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Article title:

A View of Microgrids

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Abstract

Large-scale integration of Distributed Energy Resources (DER) in Low Voltage (LV) distribution grids will have a serious impact on power system operation. The development of the microgrid concept is presented as a solution to overcome some of the negative impacts of massive microgeneration deployment and pave the way for an active network management approach within the smart grid paradigm. The microgrid concept is able to address the integration of geographically dispersed energy resources, thus avoiding significant technical problems that may affect the security of operation.

Within the microgrid concept, advanced control and management functionalities will be available to support the distribution system operator in managing the distribution grid. This will enable the development of new ancillary services that can be provided by these active cells.

Furthermore, several technical requirements are needed for ensuring safe microgrid operation in both interconnected and islanded mode, including the development of specific control strategies namely for the power electronic interfaces of the microgenerators.

Finally, a deployment map must be outlined in order to illustrate the expected evolution of the microgrid concept according to the smart grid vision.

A progressive integration of DER to LV systems will have a significant impact on planning and operation of the electrical power system. This will require a major change in the operational paradigm, evolving from an outdated passive perspective towards a future grid active management approach.

In order to enable a massive deployment of DER, especially Distributed Generation (DG) based on Renewable Energy Sources (RES), it is necessary to develop advanced monitoring and novel control functionalities that will enable the mitigation of the technical impacts resulting from large-scale integration of these units, while simultaneously trying to exploit the benefits brought forward by their presence in LV distribution systems.

In this context, the microgrid concept appears as an intelligent solution to enable large-scale integration of DER in LV networks without compromising the robustness of operation of the overall power system. The microgrid behaves like an active cell that can be regarded as a single controlled entity from the perspective of the upstream Medium Voltage (MV) system that provides flexibility to the operation of the whole electrical distribution system.

The full deployment of the microgrid concept requires the development of a dedicated smart metering infrastructure that will provide the means for communication between all the players involved (microgeneration units, consumers and system operators) in order to fulfil the smart grid vision.

In addition, the microgrid will be able to operate in normal mode, *i.e.* interconnected to the upstream Medium Voltage (MV) network or in emergency conditions, isolated from the main mode power system (electrical island). The islanded mode is particularly important since it brings additional benefits regarding security of operation given the vulnerability of the power system to external attacks, resulting either from man-made threats (such as terrorist actions) or from natural disasters (the occurrence of hurricanes, storms, *etc.*).

DISTRIBUTED ENERGY RESOURCES

The traditional organization of electrical power systems dated from the 1950s followed a hierarchical structure with three different levels: generation, transmission and distribution. The generation level was characterized by large generators that relied mostly on three types of technologies: hydro units, thermal units based on fossil-fuels (burning fuels such as coal, oil or natural gas) and nuclear units. These central generators would feed electrical power through generator transformers to a High Voltage (HV) transmission system. The transmission system, which could cover large distances at HV levels, was then used to transport the electrical power to be delivered to the final customers through distribution transformers [1], [2] as shown in Figure 1.

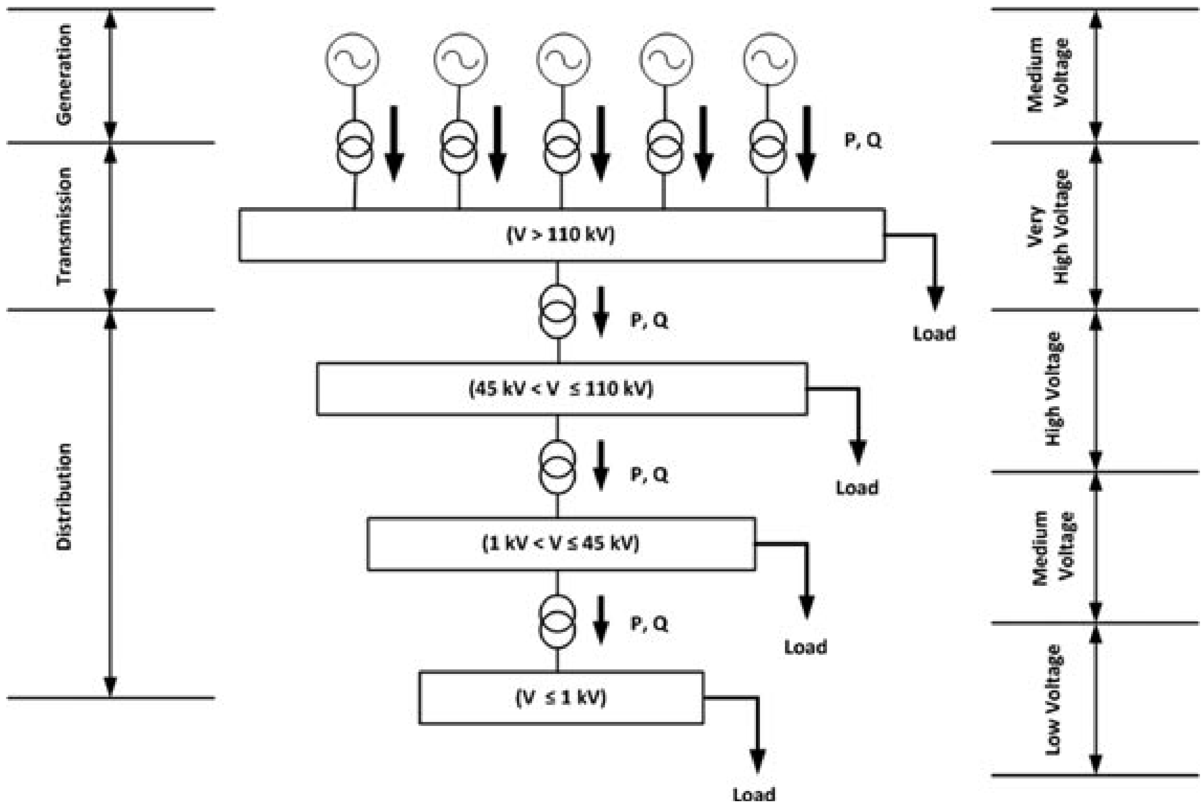

Figure 1 – Organization of Conventional Electric Power Systems

As a result, the conventional power system was characterized by unidirectional flows of energy from the generation to the distribution levels using an interconnected transmission network, resulting in rather straightforward planning and operation approaches. Furthermore, traditional utilities usually operated in well-defined geographical territories within local market monopolies under the strict supervision of regulatory bodies. These utilities owned the generation, transmission, and distribution facilities within their assigned service territories and financed the construction of the required facilities subject to the approval by the relevant regulatory bodies [2].

In recent times, and particularly in the turning to the 21st Century, a growing interest in the development of DG has occurred, as opposed to the traditional central generation. However, this does not mean that DG is a purely new concept. In fact, in the early days of electricity generation, electricity was only supplied to customers that were located in close proximity to the power units [3]. Moreover, in order to keep the balance between generation and consumption, local storage (typically in the form of batteries) was used in addition to small-scale generation.

The advent of DG faces considerable challenges and requires significant changes in the way the electrical power system is regarded at many levels, from planning to operation of the electrical power system, since the networks are changing from mere passive networks to fully active networks. The new organization of the electrical power system is shown in Figure 2.

