Chapter 1

Electrical Power Systems: Evolution from Traditional Configuration to Distributed Generation and Microgrids

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Abstract

Microgrids can be understood as a complete electrical power system in all characteristics which are inherent to them but on a tiny scale. Although small scaled, they are endowed with high operational and constitutive sophistication enabling them to operate independently, sometimes connected to the distribution system and other times, appropriately, as an isolated system. The paradigm of central control does not exist anymore in this operational philosophy. Thanks to the high quantity and quality of information received from the bulk system summed to the decentralized operation, microgrids can locally provide a higher level of reliability than that provided by the whole system. This chapter gives an overview of electrical power systems evolution stating its current situation with in regard to its own function, economic aspects and environment relationship.

Keywords: Power System Evolution, Microgrids

1.1. Evolution of Electrical Power Systems

Electric Power System begins in last two decades of nineteen century. At that time, it only provided energy to street lamps. Energy was generated in low DC machines of hundreds of kilowatts from prime steam movers. The energy was transmitted in low voltage through thick copper wires until a group of 1400 lamps located in a squared mile. This load was supplied by generators, called dynamos, in Pearl Street Station in New York – USA. The year was 1882.

At that time, AC system was showing several advantages over DC system. Eventually, DC system prevailed. Intense research has been made in the AC field since then. The advent of the transformer has made possible the use of different voltage levels for generation, transmission, and distribution, enabling the energy transmission to more distant places. Poly-phase motor was built and proved to be superior to single-phase ones, solving an important problem to industrial and commercial services and transportation. Thus, three-phase conception was accepted as standard.

Electricity had increased its participation in industrial, commercial, public utilities services and household energy needs. This way it has become support for economic growth.

Voltage regulation problems came along with electrical power transmission. In addition to that, as soon as the first interconnected system appeared, solutions to stability problems became necessary. It is convenient to note that lighting, heating, and electrical motors were then the main types of loads fed by electric power systems.

Transmission lines impedance and terminal voltages determine the active and reactive power flow. It has been observed that energy transmitted over long distances may result in problems related to voltage and

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stability. This problem can be caused mainly by sake of reactive power unbalance. Whereas the interconnected system has provided reliability to the power supply, no control over power flow existed unless there are means to change line's terminal voltages and/or its parameters. This situation can result in bottlenecks and loop flows, decreasing the efficiency of transmission service.

Varying terminal voltages through generator excitation systems and on load tap changers have been the most common means used to control the power flow to the load. Series and shunt reactive devices have been commonly employed to alter line impedances but, in general, as power transfer grows, it becomes much more complex and insecure to operate such large-scale interconnected systems.

As systems have their transferred power and size increased, to keep them operable, more and more interconnections through new transmission lines installation and new substations building have been made necessary.

1.2. Environmental Problems

All forms of electricity generation have some level of environmental impact. Many countries have their primary sources from fossil fuels, such as coal, natural gas, and oil. Nitrogen oxide, carbon dioxide, sulfur dioxide, methane and mercury compounds are the more common products resulting from coal, oil and natural gas. These power plants emissions increase the risk of climate change.

Nuclear power plants do not have any oxide or dioxide emission. However, it does not mean that they do not cause any environmental impact. Nuclear components, whether in the form of fuel or waste resulted from nuclear cycle, represent risks of tragic occurrences in a situation of mismanagement or containment failure.

Hydropower emissions can be considered negligible because there is no fuel burning. In spite of that, hydropower plants can change the environment, due to the fact that redirecting wind added to isolation increasing could produce moisture decreasing, causing remarkable impacts to flora and fauna. Modification in wildlife habitats could determine even the death of some species.

Transmission lines, being it short or long, affect the environment since installation to their normal operation. The impacts include land use restriction and permanent removal of wood and vegetation. It can also alter local hydrology creating new drainages and extinguishing the former ones. Removing vegetation can also provoke erosion and soil compaction.

Given the environment modifications induced by power systems evolution, it is necessary to minimize their impacts. The cost, in currency terms, is very difficult to be evaluated but it is certainly very high to humanity as a whole. Load grows persistently. Power system must be able to serve it.

