Chapter 7
Micro-grid an Integral Approach to Long-Term Sustainability

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Abstract This chapter shows a complete review of micro-grids as the main intelligent blocks in new electric grids, which are essential part of smart grids. Hence, it presents the micro-grids from their economic, environmental, social, and technological requirements, objectives, and impacts. The paradigmatic changes now imposed to the conventional grid are emphasised and contrasted with the micro-grid capabilities and benefits. Then, bidirectional power flow, local and centralised control, and the active participation of consumers are introduced and described. Given that most of micro-grid potentials are enabled by power electronics, a full section is devoted to the power converters used and their common control strategies, introduced from a qualitative viewpoint. Also, the main obstacles hindering micro-grids implementation are analysed, demystifying the "green" label normally associated with renewable energy sources and the expectance of them being plug-n-play systems. Then, a section dealing with grid protection systems and their technical incompatibility with distributed generation is also presented. Finally, a list of recommendations for implementing micro-grids in the Mexican context is provided, considering social, technical, economic, environmental, and policy factors.

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Abbreviations

CB	Circuit breaker
CSI	Current source inverter
DER	Distributed energy resource
DSO	Distribution system operator
EMS	Energy management system
FiPs	Feed-in premiums
FiTs	Feed-in tariffs
MC	Management controllers
MG	Micro-grid
MPPT	Maximum power point tracking
NO_x	Nitrogen oxides
PCC	Micro-grid, point of common coupling
PD	Protective device
SB	Switchboard
So_x	Sulfur oxides
VSI	Voltage source inverter

1 Introduction Micro-grid Concept and Challenges

Micro-grids (MG) come as a response to a wide variety of problems about the power system in general. The electric grid is comprised of many cooperating—even redundant—subsystems and, mostly due to its progressive deployment, they have become an intricate, poorly automated service over which high stakes are set in terms of power quality. Also, energy demand is on the rise while fossil fuels are depleting; nuclear power could not hold for much longer after them, and the aging and environmental issues the grid is subjected do not put forward the idea of a bright horizon (Ding et al. 2009). The modernisation of the power grid is a recurrent topic when approaching these issues, being the renewable sources an alleged significant contribution to the overall enhancement of the power grid.

Renewable power sources yield a direct solution to the final collapse of traditional energies; however, different, indirect benefits have been foreseen, and, simultaneously, novel challenges emerged. In order to trim down the required grid investments and reduce transmission losses, alternative sources are mainly planned to be inserted at the distribution level, locally. Such distributed energy resources (DER) also come with negative impacts related to the weakness of the grid at the distribution level (Lu and Wang 2017), and the desired plug-n-play capacity, implying installation randomness and variable—sometimes uncontrollable—operation. In the pursue of preserving the benefits while minimising the DER's problems, the micro-grid concept was proposed (O'Neill-Carrillo et al. 2018).

Likewise, today's grid architecture—top-down radial transmission system—assumes that energy is distributed to strictly passive loads, with no generation or storage capabilities. As new storage and generation technologies are being put to service, this approach is becoming obsolete (Asmus 2014). Moreover, new markets now favor business models based on local availability and timing instead of estimate-based centralised generation (Asmus 2014; Vanadzina et al. 2019). Such topological changes have paved the way for new proposals to be designed and tested.

The micro-grid (MG) concept is sometimes broadly defined as an energy supply and network management technology that deals precisely with DERs, enabling demand-side energy management (Ding et al. 2009). Such a local grid may contain many DERs, energy storage systems (ESS), local loads: it is a grid on itself that can operate either connected to the main grid or stand-alone, switching seamlessly between them both (Ding et al. 2009). Its pursued objectives are efficiency, sustainability, reliability, energy cost reduction, and resiliency (Alam et al. 2019; Parag and Ainspan 2019). Hence, those problems brought by DERs are to be solved locally (O'Neill-Carrillo et al. 2018) by taking a closer eye into fewer systems, also empowering the demand-side by enabling a new local energy market (Vanadzina et al. 2019).

However, taking the overall picture to reality imposes soaring technical requirements. For instance, one concern is the categorical need of a support grid to amend the variability of renewable resources (Fu et al. 2013)—customarily assumed to be a reliable, traditional one. Moreover, the uncertainty brought by installation randomness—e.g., grid reconfigurations and protection against faults (Lu and Wang 2017; Vukojevic et al. 2020)—and the electronic contamination of an already weak grid are supposed to be tackled naturally. Similarly, finding a solution for a partially/fully automated and communicated intra-MG operation is not necessarily sufficient as many MGs are supposed to be integrated over a common grid. Interacting MGs pose further problems mostly pointing toward stability, protection, coordination, privacy of private and community information and the threat of cyberattacks (Alam et al. 2019).

Similarly, interacting with the main grid is risky and must be in line with the utility interests. Utility stands as an obstacle in MGs adoption inside existent grids, normally demanding excessive requirements for interconnection (Burr et al. 2014). In the context of a non-changing, indispensable electric grid, disruptive technologies are not expected to find an organic growth path, requiring some first-adopters to increase the MGs credibility of the skeptical, standards-accustomed electric industry (O'Neill-Carrillo et al. 2018). Such a process is like the paradigm change in the telecommunications area that led to the internet itself, for which the military and universities were pioneers (Burr et al. 2014).

Such a context has modified the expected integration of MGs which have, in turn, found successful case-studies in remote communities and developing countries unable to establish a traditional power infrastructure (O'Neill-Carrillo et al. 2018). Likewise, other success cases are related with emergencies in which users experienced grid unavailability (Ravindra et al. 2014). The expected transformation of the existent grid has taken a step aside to ultimately deal with extreme weather, vulnerable and aging electrical infrastructures, changing transportation needs, and socioeconomic disparities, making the MGs stand-alone operation capability and ad hoc design their most valuable current assets (Cuzner 2018; Vukojevic et al. 2020).

Then, major changes in the electric grid are foreseeable; however, they will come at a different rate and with particular characteristics depending on the dominant contexts where MGs are deployed. Up to this day, MGs have passed the reliability and resiliency tests as stand-alone "safe havens" during emergencies (Shahidehpour and Pullins 2014) and as enablers of better life quality for some communities in need. Indeed, there are technical, financial, social, and governance challenges to solve before observing the definitive development of the future power grid.

One of the remaining benefits of a micro-grid can be assessed by (Parag and Ainspan 2019): the addition of economic, reliability, environmental, deferred transmission minus distribution- generation and construction. In fact, the micro-grid is a controlled entity in the main electric grid that can be seen as a single aggregated load. Moreover, it can store energy in order to handle the market prices of electrical power in a local or global condition.

A general classification of micro-grids is based on AC and DC types. The DC micro-grid has an excellent short circuit protection system, and the efficiency is good enough for local generation in low and medium electrical loads. On the other hand, the AC micro-grids can be connected to the main electric grid, and they are reliable for the end-user. Still, they have a sophisticated control system strategy for synchronisation with the main electrical grid to be a stable system (Gao 2015). In this chapter only AC micro-grids are presented since they can accomplish an excellent demand-response when the electric load is swiftly changing.

Briefly, a micro-grid can be defined as a set of interconnected micro resources, flexible loads, and storage systems in a local distribution system. The form of operating characterises the micro-grid since it can connect and disconnect to the main grid. The micro-grid operation, when it is disconnected to the main grid, is called island or stand-alone mode, and when it is connected to the main grid is named grid-connected mode. The operation in both methods increase the functionality and provide benefits to the primary grid. The micro-grids are constructed by microgeneration, such as solar energy, wind energy, fuel cells, etc., storage devices as batteries, energy capacitors and flywheels, and flexible and controllable loads.

1.1 Economic Impact

One of the main benefits of installed micro-grid is the economic impact that is generated since the investment of transmission and distribution cost is reduced; thus, the conventional bulk transmission and distribution systems are eliminated from the electric topology. In micro-grids, the load centers are next to the generation systems, so the cost of transmission is not considered. Also, the micro-grid is a flexible topology that allows reconfiguring its components according to the electric load, renewable energy demands, and so on. Hence, the concept of option value system is applied to it. This option value concept removes the risks since it can continue, adapt, or abandon an investment. In the micro-grid, which is an adaptable system that can be re-configured, the option value concept is applied to reduce the economic risk (Ruotolo 2018). In the case of renewable energy, the micro-grid can be adapted according to the increment of electric load under a programmed structure that permits to reconfigure and to add new electric generation modules.