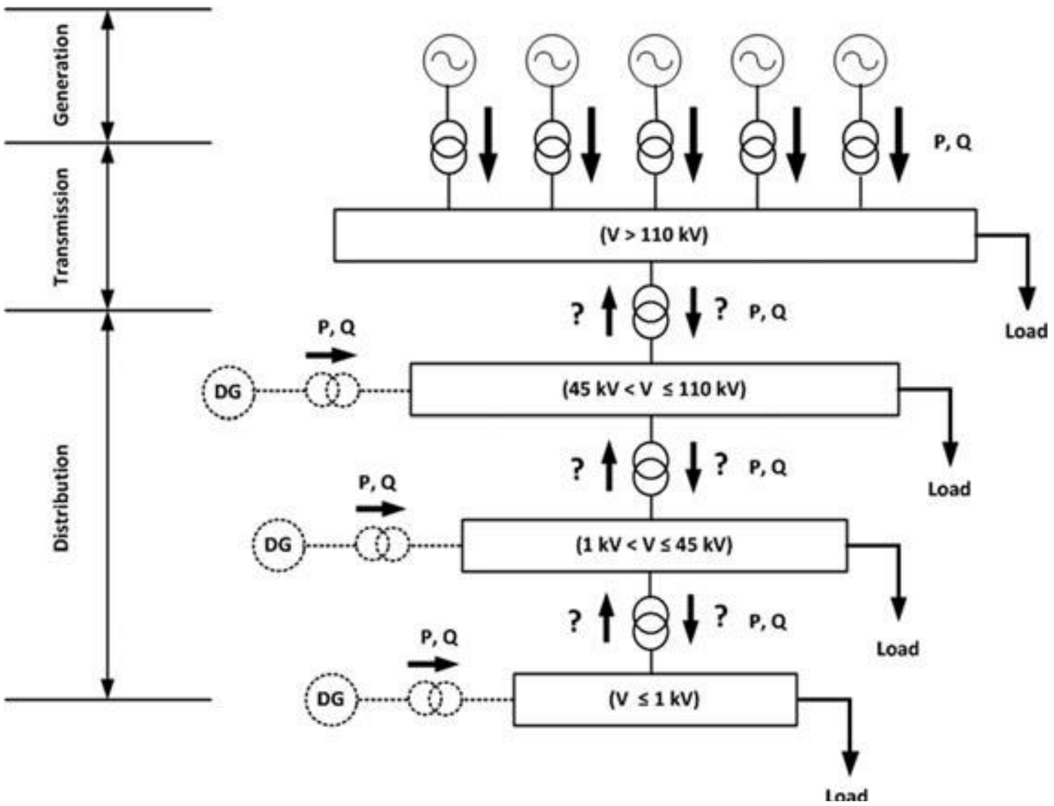

Figure 2 – Integration of Distributed Generation in Electrical Power Systems

Nowadays, DG is considered within the wider context of DER, which will play a key role in future power systems. According to Lopes *et al.* [4], DER include not only DG but also distributed energy storage devices as well as responsive loads while other authors do not include storage within the DER concept [5], [6]. Throughout this paper, the term DER will follow the definition proposed by Lopes *et al.* [4].

In addition, important resources can also be found in the demand side. It is considered that these resources include load management systems that are able to shift electricity use from peak periods to off-peak periods and ensure energy efficiency options (*e.g.* reduce peak electricity demand, increase building efficiency or reduce overall electricity demand). Consequently, DER are not only based on local generation on the customer's side of the meter but also on means to reduce peak or average customer demand, which will largely influence the electricity supply from the distribution.

ACTIVE DISTRIBUTION NETWORKS

Active distribution network management is considered as a key factor to achieve cost-effective solutions following DG integration in distribution grids at both the planning and operation stages of the distribution system. In fact, this is a huge step beyond the current "fit-and-forget" approach. However, with the advent of DG and improved control solutions by means of Information and Communication Technologies (ICT), this approach needs to be revised as it can severely limit the amount of allowable DG integration.

In a future scenario, controllable DG and demand side management are expected to also share the responsibility of delivering system support services, a role that was previously reserved to central generation. In this case, DG will be able to displace effectively not only energy supplied by central generation but also its controllability, thus reducing the required central generation capacity and transmission infrastructures. In order to achieve this, the **operating practice of distribution networks needs to change from passive to active**, which will require a shift from traditional central control philosophy to a new distributed control paradigm. This scenario will require significant ICT capabilities, as well as new decision support tools to use all the information available from DG and demand side. Of course, this will bring additional complexity to system operation but, with correct development, this new paradigm may facilitate more reliable, cost-effective system that are able to achieve maximum utilization of all resources available.

Active management of distribution networks will enable the Distribution System Operator (DSO) to maximize the use of existing circuits by taking full advantage of generator dispatch, control of transformer taps, voltage regulators, reactive power management and system reconfiguration in an integrated, coordinated way. This active approach to system operation can reduce the negative impact of DG on the network, thus minimizing requirements for reinforcements [7].

The Need for Distributed Resources Management and Control

As already mentioned, DG connection to the distribution system has been managed on the basis of a "fit-and-forget" philosophy, in which DG is regarded as a mere passive element of the system. Although this philosophy works for relatively moderate penetration of this type of sources, when considering high penetration levels there is a considerable impact on the distribution system. The main technical impacts resulting from large-scale DG integration are mostly related to the voltage rise effect, power quality issues, branch overload problems, protection issues and stability issues [4].

In this context, it is necessary to know the possible solutions to cope with the problems resulting from large-scale DG connection to the MV level or to the LV level (microgeneration). Considering relatively low levels of DG and microgeneration integration, present distribution networks are able to accommodate this generating capacity without major operational issues occurring. However, when the main aim is to maximize the penetration levels of these sources (in order to cope with the European Union's Climate and Energy Policy [8]), the impacts on the distribution system are no longer negligible. Therefore, in order to face the challenges posed by a massive deployment of DG and microgeneration, while simultaneously obtaining the potential benefits of these units, it is imperative to develop coordinated and efficient control strategies for the operation and management of these resources. These solutions should rely on advanced control and management algorithms that may be integrated as software modules to be installed in distribution network control centres. In fact, regarding coordinated control, an analogy can be drawn between data and energy storage for the transfer of concepts of system integration from computer to power engineering. In particular, the method of "cache control" presented by Strunz and Louie in [9] addresses coordination between storage systems to support effective system integration.

Furthermore, the connection of small DG sources directly to the LV level of distribution networks – microgeneration – is also expected to grow rapidly in a near future, thus creating autonomous active cells called microgrids. A microgrid can be defined as an LV feeder with several microsources (such as microturbines, micro wind generators, solar panels, *etc.*) together with storage devices and controllable loads connected on that same feeder and managed by a hierarchical control system [10]. These LV microgrids may be operated either in interconnected or islanded mode, under emergency conditions [11].

The Microgrid as a Flexible Cell in Active Distribution Networks

Different DG technologies such as microturbines, photovoltaic (PV) panels or fuel cells may have rated powers ranging from a few kW up to a hundred kW and can be directly connected to the LV networks. This type of DG, integrated directly next to the customer side at the LV level, is usually called microgeneration and the corresponding generating units are called microgenerators or microsources. In this context, microgeneration units, located at user sites, emerge as a promising opportunity to meet growing customer needs for electric power, with an emphasis on reliability and power quality. Furthermore, considering increased levels of microgeneration integration, the distribution network (particularly at the LV level) can no longer be considered as a passive element. On the contrary, microgeneration can have a significant impact on the LV network and the focus has been on assessing how much DG can be **tolerated** before its collective electrical impact begins to originate problems in the distribution system in terms of stability or voltage, for instance.