Nowadays it seems to be desirable for the efficient and clean energy production, not only from power systems standpoint but also to spare the environment from degradation.

1.3. Deregulation

Since the advent of electric power systems, electrical utilities have embodied all duties in charge to provide electricity to consumers. They were responsible for generation, transmission, and distribution. The distribution system consists, in general, of small pockets of demand served by local grids. These distribution grids are connected to generation through a transmission system. The economy of scale in generation and transmission systems makes sense to have a low cost rate of produced or transferred US$ per kWh. This gave birth to large structured companies that could face the kind of challenges electricity services needed. Then, large power plants and transmission systems were built to supply a number of scattered distribution systems in charge of delivering energy to customers. This has been called a vertically integrated utility. In several countries, they were public companies, given the huge volume of capital needed and a large amount of work necessary to deliver the services.

This kind of enterprise implied in the commitment of large sum of money. In such type of intensive capital industry and being energy a crucial service, governments have guaranteed a fair return on investments necessary to face the risks withstood. A stable market in the form of monopoly was ruled helping even more in risks reduction. This way, it was expected that all economic efforts could be done in keeping the electric system reliable, secure and fairly priced. In the same way, communication and transportation, like electricity have also been the targets of government regulation due to their importance. Energy prices, as an economic factor, are spread in almost all other services and sectors of economy. Therefore, prices are always closely watched by governments [1].

As a basic need, the regulation of electric energy industry had the goal of controlling its prices. Essentially, from the regulator point of view, the energy price should reflect the cost of the services. So, considering utilities' total costs, prices should be set in a way that the average revenue of energy per unit sold represented the average cost to produce it. Therefore, the total costs of providing services should consider several cost allocation schemes regarding residential, industrial and commercial sectors, different seasons of the year and different time of the day. Prices had to be able to cover yet capital costs, operational costs, etc. [2]

However, energy prices are not so frequently adjusted. When utilities needed to correct their prices, they should request competent bodies, which would analyze and then judge them. It usually took a considerable time. Additionally, prices could remain unaltered for years. In this fashion, considering a slow price adjustment summed to changing costs, actual return rates could be either over or under a fair rate.

Regulators should be careful enough to set prices sufficiently above costs in a way to avoid utilities' bankruptcy. On the other hand, prices could not be too high to prevent unfair rates to costumers. A price-cap appropriately set could even work as cost reducer. Nevertheless, a price based regulation could promote cost reducing and lower price but could not provide utilities with an incentive to improve quality. [3]

The regulator faced the challenge of adjusting prices in a range allowing for utilities costs supply with a reasonable profit. Therefore, regulation did not work giving incentives to energy consumption reduction. Quite the contrary, as in a vertical structured industry, cost allocation is something not exactly nor transparent. The utility aimed to approve all cost request demanded to raise prices and in search of maximize revenue would support the energy demand growth.

The difficulty met by the regulator to define prices explains the economic inefficiencies of this model [1]. There is a belief that market forces instead regulation are more efficient to establish prices.

Regulator's acting should be a combination of price incentive and firm monitoring to induce equilibrium between the two situations. Regulation cannot be as efficient as competitive markets. Indeed competitive markets can push prices down to marginal cost and minimize cost. This is a relevant argument stressing electricity industry towards deregulation [4]

The belief is that a competitive electricity market could be economically more efficient. Summed to it there are technological innovations such as improved efficiency in generation, computerized control systems and modern data communication and off-site monitoring systems capable of controlling units from centralized remote centers where one operator can monitor several units in various sites. This weakens the need for larges generation and transmission systems necessary to get economy of scale. New technology is efficient enough to have a comparable kWh per US$ with the extra benefits of being less polluting and less capital demanding [5].

In deregulated scenery, the generation monopoly disappears, and competition comes into play. Power generators companies, now working in this exclusive function, have to compete, in a power generation market, to sell their energy and so produce and dispatch the amount of energy negotiated. A spot market, permitting optimization of generators profit is also part of the scene. But in this deregulated framework, the price volatility is to be expected [5].