On the other hand, the economic impact of micro-grids also depends on the type of connection that is used: islanded or grid-connected. Usually, the type of electric connection of the micro-grid determines the demand response program that is implanted, so the dispatchable or non-dispatchable price program varies the price rates. This kind of program motivates the end consumers to try increment their electric consumption when off pike period of electric demand is reached and decrement the electrical consumption when higher peaks of electric load demand are achieved. This consumer's behaviour flattens the demand curve so the prices can be reduced. As a result, the costs can be divided as the time of use, critical peak pricing, and real-time pricing. Sometimes extra rates are added because the rates are changing continuously, and they reflect the total sales price. When a high demand response is needed, the end consumers are informed about the electric price one hour/day ahead. If the demand response is not critical, participation based on incentives could be implemented. In addition, the micro-grid can store energy, so the micro-grid regulates the energy import. Thus, the congestion of the electrical network at peak demands is also reduced, and the physical capabilities of the electrical grid are not overloaded. Therefore, the quality of energy and reliability of electricity is kept.

Moreover, the inequality provision of energy is mitigated, as well as the replacement cost linked to non-programmed maintenance (Gui et al. 2017). In fact, the investment for developing micro-grids integrates energy efficiency and generating smart technologies. Besides, the optimal configuration of a micro-grid is also defined by economic incentives, for instance, a 50% tax credit of investment cost for renewable energy promotes the adoption of wind energy more than a 30% tax credit. Besides, this kind of incentives increment the total amount of electric power generated by renewable energy and can accelerate its implementation (Zachar et al. 2015). It was shown that the cost of developing a micro-grid is around the following percentages: 15% for the controller, 50% generation, 35% remaining costs (Astriani et al. 2019). Besides, investment of small micro-grids into a community depends also on idiosyncratic activities since micro-grid operation requires specific equipment, a substantial investment has to be made in the community, and the participation of end consumers who are not part of the community for this investment is small (Gui et al. 2017). For estimating the cost of a micro-grid, the main characteristics have to be defined as shown by (Parag and Ainspan 2019):

- Installed capacity
- Structure of that capacity
- Costs associated with building, operating, maintaining the micro-grid

Using these characteristics, a comparison between the cost of fossil-based and renewable technologies can be done using Eq. (1) to find the levelized cost of electricity

$$LCOE = \frac{\sum_{i=0}^{n} \frac{I_i + O_i + F_i + ITC_i - PTC_i}{(1+r)^i}}{\sum_{i=0}^{n} \frac{E_i}{(1+r)^i}} \tag{1}$$

where I_i is the investment cost in year i, O_i is the operation cost in year i, ITC_i is the investment tax credit in year i, F_i fuel cost in year i, PTC_i is the production tax credits in year i, E_i is the energy generated in year i, r is the Weighted Average Cost of Capital and n is the life time of project (years).

It is essential to mention that carbon taxation does not make a difference regarding the technology deployed in the micro-grid with or without carbon taxation since the cost of carbon is too low (Milis et al. 2018).

1.2 Environmental Impact

To achieve an entire structure of the micro-grid that considers the environmental protection and economic dispatch into a decentralised generation system, the micro-grid has to be adjusted to find the minimum generating cost and the minimum greenhouse emissions cost. Also, power balance and load demand are reached (Liao 2012).

The environmental impact can be assessed using the emissions avoided monthly using a typical emission curve, as shown in Eq. (2) presented by (Hatziargyriou et al. 2009).

$$p(h, m, po) = \frac{\sum_{i=1}^{n} fc(h, m)_i * em(po)}{days(m)} \tag{2}$$

where: n is the number of units that may be affected by applying distributed generation, fc is the frequency at which unit i expects a critical value for the month m and the hour h, and em is the emission factor of the pollutant po for the unit i, and $days$ is the number of days in month m.

1.3 Social Impact

A couple of years ago, an estimate of almost 4 billion people, mostly in developing countries and isolated communities, had no reliable access to electricity, whereas 1.1 billion had no access whatsoever (Cuzner 2018; Podmore et al. 2016). Electricity represents not only the possibility of artificial lighting, but the access to a better life quality as it can be thoughtfully coupled with the community prosperity (Shahidehpour and Pullins 2015; Podmore et al. 2016). Not surprisingly, electrification has been recently outlined as one of the United Nations Sustainable Development Goals, among clean water, sanitation, access to education, medical services, and communication technologies (Anderson et al. 2017; Anderson and Suryanarayanan 2018). Undoubtedly, those goals are empowered, if not entirely enabled, by providing access to electricity, which also drives job creation, agriculture, and transportation, to name a few.

Providing energy through distant, isolated MGs is regularly preferred over expanding the existing grid, if any. The main drivers are, perhaps, the short-term applicability and its lower cost; however, MGs exhibit additional benefits that help such societies further. Indeed, every community is different and MGs can be designed specifically for their present needs and foreseen expansion; they generate value with local available resources, taking into account their variability, considering definite timing and potential social and governance issues (Ravindra et al. 2014). The direct participation of the electric industry would find difficulties due to the potential lack of existent technical standards and regulatory certainty (O'Neill-Carrillo et al. 2018).

On the other hand, the usefulness of MGs on existent grids has been advocated mainly due to their independence from a main grid prone to faults under emergency conditions. For instance, the hurricane Maria on Puerto Rico brought to light that the availability of electricity is a life or death matter, i.e., a proper human right (Cuzner 2018). MGs are, in the end, not a step toward the modern, traditional electric architecture but value-based entities, able to interact with the main grid if necessary or possible (Ravindra et al. 2014).

However, as beneficial as MGs may be in the socioeconomical context, they face challenges far from technical applicability. Ravindra et al. (2014) present a list of common obstacles of MGs implementation that have been summarised here under three categories:

- Financial issues
    - Affordability, financing, insurance, and return of investment
    - Application procedures and planning
    - Cost and pricing models, including further interaction of consumers and providers (exit fees, feed-in tariffs, load retention rates, interconnection, and standby fees)
- Social
    - Ignorance/lack of interest of stakeholders and consumers
    - Cultural dimensions in terms of usage of energy technologies
    - The growing rich-poor division
- Governance
    - Stakeholders lack of commitment, harmony, and trust
    - Lack of coordinated efforts and accountability
    - Political interference and lack of regulatory and policy frameworks.

1.4 Sustainability Impact

The sustainability in micro-grids could be measured by several indicators that comprise economic, social, and environmental conditions, so an adaptation of the sustainable factors presented by (Evans et al. 2009) is described in Table 1.

When a micro-grid has renewable energy included the greenhouse emissions are calculated during the entire operating life. Hence, the starting point is the manufacturing emissions of the plant. The greenhouse emissions are measured as grams of CO_2. Thus, solar and wind energy have a maximum emission value during the manufacturing process. The best generation energy in terms of availability, reliability, and flexibility is the hydropower (Egre and Milewski 2002). However, hydropower does not have a constant footprint, and the topography is not uniform in each location, so the land use is significant: around 73 km^2/TWh (Gagnon and Vate 1997).