Therefore, an adequate control and management architecture is required in order to facilitate the integration of microgeneration and active load management schemes. Besides, the control and management of such a system should answer for all the benefits that may be achieved at all voltage levels of the distribution network. This means that different hierarchical control strategies need to be adopted at different network levels [12]. One promising way to fully accomplish the emerging potential of microgeneration is to assume a systemic approach – the microgrid concept.

Microgrid Concept

The microgrid concept may be implemented in a variety of scales, considering a part of an LV grid, an LV feeder or even a facility, such as a house. A general classification of possible microgrid architectures and their characteristics based on type of application, ownership structure and type of loads served is presented in Table 1.

Table 1 – Possible Microgrid Architectures and their Characteristics ([13] and personal research)

	Utility Microgrids		**Industrial/Commercial Microgrids**		**Remote Microgrids**
	Urban Networks	**Rural Feeders**	**Multi-Facility**	**Single Facility**	
Application	Downtown areas	Planned islanding	Industrial parks, university campus and shopping centres	Commercial buildings and residential buildings	Remote communities and geographical islands
Technologies	PV, wind, microturbine, and CHP	Hydro, PV and wind	Microturbine, PV, CHP and fuel cell	Microturbine, PV, CHP and fuel cell	Hydro, PV and wind
Main Drivers	Outage management and RES integration		Power quality enhancement, reliability and energy efficiency		Electrification of remote areas and reduction in fuel consumption
Benefits	GHG reduction, supply mix, congestion management, upgrade deferral and ancillary services		Premium power quality, service differentiation (reliability levels), CHP integration and demand response management		Supply availability, RES integration, GHG reduction and demand response management
Operating Modes	Interconnected and islanded mode		Interconnected and islanded mode		Islanded mode
Unplanned Transition	Faults (on upstream or adjacent feeders)		Main grid failure and power quality issues		–
Pre-planned Transition	Maintenance actions		Maintenance actions and energy price (peak time)		–

Two of the main microgrid concepts, described in detail in the following lines, are the Consortium for Electric Reliability Technology Solutions (CERTS) microgrid approach [14] from the US and the European approach from the EU project "MICROGRIDS – Large Scale Integration of Microgeneration to Low Voltage Grids" [15].

The microgrid concept was originally developed within the CERTS [16]. The CERTS microgrid concept assumes an aggregation of loads and microsources operating as a single system providing both power and heat [16], [17]. According to this concept, the majority of the microsources must be power electric based to provide the required flexibility to ensure operation as a single aggregated system. It is this flexibility of control that allows the microgrid to present itself to the bulk power system as a single controlled unit that meets local needs for reliability and security. This approach does not accommodate the traditional operating principle that DG must be shut down automatically if problems arise in the grid. In fact, the CERTS microgrid is designed to seamlessly separate or island from the grid and later reconnect to the grid once these problems are resolved.

The European microgrid concept was developed within the framework of the European project MICROGRIDS. According to Lopes *et al.* [11], a microgrid can be defined as an LV distribution system to which small modular systems are to be connected. In this sense, a microgrid corresponds to an association of electrical loads and small generation systems through an LV distribution network. This means that loads and sources are physically close so that a microgrid can correspond, for instance, to the network of a small urban area, to an industry or to a large shopping centre. Apart from an LV distribution network, microgeneration devices and controllable electrical loads, a microgrid may also include storage equipment, network control and management systems and heat recovery systems (Combined Heat and Power applications – CHP).

It is also assumed that the microgrid can be operated in two main situations:

- **Normal interconnected mode** – The microgrid will be electrically connected to the main MV network either being supplied by this network totally or partially or injecting power into the main MV grid.
- **Emergency mode** – In case there is a failure in the main MV network, the microgrid must have the ability to operate in an isolated mode, *i.e.* to operate in an autonomous way similar to the power systems of geographic islands.

In short, a microgrid can be defined as a new type of power system comprising LV grids with small modular generation sources, controllable loads and storage systems, which can be connected to the main power system or be operated autonomously.

Depending on the primary energy source used, on the microgenerator dimension and on the type of power interface, these microsources can be considered as non-controllable, partially controllable and controllable. To the utility, the microgrid can be seen as a controlled cell of the power system. To the customer, it can be designed to meet his special needs and provide additional benefits such as improved power quality and reliability, increased efficiency (through CHP applications) and local voltage support.

Regarding storage systems, several different technologies may be employed depending on the type of application required. For short term storage, flywheels and ultra-capacitors are able to ensure a fast response to events such as sudden load or renewable generation variations, which will improve safety of operation and power quality. For medium and long term storage solutions, other technologies such as electrochemical batteries may also be used to allow managing power balance and ensure load supply for larger time periods.

The microgrid concept is usually associated to AC systems; however, DC microgrids are also an interesting possibility since the connection of DER to the networks is generally done through power electronic interfaces that can be enhanced to perform other functions apart from power injection/absorption [18]. Furthermore, several problems related to AC microgrid systems have pushed forward the development of DC solutions for microgrids. These problems are mainly related to the lack of quality of supply, the losses produced along the line due to the pollution caused by harmonics, unbalanced and reactive powers and line overloads due to that pollution[18]. Several papers can be found in the scientific literature addressing the topic of DC microgrids[19], [20], [21].

Microgrid Architecture

The architecture of the microgrid concept is presented in Figure 3.

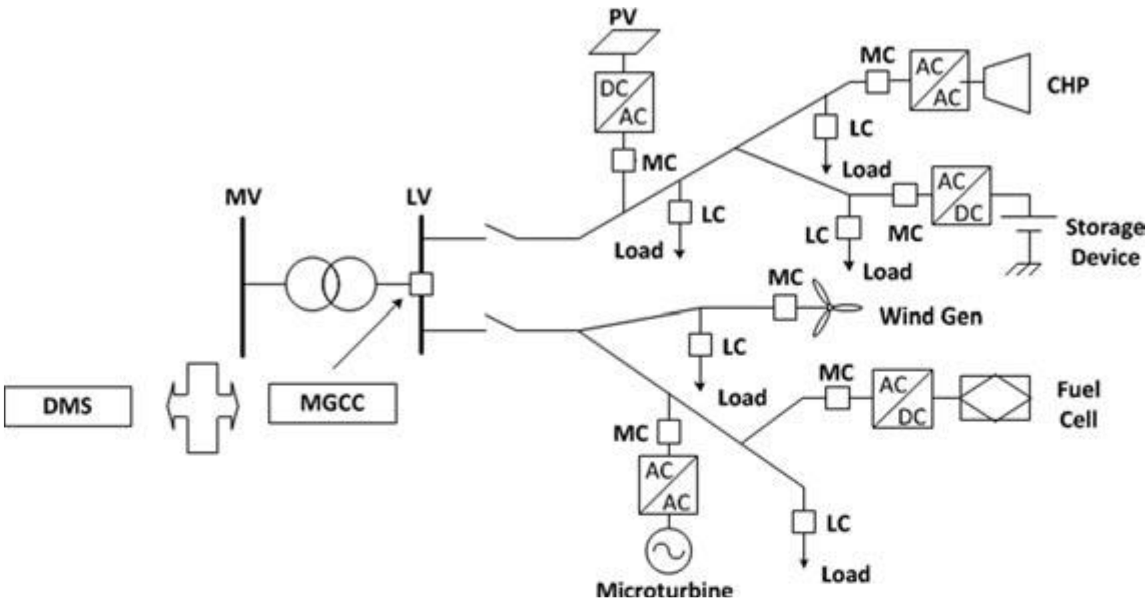

Figure 3 – Microgrid Architecture (adapted from [11])