In regulated regime, either prices are calculated as a rate of return over an average of costs or they are fixed. They have the same value any time of the day. Put in a simple way, energy delivered to consumers are accumulated over a period and the price is applied to this amount. This is one of the inefficiencies of regulation. It does not take into account the variation of demand along the day neither the dispatch the more expensive generation units in periods of heavier load [5].

At the other end, in retail, the competition is upon offering low prices, good services, and any other additional service features to consumers. Ideally, a restructured and competitive electric industry embraces generation and retail, remaining as monopoly transmission and distribution [5].

Volatility or fluctuating prices in the spot market, not only hourly but daily or even yearly are problematic. Far from being perfect, some inefficiency inherent to the new framework is very difficult to manage, contributing for this sake to volatility increasing and creating an ideal condition to attract traders [6].

Deregulation, which came to eliminate the inefficiencies attached to vertically utility structure, created a new framework which brought in itself others inefficiencies. The question is: Has there been any improvement? From the point-of-view of traders, the answer to this question is yes. At least the risk has been shifted from consumers to investors [6].

What about the vertical structured utility inefficiencies? Another change, now in the electricity company structure was necessary. They had to be reshaped.

1.4. Diverticalization

Power industry scenario has changed. The traditional utility, which could formerly produce energy supported by the economy of scale, has seen its era come to an end. In 1960's and 1970's it was discovered that large generation thermal units (1000 MW), which represents the majority of the units installed, had operational problems limiting their efficiency [7]. This limitation stopped the process of getting cheaper energy come from increasingly larger power units. At the same time, small units have their efficiency improved with new technologies like gas turbines, combined cycle, hydro and fuel cells. Also, computerized systems and data communications have helped in monitoring and controlling the electric system driving to operational cost reduction.

Apart from this, deverticalization is a way of separating functions and services from an integrated business (generation – transmission – distribution) administered by a single company in independent business units. In this way more efficiency and transparency are expected. The costs inherent to each separated business become more visible, which is desirable for investors.

The regulatory process and its inefficiency in motivating costs reduction summed to the argument that in a competitive market there are stronger pressures to drive costs minimization helped to change the current situation. Framework reshaping has been carried out to decompose the integrated industry in three components: generation, transmission, and distribution. Figure 1 illustrates the interconnection of these components [8]. Indeed, two others entities should be created to accomplish independence and balance among the newly remodeled power system participants: independent system operators and retail energy providers.

1.4.1. Generation

Generation is represented by the companies that embody the power plants. Once in a deregulated market, their prices are not fixed. They must sell their generated energy using contracts made with customers. The interplay among other generation companies is also possible in a short-term market for the sake of optimization of their service or any energy deficit coverage.

Although the owner of their assets, generation companies' operation must be submitted to an independent operator. The operator is responsible for the power system optimal and efficient operation. It is up to the operator the task of establishing the dispatch of every generating unit. Nevertheless, it is the generator's responsibility to submit to the system operator the request of unit's outages for maintenance. After approval, outage may take place.

As an independent entity, the economic objective of the generator agent is to maximize their profits. They are then responsible for all the risks that this behavior brings on.

As vertical energy industries, utilities planned to build a new plant or expand an existing one according to a reliability criterion. Nowadays, in deregulated condition, generation will be constructed or increased if there is a price signal. If electricity price is high enough enabling the company to yield profits, investments will be made. As time passes, available supply vanishes and prices rise. This condition can even prevent demand raise. The real-time consumers' response to energy price gives feedback to planners that reliability has to be improved.

1.4.2. Transmission

The transmission system makes the bulk transport of energy from generation to distribution and independent consumers. It is structured in a grid accessible by all agents. Radial links connect generating units and customers to the main network. System ruler must guarantee that there are not discriminatory connections between transmission grid and any of the other agents. A just access condition must prevail among them all.