An evaluation of sustainable indicators to generation technologies was presented by (Evans et al. 2009) in which each renewable generation technology is evaluated. As a result, photovoltaic technology is the worst technology in terms of price and the best is geothermal, wind energy is the best in terms of CO_2 emissions and the worst is the geothermal, hydro technology is the best one in terms of efficiency and photovoltaics is the worst, hydro is the worst in terms of land use and photovoltaics is the best, geothermal is the worst for water consumption and the best is the wind, hydro is the worst in terms of social impact, and the best technology is wind energy. Finally, the best technology in terms of availability and limitations is hydro and the worst photovoltaics. In a nutshell, photovoltaics and geothermal lead the rankings

Table 1 Sustainable factors in micro-grids

Economic factor	Environmental factor
Cost of generating electrical energy in terms of investment and development. In this factor also the quality of life for all the communities in excessive need of electricity has to be considered in terms of the Human Development Index used by the United Nations Development Program	Sometimes, incrementing renewable energies leads to the production of greenhouse emissions. Also, some visual damage and audible noise is added when some renewable energies are deployed such as wind energy
Efficient energy transformation leads to an extra cost	Land is needed to keep biodiversity and environmental conditions. Besides, the operation of the micro-grid could impact the environment if the disposal and recycling are not included as primary tasks
Heavily resource-constrained regarding technological limitations, mainly caused by intermittency and storage	Water consumption for operating the micro-grid. For instance, a significant amount of water is used to manufacture solar cells and wind turbines
Reduction of human risk during the manufacturing and operating process of micro-grids	Acceptance and adoption of communities

in terms of the worst sustainable technologies to generate electrical energy, and wind and hydro are the best technologies in terms of sustainability technology to generate electrical power. Hence, an investment to implement a micro-grid has to include a set of generation technologies in order to reduce the sustainable impact. Sometimes, additional sustainable indicators are included in power systems such as annual emissions of CO_2 (Mton/year), yearly emissions of NO_x (kton/year), yearly emissions of SO_x (kton/year) according to Prete et al. (2012), it is recommended to implement a sustainability evaluation framework to study different scenarios in which the micro-grid operates. Lastly, it is essential to mention that implementing micro-grids could promote economic growth, so rural and remote communities are impacted in a positive manner. However, the use of decentralised generation units is a technological challenge that requires to develop new technologies and economic regulations.

2 Micro-grids

2.1 Operation of Micro-grids

The operation of a micro-grid can be based on several features such as the connection scheme, environmental, technological and economic factors. This aspect defines the actions and participation of the micro-grid and stakeholders in activities such as the power exchange, energy security, economic, clean energy integration, pricing conditions of trading profit and ancillary services to mention some. The combination of the economic, environmental and technological aspects offer a solution to the optimal dispatch problem in the distributed generation (Hatziargyriou 2014).

The environmental aspects are determined by the emission quotas, and do not take under consideration the financial or technical aspects. Recently, there are new formulations related to the development of various policies, which are focused on increasing the promotion, development and implementation of renewable energy generation and distributed generation in order to reduce the dependency of electrical energy produced by fossil fuels resources. Nowadays, it is suggested the development of new policies, regulations, and incentives related to the micro-grid use, this with the main objective of increasing their penetration and implementation. The increment and utilisation of distributed energy will enable the reduction of the impact caused by the fossil fuel use.

The economic aspects are concentrated on minimising the total costs neither taking in consideration the performance and impact of the grid nor the environmental aspects. The infrastructure of micro-grids can provide a cost reduction because it is able to avoid the investment in the replacement and expansion of transmission lines, transformers and power plants. Moreover, the performance of micro-grid enables the increase of efficiency due to reduced congestion and line losses, distributing directly the power generated. The micro-grid can also provide ancillary services such as black start, reactive power and voltage control, power quality, frequency regulation and load following. The ability of micro-grids to emulate the inertia of conventional generation enables ancillary services and represent customer benefits.

The technical aspects are mainly concentrating on the losses, variations of voltage and device loading without considering environmental or/and economic aspects. Such features are related to the physical connection which is classified like the connected mode, transition-to-island mode, island mode and reconnection mode. During the operation under the aforementioned schemes, the solutions deal with the minimisation of losses, voltage stability, distribution system operation, control and protection in each mode in order to provide and offer a stable and high quality in the energy supply. The control system is designed to ensure the operation in the modes of connections.

2.1.1 Environmental Objectives

The power generated by the conventional power plants is transmitted along large distances in order to cover the electric demand. The transmission lines are commonly used to transmit over large distances high amounts of power. However, their installation generates visual inconveniences, communication interferences, and can represent a danger to low flying aircraft. In addition, there are health problems which might be provoked by the lines related to electromagnetic radiation.

The use of fossil fuels in the conventional process of electricity generation has an important participation in the production of greenhouse emissions to the environment. The environment is affected by several factors such as air pollution emissions, water use and discharge, waste generation and land use, which are derived by the conventional electricity generation. As a result, there are strong concerns in worldwide about the climate change and global warming.

The penetration and promotion of renewable energy technologies and installation have gained interest since they can help to reduce the production demand for electricity produced by the conventional processes. Micro-grids are characterized by the use of renewables to produce electrical energy. The adoption and use of micro-grids result in several benefits such as the increased efficiency, reduction of greenhouse emissions, minimization of health risks and conservation of the resources.

2.1.2 Economic Objectives

Energy markets operate according to several layers of complexity which are delimited from the completely regulated to completely liberalised models. Thereby, the generation and retail are considered as competitive activities, and the transmission and distribution as regulated activities. In particular, the wholesale market and the retail market are two major markets which deal with the trade and supply of energy. These markets can work with each other by way of group or/and via two-sided. An open transmission access to producers and energy importers has established a competitive wholesale market. On the other hand, the competition at the retail level is given by several options and offers in the supply and electricity cost.

There are different stakeholders involved in the energy market such as the consumers, distributed generation owners or operators, prosumers, market regulators, retail suppliers, energy service companies, distribution system operators and micro-grid operators. The consumers are persons or institutions that pay for the use of energy, the producers also called distributed generation owner or operator inject the energy produced to a network of distribution. The prosumer is a definition related to a customer that can deliver energy as well as consume energy. A market regulator is an authority to establish a correct and transparent operation of the market. The retail supplier/energy service company (ESCO) establish a contract to customers and can acquire energy from the wholesale market or spot market or local production. The distribution system operator (DSO) is the entity in charge of the operation, management, maintenance, regulation, and growth of the distribution network in a determinate area. In addition, DSO play an important role since providing a field neutral as market facilitators. Lastly, Micro-grid operator has in charge the same role of DSO in a local distribution network produced by the micro-grid.

The micro-grids are financed by facility owners as institutions and campus, which can use the distributed system infrastructure in order to reduce their installation cost. However, the relatively small size of a micro-grid limits their direct participation in the wholesale market or retail market. Hence, there are models that enable the micro-grids participation, which can be as part of a portfolio of a retail supplier or an energy service company, as well as the Direct control of DERs by DSOs. In this context, four scenarios have been proposed in order to generate a market decentralised structure to the micro-grid resources ownership such as ownership by the DSO, ownership by the end consumer or even consortium of prosumers, ownership by an independent power producer, and ownership by an energy supplier in a free market arrangement. In the same way, the participation of prosumer and integrate the energy prosumers under the next schemes peer-to-peer, prosumer to grid, and prosumer community.

The use and adoption of DSO, as well as the agreements between suppliers and DSOs, will enable major benefits to the customers by means of an adequate market, smooth process, local stability, reliability and security in the supply of energy.

2.1.3 Technical Objectives

The technical features are related to physical constraints such as the micro-grid capacity, energy balance, power loss, and reliability. In this sense, the levels which can be adopted by the micro-grid are divided into four and they are listed from zero to three. The zero is called inner control loops which adjusting the output voltage and control current while keeping the system stable. The first emulates the physical behaviours which produce a stable system and it is called primary control. The second or secondary control is in charge of supervising and guaranteeing the limits of the electrical values and it includes the management of the control loops to realize a seamlessly connection or disconnection of the micro-grid to or from distribution system. The third level involves the power flow control between the micro-grid and the main grid and it is also called tertiary control.

The micro-grid can operate by several modes, which are defined under certain ranges and operating points and it also provides active and reactive power to supply their loads or to be transferred to the main grid, this transfer is carried out without affecting the system stability. The micro-grid can operate as an island mode or grid-connected mode. The island mode is characterised by the stand-alone operation of the microgrids, auto-satisfy their loads. The island mode supplies the local demand since it is able to produce its own energy. In order to ensure an uninterrupted supply, the island mode prioritises the supply to the crucial, important and critical loads.

The grid-connected mode is described by the connection and exchanges between the micro-grid and the distribution system via PCC. In this mode, the distributed generators and storage system are synchronised according to the reference values of frequency and voltage provided the grid. Lastly, the transition mode is an important condition in order to reduce the power losses, since a smooth transition can reduce the aforementioned power losses which happen during this process.

2.2 Control of Micro-grids

There are several features from the literature that can describe and classify the objectives of control or functionalities. The droop control, voltage and frequency regulation, power sharing, energy management system (EMS), micro-grid optimisation and interaction between micro-grids are the main and important concerns related to micro-grid operation.