The microgrid is supposed to be controlled and managed by an entity installed on the LV side of the MV/LV substation – the MicroGrid Central Controller (MGCC). The MGCC has a number of crucial functions and can be seen as the interface between the microgrid and the main distribution network. At a second hierarchical level, each microgeneration and storage device is locally controlled by a Microsource Controller (MC) and each electrical load is locally controlled by a Load Controller (LC). In order to be able to ensure proper operation of the whole system, communication between two sets of devices is required:

- The LC and MC, as interfaces to control loads (through the application of an interruptibility concept) and as microgeneration active and reactive power production levels, respectively;
- The MGCC, as central controller that aims at promoting adequate technical and management policies and providing set-points to both LC and MC.

Simultaneously, it is expected that the MGCC will be able to establish some type of communication with the Distribution Management Systems (DMS), located upstream in the distribution network, thus contributing to an improvement in the management and operation of the MV distribution system.

Regarding the MGCC, its main functions are:

- During normal interconnected mode – The MGCC collects data from microsources and loads in order to automatically perform a number of operations such as forecasting studies, economic scheduling of microgeneration, security assessment evaluations, Demand Side Management (DSM) functions and interface with the DMS.
- In emergency mode – A change in the output power control of the microgenerators is required since they change from a dispatched power mode to a frequency control mode in the isolated grid. In such an event, the MGCC reacts as a secondary control loop. It is also important for the MGCC to have accurate knowledge of the type of loads in the grid (to eventually adopt interruption strategies) and to use support from storage devices. As a whole, the MGCC can also be responsible for local black start strategies[22]. The black start function ensures an important advantage of microgrids in terms of improving reliability and continuity of service, by reducing interruption times.

The MC and LC are local controllers aiming at contributing to the economic scheduling activities, to local control of storage devices, to load tracking activities and to manage loads with interruption or peak shaving capabilities. At an advanced stage, the microgeneration and loads will be fully integrated in electricity markets and local controllers will be in charge of preparing selling and buying offers to communicate to the MGCC.

As previously stated, this control architecture must rely on a communication system the main function of which is to allow the MGCC to be able to coordinate all microsources and controllable loads, through their corresponding local controllers. In normal interconnected operation, fast communications are not required. Therefore, a communication solution based on Power Line Communication (PLC) may be adequate, especially given the small geographic-span of a microgrid.

An alternative to the hierarchical control architecture proposed is the use of Multi-Agent Systems (MAS). In fact, MAS have been used for some time now in order to facilitate the control of individual microgrids [23], [24], [25], [26].

According to Dimeas *et al.* [23], the use of MAS technology can solve a number of specific operational problems, such as:

- Centralized control is more complex, since small DG units have different owners, and therefore several decisions should be taken locally;
- There is a lack of dedicated communication facilities;
- Given that microgrids are expected to operate in a liberalized market, controller decisions for each device concerning the market should have a certain degree of "intelligence".

In [24], the same authors propose some changes to their original framework. Here, the MAS approach was developed as a tool not only to provide intelligence for the needs of complex tasks, but also to facilitate the design of the algorithm. In this work, microgrid operation and namely its participation in the energy market is addressed. The main idea of the algorithm presented is that every device should be able to decide what is best for itself as an individual. Of course, MAS does not aim exclusively at market participation and may also be used for other functionalities. Therefore, the proposed MAS architecture is considered as a first step towards a more comprehensive control mechanism.

Test Systems and Real Experimental Microgrids

Most of the concepts presented have been tested in simulation environments, using microgrid test systems. Several of these typical microgrids with different configurations and parameters may be found in the available scientific literature[27], [28], [29]. The microgrid test system developed in the MICROGRIDS EU project is shown in Figure 4. This test network comprises several different microgeneration technologies, as well as a central storage device based on a flywheel system.

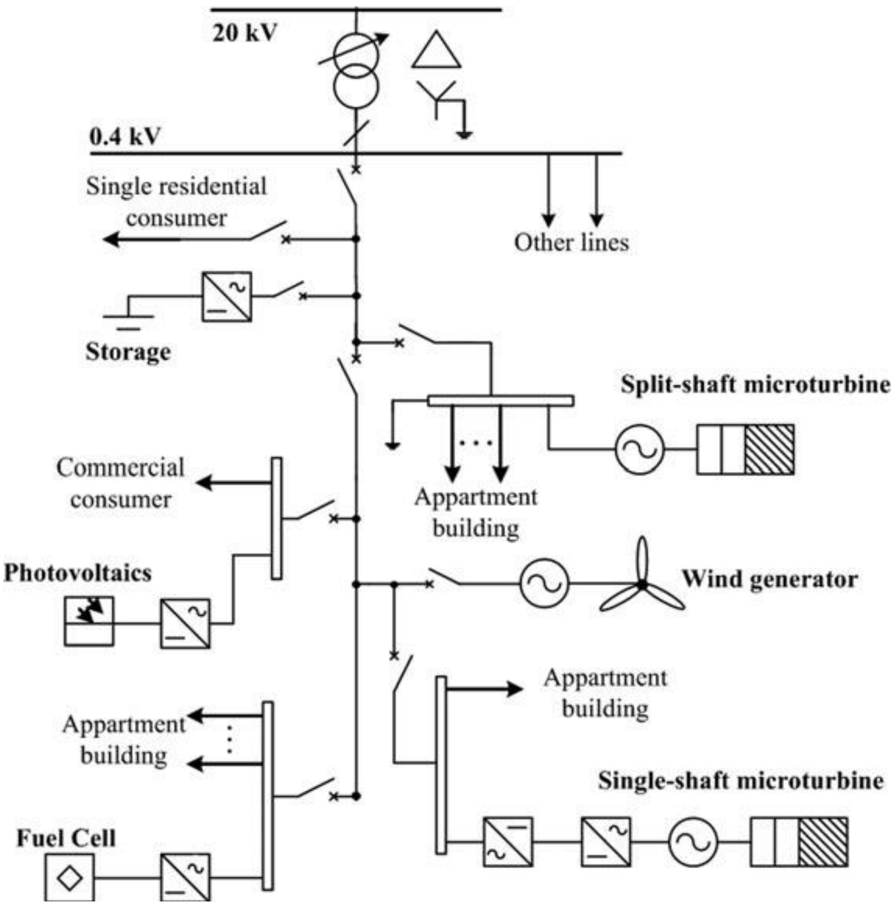

Figure 4 – LV Microgrid Test Network (adapted from [30])

Furthermore, some concepts were also implemented on a small laboratory microgrid and on real networks, following the work developed within several research projects in Europe, America and Asia.