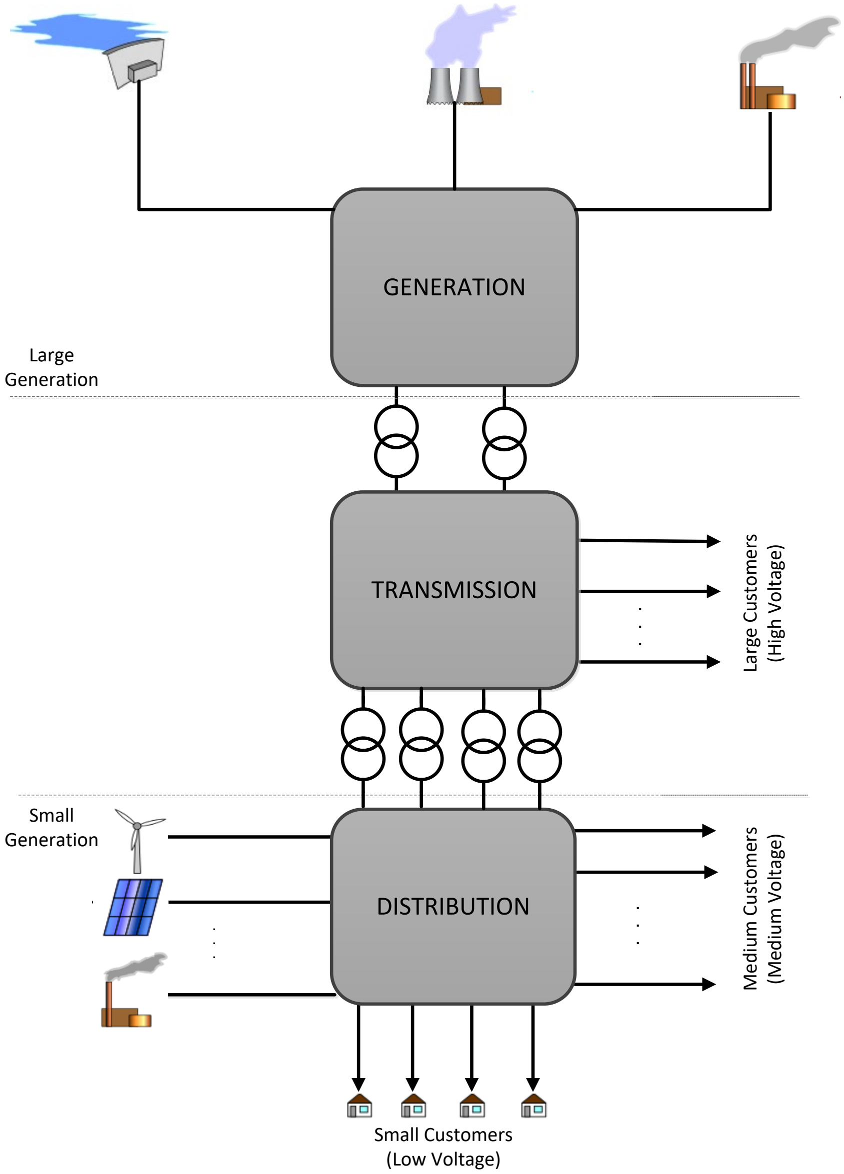

Fig. 1.1 Power system traditional structures

Transmission companies own the assets but do not operate them. In a similar condition to generation, transmission makes them available to the system operator control. The role of transmission companies is to own, build according system operator's planning and maintain their assets keeping reliability level of the electrical system.

1.4.3. Distribution

Distribution is responsible for the energy delivery to costumers. A regulatory agency coordinates distribution services ensuring that energy reaches costumers in adequate reliability, availability and quality of attendance. It is competence of distribution companies the building, maintenance and operation of their grid and ancillary services in order to accomplish the regulatory agency's pattern of quality concerns.

1.4.4. Independent System Operator

In the new paradigm, the system operator must be independent of any other market participants. A balanced control of the grid is not possible without such independence character. In this new scenery, the energy market needs to be competitive and efficient. System Operator must then be able to maintain system reliability. For this sake, it must take charge of establishing rules, coordinating maintenance and long-term planning, regardless of any other agent own interests. It has the authority to operate any services needed to maintain the system security. It manages the system in an indiscriminate and transparent way ensuring a fair condition to all agents. An Independent System Operator is responsible for electrical power system security. Another important responsibility is to provide the market economic operation enabling cost and price reduction.