The droop controls simulate the process of energy demand in a conventional power system. During this process if the active power increases a frequency droop is provoked. Conversely, when the frequency increases then the active power falls, and, in the same manner, a similar effect occurs between the reactive power and the voltage's amplitude. A conventional power system is integrated through the use of huge synchronous machines with large inertia. The DERs are integrated into the grid by micro-grids and the micro-grid interface DER sources through inverters. The island mode in a micro-grid is represent by a scheme of multiple inverters connected in parallel.

- Centralised: The droop control has been designed to have a parallel operation of DERs inverters which work as in the island mode and grid-connected mode. During the island mode the controller works under voltage control mode and when it is connected to the grid it works in current control mode.
- Decentralised: In this scheme, the droop control is the most commonly implemented. The controller design takes into account the voltage-frequency control and power sharing using three loops which are nested. The first regulates the output voltage in the inner loop, the second is the loop of the output resistive impedance, and the third is the external loop to share active and reactive power

- Hierarchical: The proposals and use of droop controller are limited.
- Distributed: The coordination between the primary and secondary level in order to reach a proper power sharing and frequency synchronisation are the main recent proposals. The main concerns are the effect of communication delays and loads balance.

The objective of the voltage-frequency control is to reduce the effect generated by the small and large fluctuations in system frequency and voltage. The controller's objective is to hold the micro-grid within operation limits to the micro-grid in order to reduce the stability problems, distorted power quality and equipment failures.

2.2.1 Intelligent Local Controllers

Integration of control systems in micro-grids (MGs) is essential to guarantee reliability when MGs are working in connected and/or island mode. The control systems regulate voltages and frequency to maintain the operation of micro-grids within nominal values. Also, the power flow inside a micro-grid or between micro-grids, is under the care of the control system. The task of control systems operating in MGs are the following (Hirsch et al. 2018): to make the micro-grid a single self-controlled unit capable of providing frequency control; limiting the power flow within line ratings; to adjust frequency and voltage within admissible values, when the MG is working in island mode; to keep energy balance by means of the management of resources: and, to smoothly connect, disconnect, synchronise, and resynchronise, the MG with the electric grid.

2.3 Control Architectures

In order to accomplish the aforementioned tasks, the following control architectures have been developed (Sen and Kumar 2018):

- Centralised: it is composed of a central controller, which receives information from all MG sensors, and then the computation and execution of control actions are carried by the central controller, and the control law and set-points are sent to each unit;
- Decentralised: in this architecture, a local controller is integrated into each unit, which collects both local information and global information such as neighbourhood controller actions, while system-wide information is disregarded.
- Distributed: the distributed architecture is similar that decentralised, the main difference being that each local controller shares information with its neighbouring units, and then, a global management of the MG can be achieved while the autonomy of each unit is preserved.

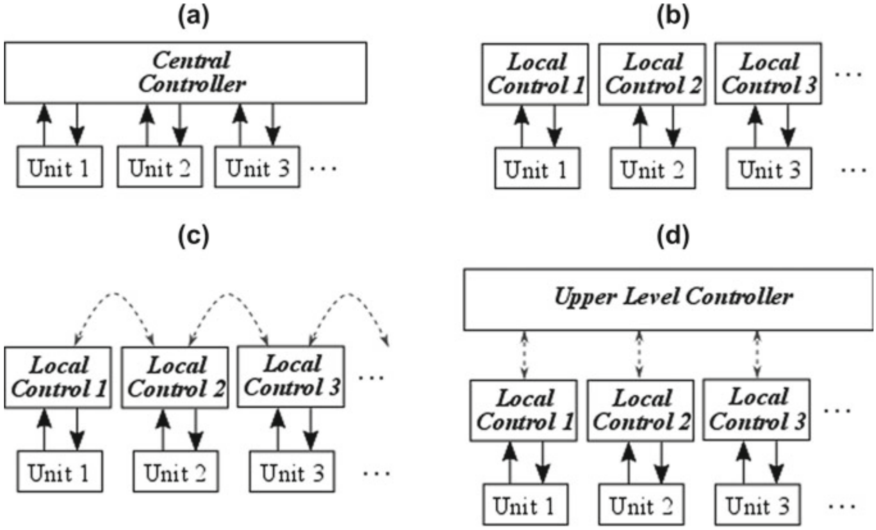

Fig. 1 Schematic diagrams of MG control architectures

- Hierarchical: this architecture defines a control structure divided into layers, usually three, segmented in accordance with time scales, which correspond to the time of execution and time of application of the control signals.

The schematic diagrams of each control architecture are presented in Fig. 1.

Considering MGs are conceived as the main element of smart grids, MGs have to work either in islanded, connected, or interacting mode. Thus, the combination of more than one control architectures is required, since hierarchical architecture has the advantage of integrating centralised, decentralised, and distributed control schemes to accomplish the MG targets of smart grid conception.

2.3.1 Hierarchical Control

Hierarchical architecture is composed of three control levels named primary, secondary and tertiary. The primary control interacts with the inner control of the distributed units, including the virtual inertia and regulating output impedances. The secondary control deals with frequency and voltage fluctuations caused by changes in the output impedances. The tertiary control is in charge of the power flows between the electricity grid and the MG at the PCC. A scheme of the hierarchical control is presented in Fig. 2, and more details about the control levels are given in the next subsections.

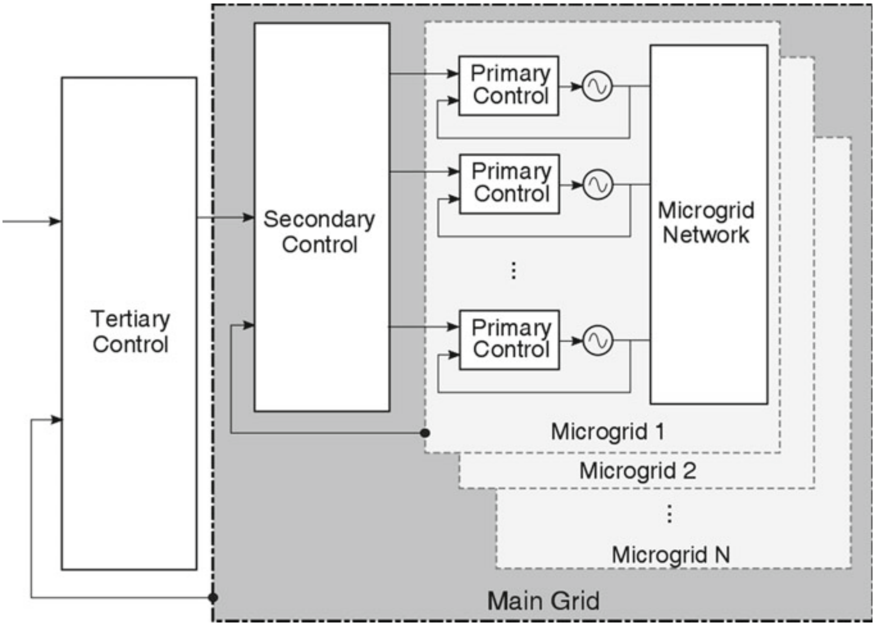

Fig. 2 Hierarchical control scheme

Primary Control

Primary control works with local measurements, has the fastest response in the hierarchical architecture, and is integrated locally inside each unit. The tasks of primary control include output control, power sharing control, and islanding detection.

The control actions are executed through intelligent power interfaces: voltage-source inverters (VSIs) and current-source inverters (CSIs). Output control consists in regulating current and voltages at the output of the power interface. Power sharing control deals with the regulation of reactive and active power by employing local measurements since voltage and frequency control are used to operate reactive and active power, respectively.

In this control level, the integration of virtual inertia is mandatory to emulate the behaviour of synchronous generators and compensate frequency deviations caused by lack of inertia in power interfaces.

Secondary Control

Secondary control is responsible for two tasks, to: drive to zero any frequency or voltage deviations produced by primary controls, or changes of load and generation in the MG; and guarantee a secure, reliable and economical operation of the MG. Due to the second task, the secondary control is also considered an energy management system (EMS) (Olivares et al. 2014).

When MGs are operating in island mode, the secondary control becomes the highest level in the hierarchical architecture, which is related directly with the EMS. Secondary control must manage the generation units to compensate for fluctuations in loads, the intermittency of generation, and the availability of energy in the storage systems.