For instance, in Europe, MAS techniques were applied to a small isolated power system in the Greek island of Kythnos where loads and DG units are controlled by intelligent agents that cooperate in order to solve a certain problem [31]. Also, a MAS platform was implemented in the "Am Steinweg" microgrid in Germany. A centralized control approach is used in the “Bronsbergen” microgrid in the Netherlands where several PV panels are connected in a residential area with the possibility of isolation and reconnection to the main power grid [32].

Several other cases are present in the US, such as the CERTS microgrids test bed and the “Boston Bar” microgrid as well as in Japan with the Hachinohe project and the Kyoto Eco Energy project [32], [33].

More information on these real world experimental microgrids can be found in [31], [32], [33].

MICROGRIDS: CONFRONTING ADVANTAGES AND DISADVANTAGES

The massive deployment of the microgrid concept and active distribution networks will have a significant impact on power systems and is expected to bring various technical, economic and environmental advantages but also challenges and several management and operational issues. Some of these issues are discussed in the following sections.

Technical, Economic and Environmental Benefits

The development of the microgrid concept is very promising for the electric power industry as a number of advantages can be foreseen at several levels [11], [34]:

- Operation / investment issues – Reduction of both physical and electrical distance between generating units and loads may contribute to:
    - Improvements of reactive support of the whole system, thus enhancing the voltage profile [35].
    - Reduction of transmission and distribution feeder overload.
    - Reduction of transmission and distribution losses [36].
    - Reduction/postponement of investments in the expansion of transmission and large-scale generation systems.
- Power quality issues – Improvement in power quality and reliability in particular is achieved due to:
    - Better match of supply and demand, especially when involving micro CHP units.
    - Reduction of the impact of large-scale transmission and generation outages.
    - Minimization of downtimes if microsources are allowed to operate autonomously making use of the control capabilities of the microgrid that involve the management of microsources, loads and storage [37].
    - Improvement of voltage profiles, in case of under and over voltages, if microsources are allowed to regulate voltage at their connection point through their power electronic interfaces either locally or using a hierarchical control approach [35].
- Market issues – The following advantages can be attained:
    - Possible development of market driven operation procedures of microgrids will lead to a significant reduction of market power exercised by established generation companies since the microgrid acts as an aggregator for individual loads and microgeneration units, enabling them to participate in electricity markets.
    - Microgrids may be used to provide ancillary services [38], namely regarding load-frequency control and local voltage support.

  - Widespread application of modular microsources may contribute to a reduction in energy price in the power market with appropriate economic balance between network investment and DG utilisation.
- Environmental issues – The environmental impact of microsources is expected to be smaller than large conventional thermal power stations. Also, the main benefits of the microgrid in this topic are:
  - Physical proximity between consumers and microsources may help increase consumer awareness towards a more rational use of energy.
  - Reduction of GHG emissions that may mitigate the alleged effects of climate change due to the creation of technical conditions to increase the connection of RES at the LV level.

Challenges and Drawbacks

Conversely, several challenges and potential drawbacks face the development of microgrids as follows [11], [34]:

- Technical issues – These technical barriers are mostly related to the relative lack of experience and technical knowledge to operate and control a significant number of microsources, which requires extensive real-time and off line research on issues such as management, protection and control of microgrids. Also, specific telecommunication infrastructures and communication protocols need to be developed to help managing, operating and controlling the microgrids. However, some of these technical difficulties are in the way of being overcome as more research and demonstration projects are being set up across Europe, the US and Asia [31].
- Cost issues – The high installation cost for microgrids is a big disadvantage that may be reduced if some form of subsidies from government bodies is obtained as a way to encourage investment, at least for a transitory period, given the current official environmental and carbon capture goals.
- Standardization issues – Since this is a comparatively recent area, standards are not yet available for addressing power quality, operation and protection issues, for instance. This constitutes a serious obstacle to the massive deployment of microgrid technologies.
- Administrative / legal issues – In some countries, there is a lack of legislation and regulations for the operation of microsources. However, in Portugal for instance there is already specific legislation addressing the connection of microgeneration to the grid that establishes the tariffs to be paid to microgeneration, adopting an avoided cost strategy leading to subsidised tariffs [39].

Implementation and Deployment Costs

The successful development of the microgrid concept depends very much on the regulatory structure defined, which should create an adequate general framework for microgeneration and microgrids [40], [41].

Addressing economic regulation, it must be kept in mind that microgeneration and the microgrid concept are in an unfavourable position to compete with some already established technologies, which benefited from mass production and learning effects for some time now [42]. In this situation, incentive schemes are used to foster the development of these technologies in order to facilitate competition between established technologies and microgeneration technologies. The most common incentive mechanisms used in Europe are feed-in tariffs and quota systems [43].

The identification of costs and benefits resulting from the deployment of the microgrid concept is the first step of the process of establishing an incentive mechanism and corresponding financing source [42]. A relatively large number of costs and benefits that DG and microgeneration induce have been identified in the scientific literature [11], [42], [44], [45]. The subsequent step is the definition of the principles to quantify and share those costs and benefits. These issues are addressed in the following section.

Cost and Benefit Sharing

Following the expected increase in microgeneration connection to LV distribution grids, it is necessary to quantify the main costs and benefits resulting from the deployment of these units and the development of the microgrid concept. In order to quantify these costs and benefits, a division must be made between microgrid players (microgenerator and consumers) and microgrid business participants (DSO, suppliers…) as proposed in [42].

According to [42], the main benefits identified related to microgeneration integration in distribution grids are the electricity value (related to the value of the generated electricity), avoided losses (resulting from network power flow reductions), avoided emissions (resulting from displaced electricity generation and avoided losses), networks investment deferral (related to the expenditures to acquire and install new assets or upgrade existing ones) and generation adequacy (related to the need for ensuring adequate generating capacity[46]). Moreover, the benefits envisioned for the microgrid concept are: increased reliability for microgrid participants (resulting from the possibility of islanded operation), general reliability improvements (possibility of supporting network reconfiguration) and network investment deferral and generation adequacy.

Concerning the costs identified for microgeneration and microgrids, they should include microgrid development costs and DSO costs. The first ones result from the investment in controllers, protection systems, storage devices and from operation and maintenance expenditures. The second group of costs is related to some additional capital and operation costs to the DSO from the connection of microgeneration to the distribution grids such as potential investments to overcome technical problems such as inadmissible voltage profiles or line overloading [42].

As it happens with DG, the costs and benefits resulting from microgeneration and microgrid deployment tend to be asymmetrically captured by different entities (consumers, microsources and microgrid owners, system operators…) which results in additional difficulties to their development. Therefore, the identified costs and benefits should be shared among all involved agents when establishing microgrids so as to ensure benefits to each one of them. Therefore, the funding scheme for the incentives tends to be a combination of financial contributions from different entities. The individual contribution of each entity should be based on the share of total costs and benefits resulting from microgrid deployment [42].

TECHNICAL REQUIREMENTS FOR MICROGRID OPERATION

Given the characteristics of microgeneration technologies, it will not be common to find fully controllable synchronous generators within a microgrid, which are units normally responsible for voltage and frequency control in conventional power systems. Indeed, most technologies are not suitable for direct connection to the electrical network due to the characteristics of the energy produced, as happens with PV panels or microturbines which produce DC power or high frequency AC power, respectively. Therefore, power electronic interfaces (either DC/AC or AC/DC/AC converters) are required.