1.4.5. Energy Market

Deregulation has been performed all over the world in different ways, by different reasons and has arrived to different results. In general, the retail market created in each country throughout the world has its own particularities. The deregulation of electricity industry and restructuring of electric sectors have caused uncertainties and created a high number of problems. These ones have been persistently and progressively solved in disparate markets. The specific solutions have involved legal, regulatory, technical and commercial aspects creating a generic framework.

Generation companies can sell their product using contracts to other agents. They can also sell energy generated in exchanges where distributors and other large consumers may buy it. Moreover, generation companies can also participate in ancillary services market with reactive power market and an operating reserve. As generator's prices are not regulated, it is through that generators can maximize their profits.

Transmission companies are under some regulation. As they do not own the transmitted energy, other companies using transmission grid must pay some fee to use it. In general, the system operator is in charge of these reception taxes.

Distribution companies have a role to deliver the energy contracted. Their customers can be of a retail type or medium to large consumers, which receive their energy by distribution grid.

This kind of market has its birth after deregulation. It is a new modality, which makes some entities part of this segment. The costumers, as end users of electricity, are interested in buying the amount the energy they need. There are firms which gather several costumers in a group enabling them to purchase energy in a large quantity in order to get cheaper prices. Other kind of agent is the broker, which role is to approximate buyers and sellers aiming some yield for that. Marketers buy and resell energy from generators or others marketers. They do not own either a generation or a distribution company. The purchase is made directly from contracts or titles negotiated in the energy exchange [6].

1.5. Power Electronics

Power electronics is a key technology for electrical power systems. The advances in power electronics devices facilitate the development of new power converters aimed to improve the performance of power systems. A brief discussion of these points is presented below.

1.5.1. Power Electronics Devices, Converters and Applications

The emergence of SCRs (Silicon Controlled Rectifier), in the middle of 1950's, made mercury arc valves to be substituted in rectifiers assembly. SCRs are more robust and compact than mercury arc valves. More and more thyristor, a more common name of SCRs, have raised its current conduction and voltage blocking capabilities. This has made possible the "Flexible Alternating Current Transmission", ("FACTS") proposal. FACTS are power converters based on power electronics that are able to control active and reactive power flows through grid circuits and voltage in their buses. The main objective is to enhance the transmission lines flow capability and alter the route of the flow throughout the grid.

Thyristor belongs to the first generation of power electronic devices. By its characteristics, once put in conduction mode by a trigger pulse remains in this state until the conducting current comes to zero. Even with the absence of turn-off capability this device is employed in a large number of applications such as Static Var Compensator (SVC), which is able to control voltage in the bus where it is installed, and Thyristor Controlled Series Capacitor (TCSC), which makes possible the control of the degree of series compensation in a circuit. Therefore, a decisive advantage exists in favor of those devices with turn-off ability.

A second generation of power converters came when a turning on and off controlling device has made it possible. Gate Turn Off Thyristor, or GTO, has been the first of a series of electronic devices with this ability. By using GTO, voltage and current sourced converters were designed. As part of FACTS family, Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Compensator (UPFC) have been made. The STATCOM provides voltage control to the system furnishing or absorbing reactive power without the reactor or capacitor banks need. SSSC is a converter that is connected in series with transmission line. Its basic function is to introduce an independent controlled voltage in quadrature to line's current. This way, by this reactive voltage variation over transmission line, it is possible to control the power flow through it. UPFC can simultaneously and selectively control all power flow affecting parameters such as voltage, impedance and angle variability allowing thus, independent power flow control in a transmission line. This new generation of power converters is very versatile. This feature is what provides, in part, the attainment of FACTS, High-voltage direct current (HVDC), new renewable generation, smart and microgrids [9],[10].

1.5.2. High-Voltage Direct Current

HVDC is not exactly a new technology since its conception is back to 1930's when mercury arc rectifiers were invented. It was employed in 1941 by the first time through an underground cable supplying Berlin with 60 MW. At that time, HVDC systems had a comparative disadvantage to regular AC systems. This disadvantage was explained by the cost of converters, which required much reactive power, generating harmonics that require filters. The operation was difficult. Its applications for high power transmission have only been economically advantageous in distances over 640 km [11].