Tertiary Control

Tertiary control is in charge of the organisation of multiple MGs when collaborating. Also, the power flow between the MG and the electricity grid is managed by tertiary control. Economic issues, such as economic optimisation by means of energy prices and electricity markets, are commonly considered to come under tertiary control.

When, the optimisation process is considered at this level, it refers to power flow optimisation and energy optimisation (Vandoorn et al. 2013). In power flow optimisation, the target is optimised by reactive power online. For energy optimisation, forecasting of generation and load is employ to optimize the energy with respect to energy cost.

3 Power Converters in the Micro-grid

The control actions required for any of the control levels presented in Sect. 3.2 come from a power interface, which is a power converter. Then, the power converters in the control of MGs are indispensable elements.

Power converters are capable of working as current-source inverters (CSIs) and/or voltage-source inverters (VSIs). CSIs are composed of an inner control loop plus a phase-lock loop to synchronize the CSI with the electricity grid. VSIs are the cascade of two control loops; the external one to regulate voltage and the internal one to regulate current. VSIs are employed in island mode whereas CSIs are used in grid-connected mode.

Power converters in MGs are classified as: grid-forming, grid-feeding, and grid-supporting (Rocabert et al. 2012; Schiffer et al. 2016), and are described in the following subsections.

3.1 Grid-Forming Inverter

Grid-forming works as a VSI composed of an inner loop to regulate the current and an outer loop to regulate voltage. The inner loop employs the current measured from

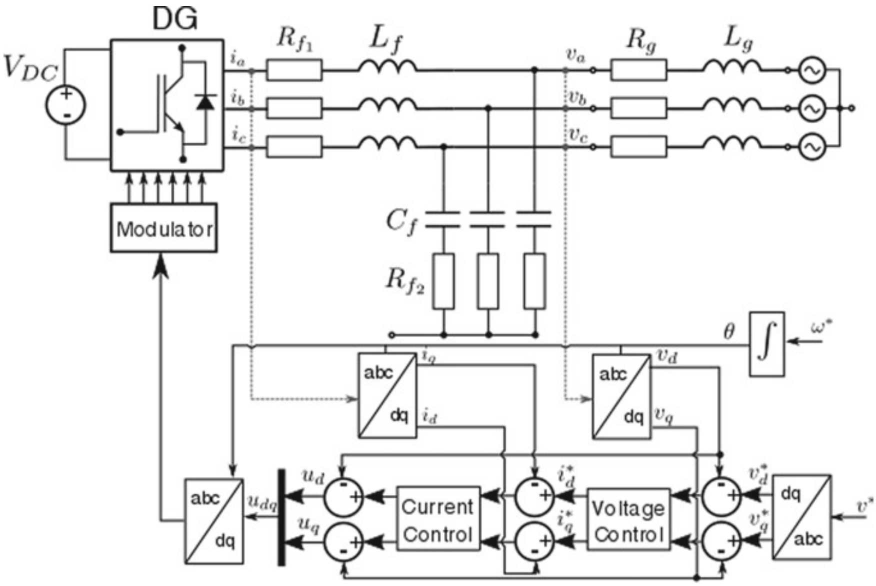

Fig. 3 Schematic of grid-forming

the filter inductance whereas the outer loop uses the voltage measured at the output of the inverter, see Fig. 3.

In primary control level, a grid-forming inverter is employed to regulate frequency and voltage when the MG is working in island mode. The secondary control level uses a grid-forming inverter when variations of voltage or frequency occur during the changeover between island and grid-connected mode. The objective is to resynchronise amplitude, frequency, and phase angle with respect to the electricity grid, before reconnection.

3.2 Grid-Feeding Inverter

The grid-feeding inverter regulates active and reactive power at predefined set-points received from energy management systems or higher control levels. This is also known as PQ control, or grid-following. Similar to grid-forming, grid-feeding is composed of a cascade of two control loops; the inner one is a current loop whereas the external one is a power loop, see Fig. 4.

In the hierarchical architecture, grid-feeding inverters are part of the primary, secondary, and tertiary controls. When generation units work under MPPT (maximum power point tracking) techniques, the grid-feeding inverter receives the references of power, P* and Q*, from the MPPT algorithm.

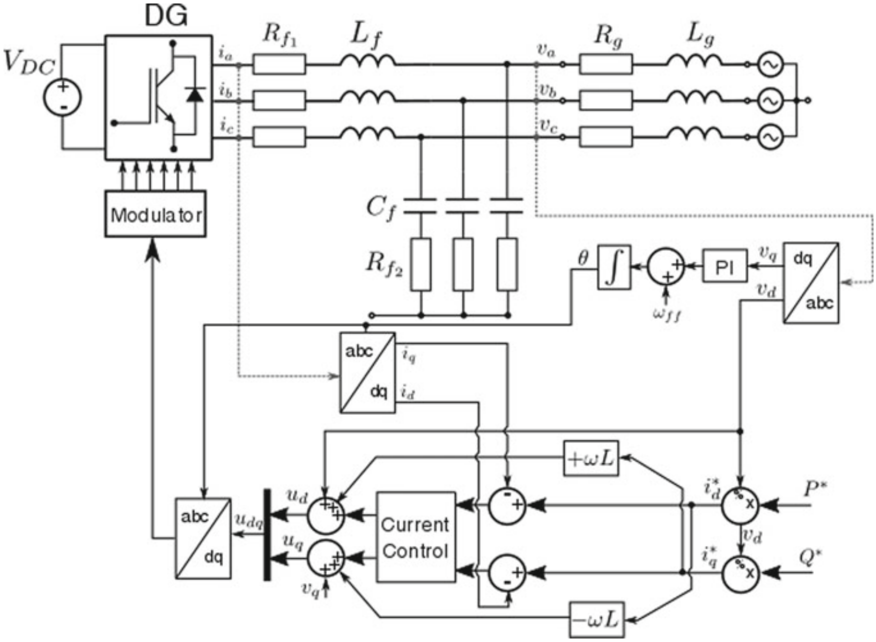

Fig. 4 Schematic of grid feeding

Under secondary control, the grid-feeding inverter takes the references of active and reactive power, P* and Q*, respectively, considering the capacity of the inverter, as well as the generation technology when the inverter is linked.

Since tertiary control deals with the optimal operation of the MG from an economical perspective, then, considering the cost of the energy generated by each type of generation technology, tertiary control provides the power references to the grid-feeding inverter.

3.3 Grid-Supporting Inverter

A grid-supporting inverter is capable of working either as a VSI or a CSI, following same target in both cases i.e. to regulate voltage amplitude and frequency via the reactive and active power injected into the grid. As presented in (Schiffer et al. 2016), the grid-supporting inverters are grid-forming with an external loop that includes droop controls to compute voltage set-points, see Fig. 5.

Grid-supporting inverters are integrated in primary and secondary control levels. For primary control, the grid-supporting inverter is used to regulate the phase angle, frequency, and amplitude of the voltage. On the other hand, when a grid-supporting