This emphasizes the importance of inverter control in microgrid operation, especially in emergency conditions [47]. As proposed in [48] and [49] a control scheme based on droop control for inverters can be used to enable islanded operation. In the case of an islanding of the microgrid system, and if no synchronous generators can be found in the microgrid, it is necessary to exploit inverter control capabilities. Such an approach will enable not only islanded operation of the microgrid system but also the participation in black start strategies.

Furthermore, one of the most interesting prospects for microgrids is the possibility of participating in ancillary services provision such as voltage control and supply of reserves. These operational issues will be discussed in the following sections.

Ancillary Services Provision

In [50], the authors state that one of the most exciting prospects of the distribution system of the future will be its ability to provide ancillary services. If one wants to be exhaustive in listing the possible ancillary services that microgrids can offer, the possibility of islanded operation and black start services should be included, although they should be classified as a special type of ancillary service.

In a near future, these ancillary services will be supplied in response to market signals and may be contracted over the Internet. It is considered that both loads and DG will be able to supply these services since supplying the services locally is usually more efficient than supplying them from distant generating units. In addition to an intelligent distribution system, an automated market system will also be necessary to make this happen. The possible development of market-driven operation may lead to the reduction of market power of already established generation companies and to the possible contribution of the microgrid to the provision of some ancillary services. The main benefits that the microgrid could offer to the distribution system are congestion relief, postponement of new generation, response to load changes and local voltage support [16].

In fact, many publications can be found that address the opportunity for microgrids in providing ancillary services [11], [13], [16], [34], [45], [51].

Therefore, microgrids might participate in open market as both suppliers and customers of electricity services, leading to overall improvement in resource utilisation. This would bring significant benefits to the main power utility, whereby the central generators would be able to generate electricity freely without having to provide the ancillary services [34]. Some ancillary services that may be provided by microgrids include [22], [34], [45], [30]:

- Reactive power and voltage control;
- Frequency response and supply of reserves;
- Regulation and load following;
- Black start.

Still, there is no generalized consensus over the services that may be provided by a microgrid. Firstly because the microgrid cannot be regarded only as a controlled load, able to control its power demand and power factor, but rather as an entity that is able to sell power to the main grid and provide several valuable ancillary services to the utility, with appropriate payment. This possibility is especially interesting under stressed operation.

For example, the possibility of controlling the load leads to excellent control of the customer voltage profile [34]. Thus, the deployment of capacitors for reactive power control at the customer end may be avoided if power is supplied through the microgrid. Most ancillary services deal with real-time energy balance between microsources and loads, whereas black start is especially meant for the microgrid itself for sustaining its major loads without any exchange of power with main utility grid. In this case, a major challenge in providing these services is the communication system and its reliability and speed.

Islanded Operation

As previously seen, it is possible to utilize a frequency droop control, which allows DG units to communicate without an explicit communication system. When a VSI is interconnected with a stiff AC system, characterized by an angular frequency ω_{grid} (and terminal voltage V_{grid}), the frequency (and voltage) reference is externally imposed [48]. In this case, the desired output power P_1 (and Q_1) can be obtained in the VSI output by adjusting the idle values of the angular frequency ω_{01} (and voltage V_{01}), as shown in Figure 5 (and similarly for a voltage / versus reactive power droop).

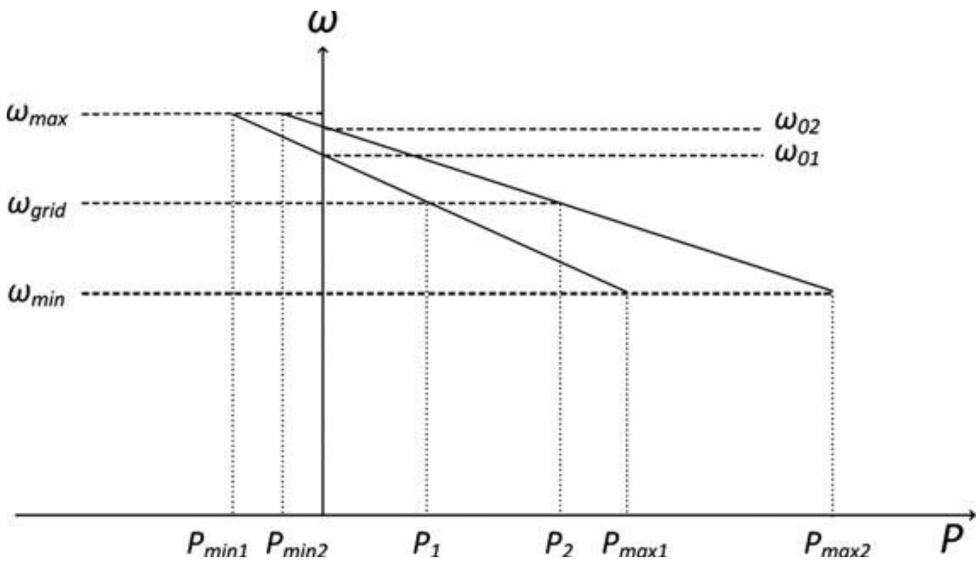

Figure 5 – Frequency versus Active Power Droop

In the case of islanded operation where no synchronous generator is directly connected to the grid, depending on the DG operation mode, two control strategies can be implemented for operating the inverter [30], [52]:

- **PQ control** – The inverter is controlled to meet a desired active and reactive power set-point;
- **Vf control** – The inverter control scheme allows an independent regulation of terminal voltage and frequency; in order to achieve these control characteristics, active power/frequency and reactive power/voltage droops are used.

If a cluster of microsources is operated within a microgrid interconnected with the upstream grid, all the inverters can be operated in the PQ mode because the voltage and frequency references are defined by the main system. In this case, a sudden disconnection of the main power supply would lead to the loss of the microgrid, since there would be no possibility for load/generation balancing, and therefore for frequency and voltage control.

However, by using a Voltage Source Inverter (VSI), operated under the Vf control logic in order to provide a reference for voltage and frequency, it is thus possible to operate the microgrid in islanded mode and a smooth moving to islanded operation can be performed without changing the control mode of any inverter. This is possible since the VSI is able to operate in parallel with other voltage sources (for instance, the upstream MV network during normal operating conditions, or with other VSI during islanded operation) [30].

Black Start

Being an autonomous entity, the microgrid can also develop a local black start action under specific conditions. If a system disturbance causes a general blackout such that the microgrid is not able to isolate and continue operating in islanded mode and if the MV system is unable to restore operation in a predefined time, a first step in system recovery can be to perform a local black start using the microgrid.

In conventional systems, tasks related to power restoration are usually carried out manually by system operators, according to predefined guidelines. These tasks must be completed as fast as possible, in real-time basis and under extreme stressed conditions. In a microgrid, the whole restoration procedure is expected to be much simpler because of the small number of control variables (loads, switches and microsources). However, the characteristics of most microgenerators (such as primary energy source response time constants) and the control characteristics of power electronic interfaces require the identification of very specific restoration sequences [22].

In the case of faults in the main grid, the microgrid may be disconnected from the upstream MV network and will continue to operate with as many microsources as possible. The strategy to be followed will involve the MGCC and the local controllers (LC and MC), using predefined rules to be embedded in the MGCC software. Exploiting microgrid capabilities to provide fast service restoration functionalities at the LV level is an innovative aspect that will enable faster restoration times to final consumers, thus improving reliability and reduce customer interruption times.

