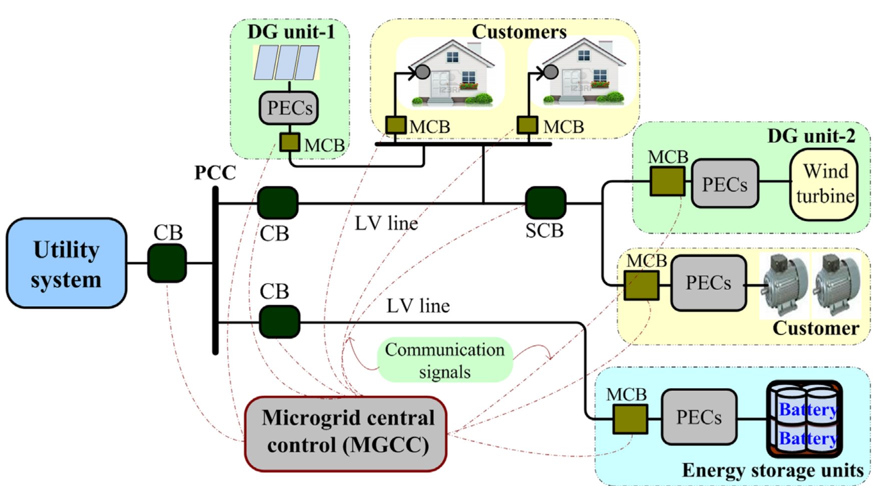


Fig. 13. Centralized protection system in the AC microgrid system.

concentrate to the customer-end inverter, customer network faults including inverter switching transients and double-fault situations between different networks (AC and DC networks). Fuses and automatic relays are also difficult to use with power converters. This is due to the fact that the power converters do not produce short-circuit currents as long time as fuses are needed to react [51,54]. Therefore, a different protection design approach is used with different fault-detection and grounding methods. In that case, the protection systems in the DC MG systems consist of the current interrupting devices, protective relays, measuring equipments and grounding systems [55–57].

Furthermore, there are five protection categories which are used namely: (i) utility protection, (ii) converter protection, (iii) DG unit protection, (iv) feeder protection and (v) busbar protection. Example of the protection devices which are commercially available for the LVDC networks are fuses, molded-case circuit breakers (MCCBs), power circuit breakers (CBs) or fast static switches (SSs) and isolated-case CBs [52,57]. These categories can be operated with decentralized/centralized system in a similar way as in the case of the AC microgrid protections. However, the inverters short-circuit current capability needs to fulfill the 'used circuit breakers' or other protection requirements. That is to say, the load power converters cannot be dimensioned according to effective power but the short-circuit current determines their dimension. In a short-circuit situation the inverter is able to operate up to 2–3 times its nominal current, but a traditional fuse protection of a low voltage AC network requires fairly high fault current to operate correctly [54]. For instance, the protection devices that are commercially available and commonly used in the AC MG system protection can be directly used to protect against the faults AC side of the bi-directional AC/DC power converter. These same devices can be used to protect the AC/DC power converter against faults on its DC side with different rating considered. If a molded case circuit breaker which uses a magnetic energizing device trips on instantaneous value of the current in the AC side (i.e. I_{rms}), then for the DC current would be 1.4142 times that of the AC current (i.e.$\sqrt{2}\times I_{rms}$).

Also, a 50 A fuse requires at least a 250 A short-circuit current to operate in 5 s (according to SFS– 6000). For this reason, the load power converter has to be dimensioned larger than the power supply capacity would require. Fuses must be replaced by much faster protection relays if smaller power converters would be used. Again, the AC/DC power converters switching-faults can be protected with protective functions integrated in it and short-circuit relaying. Uncontrolled diode bridges cannot control the current so the components are usually oversized. The active rectifier behaves similar to the diode bridge during short-circuit so the diodes are also oversized in this case. If there are some faults in the components of the power converters (say the controlled rectifiers), these are detected by over-current relay or by measuring the DC voltage level. The DC MG faults are covered with combined over-current and short-circuit protection together with earth fault protection. Furthermore, the DC MG short-circuit protection can be made with molded case which includes DC circuit breakers that are more cost-efficient than the fuses and over-current relay. On the AC side, the breaker protects against power converter switching faults.

Therefore, by taking into account all the possibilities such as operating states of every component connected within the given MG system, technical selection for the MG operation and control, MG operating mode and the microgrids fault ride-through (MGs-FRT) requirements; a proper protection scheme design for the microgrid systems can be achieved.

6. Conclusion and future trends

In this paper, the introspective review of the AC and DC MG systems with renewable based DG units, energy storage devices and loads that are available in recent literatures was presented. Based on the growing energy demands and interests in generating electricity from the renewable based DG units the need for reliability, efficiency and quality power supply can finally be achieved. The paper also described the problems associated with the conventional distribution system and the roles of the MG systems in the conventional energy systems, customer equipments and the future energy systems. In addition, the survey on possible DG units' configuration in low voltage networks (LVAC and LVDC networks), feasibility of MG systems, control strategies and their protection techniques was discussed. Also, the influence of the MG systems with the projected increase in the number of DC powered components for residential and industrial application together with more DG units that generate DC power reveals that the DC MG systems will soon be the right candidates for the future energy systems. On the other side, synchronization of the DG units, inrush currents caused by transformers, induction motors and generators and difficult in voltage control and system stability are still the main challenges to investigate in the AC MG systems contrary to the DC MG systems.

The general challenges remain on how to run every component in MG systems at its optimal operating condition; to operate the power converters while integrated with the smart grid technologies (such as AMIs, measurements and sensing instruments etc.) and to improve their capability to fault ride-through during grid disturbances. Again, the combined ESSs and renewable DG units provide the user dispatch capability of its distributed energy resources. Reliability and energy management technique of the ESSs are still a hot research topic. On the downside, the power converters account for a significant part of the total capital cost of a typical MG system installation, and they are often the least reliable part in the whole system design with low the short-circuit current limitation. Therefore, from the commercialization perspective, the key business needs for the power electronics devices are to reduce costs with improved reliability and efficiency. Hence, the short-circuit current limits require further investigations. It is also important for microgrids to have flexible protection schemes that can operate in both a grid-connected mode as well as an islanded mode with proper relay triggering currents while considering the operating state of every component, mode of operation and the recommended microgrid code for fault-ride through.

Another issue is related to information and communication infrastructures (ICTs). A more centralized system control of microgrids requires a significant data flow towards a single central point in order to achieve similar results. The problem becomes extremely difficult and expensive to solve, if the real time functionalities are required such as on line security assessment. On top of that, the issue is the openness of the system which is still a big challenge. Adopting a decentralized system, allows every manufacturer of the DG units and ESSs or loads to embed a programmable agent in the controller of his equipment according to some rules. This provides the required "plug and play" capability of the future DG units, ESSs and loads. In opposite to the centralized system, the installation of any new component would require extra programming of the central controller.

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