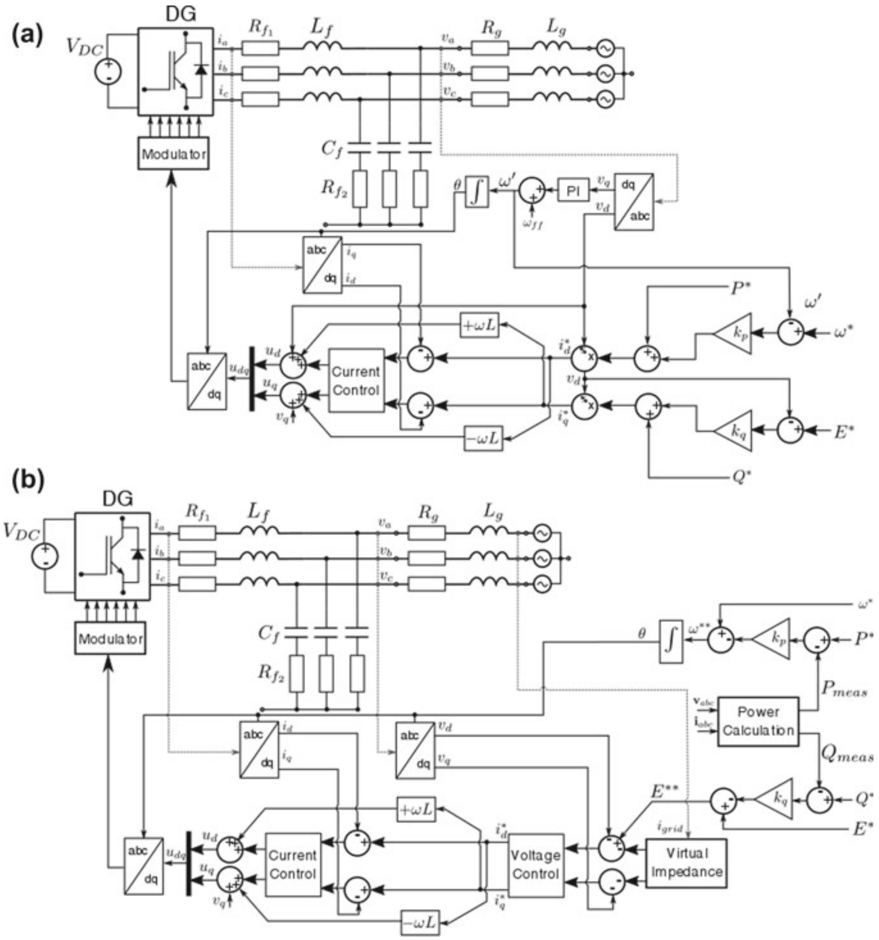

Fig. 5 Schematic of grid supporting as a: **a** CSI and **b** a VSI

inverter is employed in the secondary control, the frequency and voltage are adjusted by means of the references P* and Q*.

4 Protections

It is clear that MGs are different from the traditional electricity grid: their usage as distribution nuclei; the integration of Distributed Energy Resources (DERs); DERs can be inverters in micro-grids that also inject harmonic content into the MGs as well as the main grid; and, their constant monitoring set an obvious step towards a modern usage of electric power. However, such changes are normally discussed assuming ideal operation of the MG components, or from a superficial approach to power management, disregarding the challenges in protecting the MG. Among the differences between MGs and the traditional grid, electrical protection is perhaps the issue requiring most changes in order to enable safe and reliable operation (Kang et al. 2017).

There are several situations during the MG's operation that necessitate advanced protection capabilities; curiously enough, such added requirements are entirely related to the MG's expected benefits. This makes the protection systems not only necessary for the MG's conservation, but for its overall operation (Zamani et al. 2014). A MG is expected to be either connected or not to the main grid, to enable the "transparent" integration of DERs, and to isolate faults, etc. Such expectancy necessarily comes with added complexity, as is pointed out next (Hatziargyriou 2014):

- A grid-connected MG is susceptible to grid-side and MG-side faults
- Whenever a MG is connected to the main grid, the available fault current is larger than if disconnected
- The fault current's direction may change depending on the MG topology under fault
- Integrated DERs exhibit specific electrical dynamics which introduce uncertainty to magnitude and time thresholds
- The MG topology changes without prior notice when devices are added or removed
- The contribution of the DERs to the fault events depend on variable conditions such as sun irradiance, wind speed, and so forth
- MGs are supposed to cope with the grid codes during faults.

From a traditional point of view, protection systems rely on circuit breakers (CBs) associated with non-directional current-sensing devices. Taking into account the MG's distinctions, it is no longer possible to ensure adequate protection as one-time designed limits will seldom be useful in all the possible MG operating schemes (Kang et al. 2017; Zamani et al. 2014), and even less so for possible future scenarios. Indeed, the protection problem is not only related to non-tripping situations, but also to false-positives. Uncertainty precludes traditional design and, consequently, obliges novel proposals and enhanced protective devices (PDs).

Before describing the proposed solutions to MG protection, it is important to consider that any protection system is commonly assessed through the "3S" perspective (Hatziargyriou 2014): Sensitivity; Selectivity; and, Speed. Unlike instrumentation systems, sensitivity is related to the capacity of the protection system to identify a fault condition. On the other hand, selectivity involves near flawless disconnection of the faulty grid section. Lastly, an adequate speed is one which enables the protection system to react fast enough to avoid further damage to the protected grid.

For instance, the inclusion of DERs will directly cause a sensitivity problem for conventional protections, as shown in Fig. 6 This figure shows two short-circuit scenarios: the first one involving a direct grid-to-load short-circuit, causing the fuse (CB) to blow due to the current's magnitude; on the other hand, the addition of a generation parallel to the load would reduce the current's magnitude as seen by

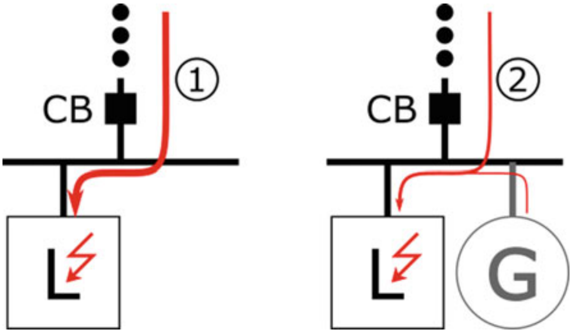

Fig. 6 The addition of a DER makes the traditional PD to fail in detecting a short-circuit

the CB, thus preventing protection. This sensitivity problem is also found when switching between connected and isolated modes, as the current availability will change depending on the presence of the main grid at the PPC.

Now, let Fig. 7 represent a radial network whose protection devices were originally designed to be unidirectional. Even if full switchboards (SB) are used at each branch, unlike the previous example, then a short-circuit may have very different implications whenever DERs are integrated. The fault shown in Fig. 7 should have tripped CB2, clearing the fault and permitting continued operation of the branch associated to CB1. However, as the added generator also contributes with current to the fault, CB1 or CB12 may trip. This clearly constitutes a selectivity issue.

Finally, the inclusion of high-power density devices, such as ultra-capacitors, commonly used in backup appliances, as well as in rotary machines, imply sudden current peaks during charging or starting, respectively. Those variations depend on the status of the MG, or at least on the power requirements of adjacent buses and branches. As changes in MG topology can come from user decisions, or unidentified CB or PCC connection/disconnections, the configuration of the related CBs may fail in considering transitory currents. This is a speed problem related to an incorrect or "naive" configuration of CBs in the presence of uncertainty.

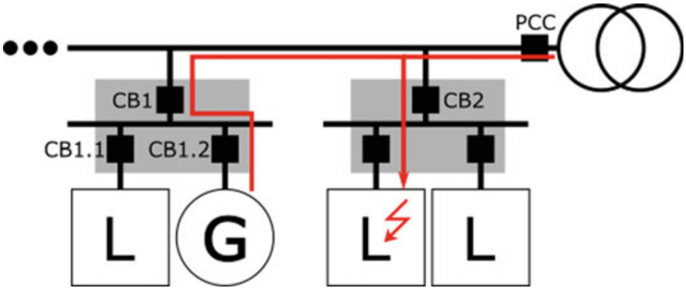

Fig. 7 Selectivity is also compromised if current direction is changed due to changes in the grid's topology

The above three examples are simple scenarios where the 3S approach to PDs is missed due to slight modifications to a traditional distribution grid. However, although MG protection implies added complexity and thorough planning, there are feasible alternatives for their effective operation. Such alternatives rely on non-conventional PDs, communication protocols, and infrastructure, and planning/management frameworks.

4.1 Protective Devices for Micro-grids

Protecting an MG is very similar to protecting a traditional but complex distribution network (Zamani et al. 2014). Actually, the devices used in MG protection are the same as those used in distribution protection tasks (overcurrent, distance, and differential (Brahma et al. 2014)), but including re-configuration and communication capabilities. If such high-level capacity is omitted and the electro-mechanical part is addressed on its own, their operation is very similar to the traditionally implemented PDs. Briefly, from a traditional point of view, an MG can be seen as a meshed distribution network.

All protective systems can be held to be comprised of an instrument, a processing unit, a decision-making engine, and a CB. The instrument is responsible for measuring the physical variable of interest, namely; voltage, current, frequency, etc., while the processing unit converts the acquired variables into meaningful inputs to the decision-making engine. The decision-making engine consists of one to several criteria, which can be time-dependent, and it normally works in an *if–then* fashion to determine the resultant state of the CB. Even old electro-mechanical PDs can be described in such terms, sometimes combining the aforesaid components into single mechanisms.