Allied to power electronic developments and the ever-increasing interconnections among systems, certain characteristics of HVDC transmission system has recently become more appealing. From an economical point of view, overhead DC transmission line is cheaper than its AC equivalent (in per unit of length). HVDC lines towers need to support only two conductors in a bipolar assembly against six or more in HVAC case. HVDC right of way width compared to that in HVAC lines is smaller. Nevertheless, DC converter stations are costlier than AC terminal substations [12].

For long distances, HVDC is always a more economical alternative to HVAC. For example, in a 6000MW stage of Three Gorges power plant in China, to transmit all this power would be necessary five 500 kV HVAC transmission lines. This same transmission could be made with two 500kV HVDC bipolar lines [13].

Nowadays several conditions have caused a reorientation about the presence of HVDC in power systems such as environmental problems and prices related to the right of way added to technological advancements [13][14].

1.6. Distributed Generation

At the beginning of electrical power industry, in early of 20th century, prior large-scale steam turbines, all-electric system, AC or DC, had their energy resources near or at the point of use. In fact, the electrical system was born in a distributed fashion. The economy of scale in production and delivery has driven the system development to the large scale and interconnected one.

As a general view, distributed generation can be seen as electric power generation providing loads in their neighborhood. To make this happen, generation must be installed in distribution systems. Generally, they tend to be small scaled (1kW – 50 MW) systems which produce electricity close to customers. Size and location are not the only novelty. They are not centrally dispatched as well.

Coming in the aftermath of the deregulating process allied to environment concerns, difficulties have arisen in new transmission lines construction and generation based on primary sources harmful to the environment. Aside from that, these sources are exhaustible too. Producing energy more efficiently, reducing land usage and being low polluting are some of the main targets of this new philosophy.

Adequately sited, distributed generation can provide electrical power system reinforcement, remodeling the demand profile, favoring losses and cost reduction, improving as voltage as power factor levels, strengthening reliability, security and efficiency.

Another significant aspect is the low capital required to build such small-sized generation units, although the investment cost by kVA can be much higher than in a large power plant. Seen by the financial aspect, distributed generation is a less risky enterprise. No large infrastructure is necessary to run an undertaking like this.

Considering the presence of new technologies added to the reasons exposed, the choice falls on renewable compact non-conventional generation.

1.7. Renewable Energy

Some of the forces pushing new deregulated framework ahead has been the need for efficiency and quality. Load proximity, small sized generation, added to a clean renewable technology is a good option. Connections of new generation technologies are also a consequence of the power of electronics development. Power electronic converters can provide necessary efficiency to the electrical system.

A number of technologies have reached a development degree that made them apt to play this role. They have become less costly too. Historical features of some of these technologies are briefly presented below.

1.7.1. Wind Farms

For electrical purposes, the first dynamo driven by a windmill model was built by the end of 19th century in Denmark. Several other countries like Germany, Russia, England, and USA have also researched in this area generally aiming to improve rural electrification. Different models with ever-increasing power have been made throughout all 20th century.

The interest for wind power to generate electricity has been related to fuel price levels. During World Wars I and II, with fuels scarcity and high prices, electricity generation by alternative means received an impulse. However, in noncrisis periods, when coal and oil were available and inexpensive, attention to wind power decreased. From 1973 to 1974, oil crisis not only rekindled interest by alternative ways to generate electricity but also brought awareness to the oil dependence as a primary energy source [15]. Until 1980's any more serious environmental worry was not yet related to electricity production or transmission.

Typically, wind power plants consist of induction generators coupled to a wind turbine. There are different wind turbines types with respect to active power control. Generally, the large wind turbines move their blades according to wind speed controlling this way their efficiency. It is also necessary capacitor banks and additional power electronics converters to control reactive power [16].

Moderate prospects points to 700 GW and 2700 GW as a global wind power capacity in 2020 and 2050, respectively. Wind power plays more and more a central role in electrical systems [17].

1.7.2. Photovoltaic Systems

Photovoltaic generation technology, after hydro and wind, is the third most important renewable energy source from global installed capacity point of view. Sun provides clean and abundant primary energy source, which can be converted in electricity. This conversion is made directly by photovoltaic cells. Photovoltaic technologies are based on semiconductor material which can convert sun light energy into electricity. Photovoltaic cells produce DC electricity. In such condition storage is easy to be made in batteries and then sent to be converted into AC electricity.