During grid reconnection, the issue of out-of-phase reclosing needs to be carefully considered. The development of local controllers in close coordination with the MGCC functions needs to be evaluated from the dynamic operation point of view. The strategies to be followed in order to deal with this two types of problems (black start and grid re-connection) will be embedded in the microgrid local controllers as a set of rules activated by the environmental conditions (characterized by the electrical variables voltage and frequency) and following orders from the MGCC. The main steps to be considered include building the LV network, connecting MS, controlling voltage and frequency, connecting controllable loads and MG synchronization with the upstream MV network, when it is available [53].

MICROGRID DEPLOYMENT ROADMAP

As previously seen, the deployment of DG and microgeneration in particular is expected to undergo several stages with different time horizons.

Presently, the integration of microgeneration in LV grids is already taking place mainly through the connection of PV panels and micro wind generators to the grid typically in southern countries and CHP applications in the countries in the north of Europe. In general, the current level of integration of these sources in the grid is low, involving only the development of simple rules of thumb, with little technical requirements which will not allow the development of the microgrid concept as described previously. In this case, mainly protection requirements for disconnecting microsources in case of abnormal operating conditions are considered as these units are not expected to be controlled (directly or indirectly) by the DSO.

At a second stage, we may assume that microgeneration integration may increase, which will require some level of control leading to the microgrid concept. Some basic control functionalities may be included namely for the power electronic devices (inverters) connected to microgeneration units in the form of local control actions. These actions can be the inclusion of a droop function for active power / frequency control in islanded mode or similar function for preventing overvoltages in LV networks by reducing the output generation of microsources, mostly those based on RES.

In the long run, it is expected a considerable number of generating units be connected to the LV distribution system, which will then require an active approach to network management. In this case, advanced control functionalities must be employed in order to mitigate the adverse effects resulting from large-scale microgeneration integration. This will require the development of a dedicated control infrastructure, such as the hierarchical control scheme presented previously. Furthermore, the advent of Electric Vehicles (EV) to be connected to the distribution system will require an even more elaborated approach in order to deal with the integration of these devices and the impacts they have on the electrical power system [54]. EV batteries will be an additional resource and specially their charging can be conceived to be controlled within the microgrid concept [55]. These issues are addressed in the EU project "Mobile Energy Resources in Grids of Electricity (MERGE)" [56], [57].

However, the high investment required for setting up a control and management infrastructure should be carefully considered. One possible alternative is exploiting telemetering schemes in order to build a smart metering infrastructure that could sustain the development of the microgrid concept.

The Microgrid under the General Smart Grid Concept

Following the change of paradigm in electrical power systems, there has been a growing awareness, within the electricity supply industry, of the need to reinvent electricity networks. With the advent of new technologies for generation, networks, energy storage, load efficiency, control and communications, as well as with the arrival of liberalised markets and environmental challenges, it is necessary to have a shared and strategic vision for the electrical power system. This is seen as the way to ensure that the networks of the future can meet the future needs of customers and have a broader range of stakeholders.

The active networks of the future will efficiently link small and medium scale power sources with demand, thus enabling efficient decisions on how best to operate in real-time. The level of control required to achieve this aim is significantly higher than that found in the present transmission and distribution systems. Power flow assessment, voltage control and protection require cost-competitive technologies and new communication systems with more devices such as sensors and actuators than are presently used in distribution systems. In order to manage active networks, the vision of grid computing should be adopted, which assures universal access to resources. An intelligent grid infrastructure will provide more flexibility concerning demand and supply, providing at the same time new tools for optimal and cost-effective grid operation. Intelligent infrastructure will enable sharing of grid and ICT resources including ancillary services, balancing and microgrids behaving as a Virtual Power Plant (VPP) [58].

According to Pudjianto *et al.* [59], the microgrid and the VPP concepts can be regarded as vehicles to facilitate cost-efficient integration of DER into the existing power system. Through aggregation, DER access to energy markets is facilitated and DER-based system support and ancillary services can be provided [12].

Following these developments, the need arose for a coherent approach to the topic of smart grids and, in 2005, the SmartGrids European Technology Platform for Electricity Networks of the Future was established in order to meet the challenges seen by network owners, operators and particularly users across the European Union [60]. According to [61], a smart grid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to deliver efficiently sustainable, economic and secure electricity supplies. Smart grids deployment must include not only technology, market and commercial considerations, environmental impact, regulatory framework, standardization usage, ICT and migration strategy, but also societal requirements and governmental edicts.

In the future, the operation of power systems will be shared between central generation and DG. Control of DG could be aggregated to form microgrids or VPP in order to facilitate their integration both in the physical system and in the market. As seen above, a microgrid can be regarded, within the main grid, as a controlled entity operated as a single aggregated load or generator and, given attractive remuneration, as a source of power or of ancillary services supporting the main network.

Of course, there are still significant technical and commercial challenges that have to be addressed in order to achieve active distribution network operation and its coordinated control with the upstream conventional networks.

Smart Metering as an Enabling Technology

As previously stated, the deployment of smart metering can be seen as a means of pushing forward the development of microgrids and smart grid concepts by providing the infrastructure to support advanced control and management functionalities within the distribution system.

Several projects across Europe have dealt with the deployment of a smart metering infrastructure. In Portugal, the InovGrid project focused on the development of a fully active distribution network based on a smart metering infrastructure, following the need to introduce more intelligence to manage and control distribution networks with large-scale integration of microgeneration and responsive loads [62]. The city of Évora is the first Portuguese InovCity [63] and a full-scale deployment of the technologies for smart metering is expected for a near future.

This approach goes well beyond Automatic Meter Reading (AMR), which is a passive approach using single-flow data communication from the meters to operation centres. In fact, smart metering exploits Automated Meter Management (AMM) as an intelligent metering service using two-way data communication between customers, suppliers and DSO. This will turn the smart meter into a gateway for providing various services with many potential benefits for all agents involved [64].

The communication infrastructure can utilize different technical solutions that may coexist such as PLC, GPRS or WIFI solutions.

Advanced Architectures for Distribution Systems: Multi-Microgrids

The new operation paradigm in electrical power systems involves a growing penetration of microgeneration in LV networks based on the development and extension of the microgrid concept. Furthermore, MV distribution grids of the future will include a massive penetration of DG and microgrids (which can operate as active cells) that should be managed under a coordinated and hierarchical control approach. This new type of system is known as a multi-microgrid system.

The concept of multi-microgrids consists of a high-level structure, formed at the MV level, consisting of LV microgrids and DG units directly connected to the MV level on several adjacent feeders [65]. For the purpose of grid control and management, microgrids, DG units and MV loads under active DSM control can be considered as active cells in this new type of network. In this new scenario, the capability of some MV loads to be responsive to control requests under a load curtailment strategy may also be regarded as a way to get additional ancillary services.

Consequently, a large number of LV networks with microsources and loads, that are no longer passive elements, must operate in a coordinated way. This means that the system to be managed increases massively in complexity and dimension, thus requiring a new control and management architecture. This concept was developed within the framework of the EU project “Advanced Architectures and Control Concepts for MORE MICROGRIDS” [66].