Mostly, faults are related to short-circuit conditions, thus making the current PDs the first line in MG protection. Non-directional current PDs, such as those meeting the ANSI 51 standard, can be incorporated at the load-only endpoints; or where a load-only radial distribution is followed inside a MG. Fuses and thermo-magnetic devices can be used safely when there is certainty about the current direction during a short-circuit; standard overcurrent CBs can be also used. Otherwise, directional overcurrent protections should be used, such as those conforming to the ANSI 67 standard.

Sometimes overcurrent PDs are not enough for effective protection as they depend on the source impedance, which is likely to change in MG operation (Kang et al. 2017). A schematic representation of this problem is shown in Fig. 8: changes in the supply side also change the fault current, independent of the distribution network and the load itself. The overcurrent PD can be directional or not, thus making no difference.

Distance protections sense both, voltage and directional current to compute an equivalent forward impedance. Tripping conditions are then established in terms of allowed impedances rather than current values. Usually, distance protections are used

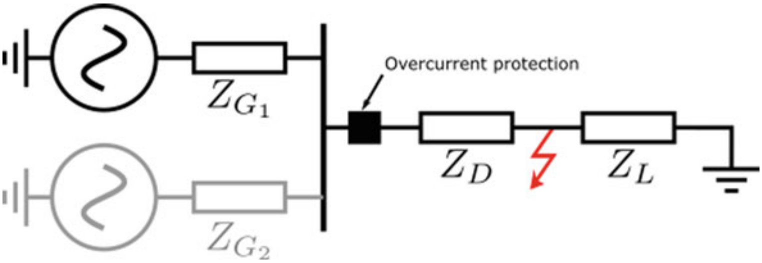

Fig. 8 Distance protection is required when source impedance may account for missing overcurrent protection missed or wrong tripping

in transmission lines whose impedance notably changes with respect to length; therefore, enabling this protection not only to detect a fault but to estimate the distance at which it occurred, hence the name. Independent from its habitual use, distance protection eliminates problems related to source impedance variations, thus enhancing sensitivity.

A distance protection (ANSI 21) will effectively account for faults in transmission lines because their impedance will seldom change and their power flow is determined from supply to loads. However, their application in MGs may also find difficulties as the foreseen impedances may change, and the integration of DERs preclude a clear identification of a "supply side," modifying the impedances of both sides of the PD. Nevertheless, distance protections extend the capabilities of the protection system beyond the effectiveness of sole overcurrent PDs.

Both of the revised PDs can identify faults *from* a given geographical point but cannot isolate their detection capabilities to a given area or grid section: a much-appreciated capability in MG operation. If ever local directional protection is not required, a differential PD must be used. These devices make two measurements, in respect of a given device or bus section, in order to detect input/output differences which can indicate a fault condition (Kang et al. 2017). Provided that the local conditions are known, the protection can be configured for known requirements and effectively trip if needed, ensuring selectivity. Differential PDs comprise the ANSI 87 standard.

A differential PD is normally distributed among different appliances, i.e., the instrumentation is not necessarily attached to the processor, nor the associated CBs. This configuration requires a reliable communication channel among its components to work properly. This link must be also fast to enable actual protection. This particular issue makes the use of supporting PDs mandatory, enabling the protection of specific devices, such as transformers and rotary machines, as their inputs and outputs are not distantly distributed.

None of the above protections is useful for MG protection in their conventional form. The aforementioned uncertainty regarding the MG topology is a major hindrance to the efficacy of protection systems. Thus, it is important for the incorporated PDs to be re-configurable and allow digital communication. Such characteristics are normally provided in microcontroller-based protection and automation systems. Ultimately, and as expected, these requirements come together in the MG's overall provision regarding sensing, communication, and automation capabilities.

4.2 MG Protection Techniques

It is now clear that a fixed, traditional, approach to MG protection would perform deplorably. Broadly speaking, its benefits come together with topology uncertainty and generation/load variability, as the MG changes stochastically. This inherent randomness means that any attempt to define a robust location and configuration of PDs is doomed to failure, while the developed alternatives involve the adaptability of the protection system.

This approach is commonly referred as "adaptive protection" (Kang et al. 2017), and involves the re-configuration of PDs settings, either continuously, or dependent on detected discrete states. Such re-configuration involves modification of protection thresholds and delay times, depending on the known/detected MG state. Due to the integration of DERs and storage devices, additional information is required, namely; weather, consumption patterns, market signals, etc., entirely contingent on the MG's added complexity.

Mainly, there are two ways in which the adaptive condition can be attained (Hatziargyriou 2014): by pre-calculated states or by real-time adaptability. Both paths require all the PDs to be communicated, and that their parameters are accessible and modifiable by such means. In this way, the communication protocols used in MG protection become paramount, and their reliability and safety issues must be minimised, e.g., cybersecurity, loss of information, latency, noise, etc. Such characteristics can be found in industrial communication systems, commonly involving a Modbus protocol over an RS-485 bus.

Although this section does not focus on the communication itself, it is noteworthy that both wired and wireless alternatives exist to handle the expected connection. Communication latency at this level imposes no real restriction on the adaptive protection operation as the data transmission is only intended to configure the PDs, not to perform the protection itself. Detecting the current state of the MG and configuring its associated PDs could take a short period of seconds, not compromising the protective capabilities. For instance, the aforesaid allowance was derived at from the implementation of master–slave topologies based on individual polling of PDs.

The adaptive approach to MGs protection can be clearly visualised from two perspectives: centralised; and, decentralised. A centralised MG controller gathers information from all PDs and returns configuration signals to establish the specifically required protection scheme, depending on the detected MG state. A decentralised MG controller moves the decision-making process to multiple decision cells, distributed among intelligent[1] PDs. Such distribution relies on modules formed to give protection adaptability, based on local information rather than on the overall MG state.

It is important to notice that the above MG controllers are not those normally referred to when describing a MG; these are management controllers (MC). The management of MGs can be divided into hierarchical stages, and protection adaptability should be the lowest stage. This distinction is important as the management and control of MGs work in parallel, but the decision-making process regarding protection systems is a management issue, not an automatic control concern.

In this spirit, MG management can be divided into three complementary levels, namely; configuration, management, and external. The configuration level includes the MCs referred to above. The management level comprises the traditional tools and interfaces for distribution systems, including an historic record of MG operation. Lastly, the external level deals with complex decision-making inputs, such as the weather status, energy market prices, and business strategies.

4.2.1 Centralised Approach to MG Protection

The centralised approach implies a master-multi-slave topology comprised of one central MC (master) and many PDs (slaves). The interaction is commonly performed by sensing and configuring the MG through the individual polling of each PD. It is clear that depending on the size and intricacy of the MG, the central controller will demand more complex computational capabilities in terms of processing and communication. There are two ways in which centralised controllers can attain adaptability; namely, precalculated states, and online state estimation.

Precalculated States

The easiest way of establishing a centralised adaptive controller is perhaps by the exhaustive testing of the MG operation. This, of course, implies the analysis of every possible configuration and all its associated potential faults. Such analysis, commonly performed by means of simulation, is later arranged in a knowledge-base: a list comprised of the discrete estimation of the MG state and the expected configuration of the PDs (the actions table). The centralised controller performs a periodical assessment of all the PDs, finds the matching precalculated state of the MG, and sends the corresponding configuration back to the PDs.

A major concern about the preceding approach is that all tests are performed with a fixed topology of the MG, prior to its actual operation. However, topology changes can be foreseen and tested, so the knowledge-base includes not certain but possible operating conditions. In addition, potential changes of the MG nodes can also be considered. For example, the inclusion of a DER at some node can be anticipated.

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[1] The term ‘intelligent’ here implies the use of embedded devices for digital processing and communications. It is not related to artificial intelligence.

On the other hand, a new set of simulations can be run once the MG has sufficiently changed or new PDs have been incorporated, and the new knowledge-base can then be transferred to the central controller.

delay times; it may actually include particular settings for specific PDs, contingent upon need. It should also include priority scales depending on the MG connections and the existence of critical loads. Maintenance and sub-grid isolation can also be considered in the knowledge-base, and triggered at the operator's request.

Online State Estimation

The online state estimation approach takes the principal functionality of the previously presented "pre-calculated states" technique, but adds real-time feedback. Such feedback is useful to test and further detect the MG state, given a set of adaptation rules. Briefly, the central controller modifies the configuration of the PDs to acquire their related electrical variables, and analyse the knowledge-base to check matching operating states, estimating neighbouring fault currents. If the fault criteria, based on the interaction of the PDs, are met, a trip would be generated, otherwise, the PD's settings are kept as they correspond to the current MG status.

Actually, this approach relies on the interaction of two subsystems: online; and, offline. On the one hand, the online subsystem is continuously assessing the PDs and comparing their status to a known condition, i.e., the discovered grid state. On the other hand, there is an offline process running the adaptation routine to discover that grid's state: the PDs related variables; the current's direction and limits are computed; and, a matching state in the knowledge base is found. Three cases can arise from this: (1) the settings remain unchanged as energy flow and PDs limits are congruent with the preceding state; (2) a new state is found and the tripping settings are communicated to the online process; or, (3) no state matches the MG's current conditions, representing an unknown status which must be prohibited.

It is noteworthy that the tripping signals depend on the centralised controller as changes must be evaluated respect of the offline subsystem. There must be some sort of communication between both subsystems which must be fast and reliable. Indeed, the decision between a state change, and a fault, is centralised, so the normal operation of PDs may be delayed. The communication problem hinders the application of this approach from spreading, broad MGs and focuses on local.

4.3 Some Notes on Decentralised Protection

Changes in the MG cannot be avoided and are the main reason for adapting the protection system. Topology modifications and fast integration of new DERs make these systems prone to failure if the protection system cannot cope with fast modifications. Admittedly, it is clear that the aforementioned techniques, relying on a centralised controller, will throw up many difficulties for complex MGs.

The decentralised approach offers a way to provide locality to MG sections, i.e., separate MG complexity, potential faults, integrated DERs, and communication burdens in individual subnetworks. Such locality then involves focused management of the protection system for a particular section of the MG, not (or barely) considering the neighbouring sections. The previously presented alternatives for adaptive protection systems can now be applied individually to each section, resulting in a decentralised protection system.

The obvious implication of this approach is that there must exist a controller per section, dealing with the local processing of the MG's protection. Industrial devices, such as PLCs and multipurpose intelligent controllers, can be used for this purpose. In comparison, there is not a centralised controller, and if there is, its protection duties would include (if needed) communication with decentralised controllers, the update of databases, the acquisition of environmental variables, etc.

Although a module version of the protection system may look like a simplification of the overall protective tasks, it must be considered that a centralised controller would deal with one main uncertainty source: the PCC. Similarly, a sub-grid will need to consider topology changes coming from "outside", but in this case it will not be one but many. Moreover, one change in the MG would affect different sections of it, requiring an effective way to account for such operating variations overall. Hierarchical communications and controllers would then be needed to cope with subnetwork interactions.

4.4 MG Protection Trends

Nowadays the problems related with MG protection are well-known and many different schemes have been developed to tackle them. Such proposals normally rely on the presented PDs and their novelty relies in the way they are integrated. Other proposals deal with novel detection systems integrated into traditional PDs as presented by Mishra et al. (2016) where an intelligent approach to feature extraction and decision making is presented. Overall, MG protection requirements are (Brahma et al. 2014):

- Detection and isolation of internal/external faults
- PCC effective disconnection in external fault condition
- Avoiding unintentional islanding
- Avoiding out-of-phase reconnection at PCC
- Layered protection for fault isolation
- Meeting S3 conditions.

Some of the works cited by Kang et al. (2017) deal with the incorporation of voltage-based protection systems, able to detect and clear faults as with current-based PDs because short-circuit conditions commonly come along with voltage sags. Admittedly, a clear trend in MG protection has been established in the ordered integration of different PDs and their management, yielding hierarchical and coordinated protection systems. These distinctions make the different PDs and their controllers to be distributed in protection layers: a primary layer is comprised of PDs with expected immediate response; and, backup layers intended to intervene if the former fail.

Complex MG topologies normally require different, systematic tests to validate one fault condition among many other potential faults. This has led to installing PDs redundantly, e.g., overcurrent, distance, and differential protections for the same MG section. Such PDs can also be coordinated directly or through an hierarchically-higher controller, so the protection is also enhanced by layering.

5 Recommendation for Implementing MGs in Mexico as the Main Factors Guide

Implementing micro-grids in a developed country could be very attractive since they could be deployed under several economic, social, and environmental conditions, such as rural communities or cities that want to become smart cities. Mexico has the opportunity to increase the generation, distribution, and consumption of electrical energy based on micro-grids. Besides, Mexico could dramatically increment the number of renewable energy sources in the main grid. However, there are factors that must be considered when deploying a micro-grid. Thus, the main factors for implementing a micro-grid have to be taken into account. The fundamental factors referred to provide some directions for their implementation (Akinyele et al. 2018), but only the main factors are dealt with here.

5.1 Social Factors

These factors include the participation of planners, developers, financiers, investors, government, and the community. In general, these parties can become involved during the system planning and development stages, but also in the course of the maintenance of the system. Besides, it is essential to know how to efficiently use and conserve energy, as well as having an understanding of how to maintain the equipment, by researching previous studies on these topics. The communities for whom a system is installed, do not necessarily assume ownership, so they expect the operation and maintenance to be the responsibility of the benefactor. Interaction with the community is required to establish their real requirements, and it must be carried out to avoid design failure. The list below shows the most important topics when planning a micro-grid.

- Increment community engagement
- General education about micro-grids
- Solve the question about the ownership
- Installation by qualified practitioners

- Practical preliminary survey
- High-level of social awareness
- Security of Infrastructure.

5.2 Technical Factors

These factors refer to the design, maintenance, standardisation, monitoring, and supervision of the system. It is required to consider the what-if or worst-case scenarios that could lead to insufficient power generation in the future. Preventive/corrective procedures are standard in solar photovoltaic systems that could be affected by dust, wiring losses, etc. Involving local expertise leads to fewer foreign experts who are not familiar with the local conditions. Adhering to international security standards avoids system failure within a few years after installation. The use of sub-standard materials to make the installation cheaper, lowers the lifespan of the system is not the correct way to design a micro-grid. Monitoring and maintaining rural micro-grid systems assiduously, obviates the number of system failures due to a lack of proper preventative measures. Some of the fundamental factors to consider are presented below.

- Appropriate complete design
- Follow standard maintenance procedures
- Local skilled practitioners
- Conformity to international standard codes
- Use standard materials
- Adequate knowledge of renewable energy
- Complete monitoring systems
- Constant project supervision.

5.3 Economic Factors

Any financial partner of the project has a fiscal responsibility, subject to a failure factor. Governments may support and promote renewable energy systems, however, communities do not usually assume ownership of donated systems, so the financial responsibility for the systems fails. Replacing micro-grid components represents a high cost that, in a financially unhealthy community, could lead to failure. The list below illustrates the primary factors that have to be integrated as economic factors to deploy micro-grids.

- Financial support by the government
- The question of who takes the financial responsibility has to be addressed at the beginning of the Micro-grid project
- Entire financial framework
- Plan revenue generation

- Consider the high cost of component replacements.

5.4 *Environmental Factors*

The environmental aspect is a vital part of a sustainability ecosystem: A comprehensive analysis of the location's energy resources is fundamental when planning a micro-grid; Environmental impact assessment for evaluating the implications about the environment for the proposed energy source; Renewable energy mistakenly taken to be impact-free environmental technologies; and, characteristics such as life cycle, correct disposal, and so on, should be considered. The following list includes the main environmental factors that have to be addressed.

- Comprehensive energy resources assessment
- Planned environmental assessment
- Environmental Awareness.

5.4.1 Policy Factors

Policies that work with social, technical, and economic factors are integrated into this section. Some examples of existing policies are feed-in tariffs (FiTs), feed-in premiums (FiPs), net metering/net billing, tax credits/incentives, etc. Governments are the dominant player in the promotion and application of micro-grids; therefore, their political will, stability, and certainty is an essential factor. Ineffective regulatory frameworks for the renewable energy market are a significant obstacle to the growth of micro-grids. Thus, a list of policy factors that have to be considered when a micro-grid is installed is presented below.

- Effective Policy Initiatives
- Political will for widespread application
- Effective frameworks that encourage the private Sector
- Accurate communication channels with society.

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