Logically, this new scenario will involve the adaptation of existing DMS tools, as well as the development of new functionalities, that are able to deal with such demanding operating conditions. An effective management of this type of system requires the development of a hierarchical control architecture, where intermediary control will be exercised by a new controller – the Central Autonomous Management Controller (CAMC) – to be installed at the MV bus level of a HV/MV substation, under the responsibility of the DSO, which will be in charge of each multi-microgrid. In this way, the complexity of the system may be reduced by sharing tasks and responsibilities among several control entities. The CAMC will behave like a mini DMS that is able to tackle the scheduling problem of generating units (both DG and microsources) and other control devices installed in the system, under normal and emergency operating conditions. The architecture foreseen for this type of system is presented in Figure 6.

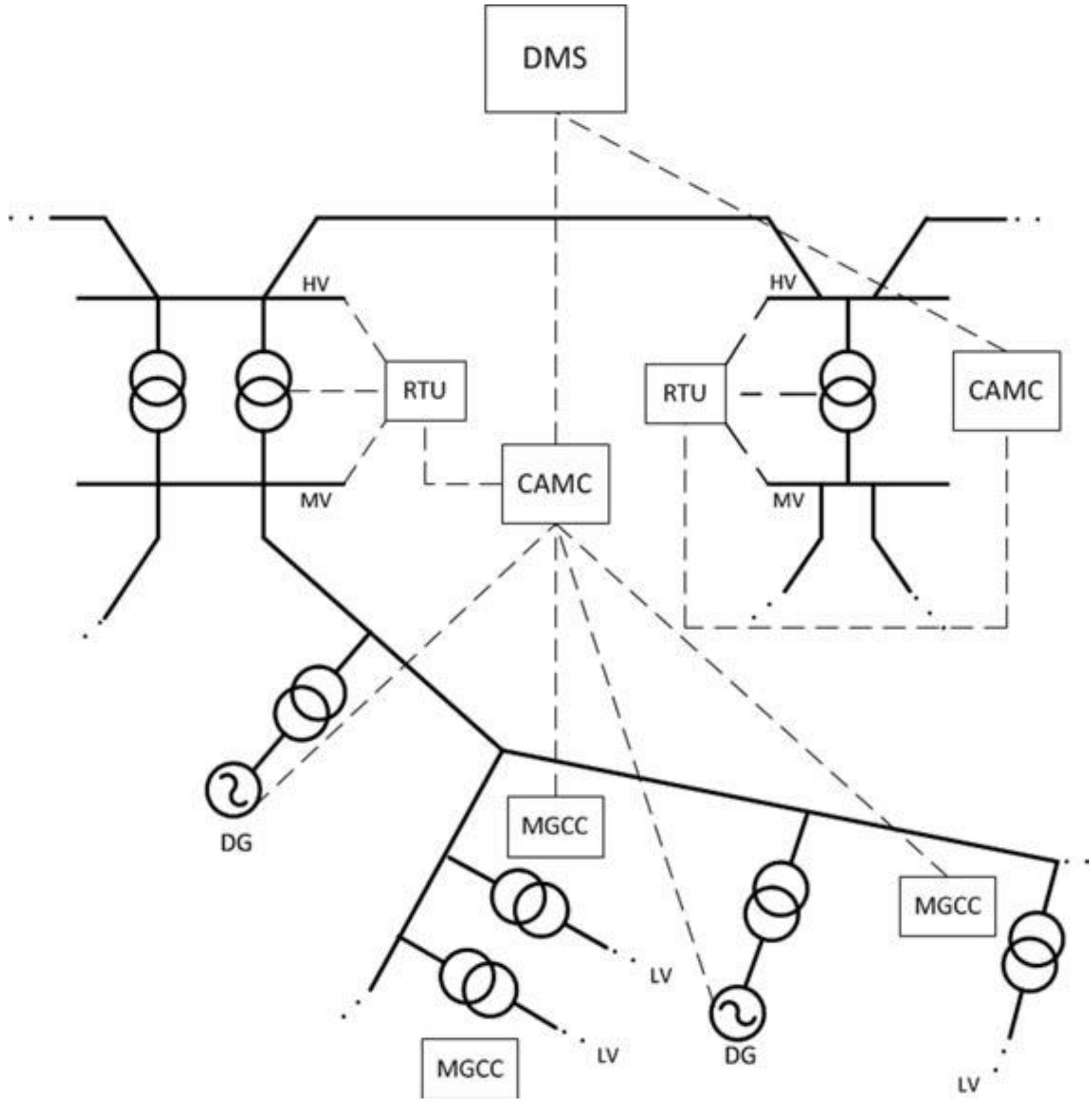

Figure 6 – Control and Management Architecture of a Multi-Microgrid System

Nowadays, the DMS is wholly responsible for the supervision, control and management of the whole distribution system. In the future, in addition to this central DMS, there may be two additional management levels:

- The HV/MV substation level, where a new management agent – the CAMC – will be installed as illustrated in Figure 6. The CAMC will accommodate a set of local functionalities that are normally assigned to the DMS (as well as other new functionalities) and will be responsible for interfacing the DMS with lower level controllers.
- The microgrid level, where the MGCC, to be housed in MV/LV substations, will be responsible for managing the microgrid, including the control of the microsources and responsive loads.

The main issue when dealing with control strategies for multi-microgrid systems is the use of individual controllers, which should have a certain degree of autonomy and be able to communicate with each other in order to implement certain control actions. A partially decentralized scheme is justified by the tremendous increase in both dimension and complexity of the system so that the management of a multi-microgrid system requires the use of a more flexible control and management architecture.

Consequently, the CAMC plays a key role in a multi-microgrid system as it will be responsible for the data acquisition process, for enabling the dialogue with the DMS located upstream, for running specific network functionalities and for scheduling the different resources in the downstream network. This new controller will also have to deal with technical and commercial constraints and contracts in order to manage the multi-microgrid both in HV grid-connected operating mode and in emergency operating mode.

CONCLUSIONS

RES and electricity consumers are in general geographically distributed across the territory. The pressing need to exploit these available resources to generate electricity and the need to ensure a larger involvement from the customer side on the management and operation of the electric power system requires the adoption of a completely new set of concepts, among which microgrids play an important role.

In fact, the microgrid concept is capable of responding to the need to accommodate in a safe and efficient way more DG in electrical grids and dealing with active management of the consumption, in particular of controllable loads, including a new type of highly flexible load that will result from a future massive deployment of EV.

It is important to stress that the future deployment of a smart metering infrastructure will be crucial in order to support the development and widespread of the microgrid concept as well as of the upper level control and management concepts associated to the management of MV distribution grids. Such a smart metering infrastructure should not be designed only to provide AMR solutions but it should instead be capable of supporting additional technical requirements. In addition, real time constraints over geographically dispersed areas require new secure communication protocols and infrastructures, which constitute a critical issue that needs to be tackled effectively.

This new vision of power systems brought forward by the microgrid concept creates many new challenges that are multidisciplinary in nature. A robust and secure operation of such a complex and distributed system requires novel theoretical approaches regarding sensing, control, computational intelligence, software and communication. The multiple software layers that the management and control of the distribution grid will require need also to be trustworthy, robust, flexible, user-friendly and seamlessly integrated with the enormous databases that will be created. In summary, these issues are at the forefront of the research agenda in many disciplines and will need to be integrated in order to conceptualize the foundations of what is now called the smart grid.

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