Until 2013, 139 GW of photovoltaic systems were globally installed. A conservative scenario points to over 320 GW installed up to 2018 [18].

1.7.3. Fuel Cells

Fuel cells generate electricity by electrochemical reactions feeding hydrogen or enriched hydrogen fuels to the anode (negative electrode) and oxygen or air, fed to the cathode (positive electrode). In these electrodes, the electrochemical reactions take place. The fuel in these cells does not suffer combustion. The energy, instead, is produced continuously and directly as long as fuel is supplied. As fuel cells do not burn fuel, it is pollution free since hydrogen is obtained from a nonpolluting source. It is a genuinely zero-emission source of electricity [19]-[21].

Efficiency in fuel cells is around two to three times higher than in combustion engines. Another characteristic is that efficiency does not depend on the size of the system, what is particularly interesting to small applications [19]-[21].

Fuel cells are used in three categories: portable, stationary and transport. Portable are units from 1W to 20 kW used in boats and vans, portable products, military applications and all small personal electronics. Stationary are units to provide electricity and uninterruptible power supplies not designed to be moved ranging from 0.5kW to 400kW. Finally, there are units designed to provide propulsive power to vehicles like cars, trucks, and buses. These last systems have their power from 1kW to 100kW [22].

1.7.4. Energy Storage Systems

With the growing presence of renewable generation in the electric grid, energy storage systems are also playing an important role in system operation. New technology generation has intermittency as one of its characteristics. Fluctuations and variations in energy generated can be mitigated when associated to storage devices. Working together, renewable generation and energy storage devices can behave as a constant power generation plant, depending on the storage system capacity [23]. Besides generation stabilization, energy storage is also important for a broad range of services and applications such as power quality assurance, voltage and frequency regulation, spinning reserve, load leveling, peak shaving, and transmission and distribution supports.

From a technological point of view, there are three kinds of energy storage systems based on its physical nature: mechanical, chemical and electromagnetic. Pumped hydro storage, flywheel, and compressed air energy storage are mechanical based systems. Batteries store energy using reversible chemical reactions. Superconducting magnetic energy storage and super-capacitors are of electromagnetic nature.

Pumped hydro storage is a hydroelectric plant which can pump back the water from downstream to upstream. This task is made during off-peak periods. The stored energy can be reconverted in electric energy driving again the water to the turbines. Its efficiency depends on the type of turbine, the diameter of the penstock, height of reservoir and plant size. That is a technology which is mainly used for large-scale applications [23].

Flywheel energy storage system stores energy in the form of kinetic energy of a spinning rotor. The rotor is assembled in the same axis of an electric generator. Energy conversion takes place by accelerating and decelerating the set generator-flywheel. As it is a simple system, it has been widely used in small unities. Applications of flywheel in electric systems are made in cases of frequency deviations, voltage sags and swells and temporary interruptions. Efficiency ranges between 80% to 85% [23].

Compressed air energy storage uses light load periods to compress air in reservoirs. In peak loads or lower generation situations this air under pressure combined with fuel in combustion is driven to a turbine to generate electric energy. The energy storage capacity depends on the air deposit size, the pressures of compressed air and the kind of fuel. This type of storage system is used from medium to large-scale systems. As the air compression is made separately from turbine, the efficiency is much higher than the conventional turbojet and costs are three times lower [23].

Batteries store energy electrochemically. They are one of the most cost-effective energy storage technologies available. Depending on battery system electrochemical reaction occurs under a potential applied between its terminals provoking charging process. If a load is connected between battery's

Table 1. Comparison among energy storage systems [23]

Storage Technology	Energy Capacity	Discharge Duration	Power Level	Response Time	AC – AC Efficiency	Life Time
Pumped Hydro	< 24 GWh	12 hours	< 2 GW	30 ms	70% – 80 %	40 years
Compressed Air	400 – 7200 MWh	4 – 24 hours	100 – 300 MW	3 – 15 min	85%	30 years
Fly Wheel	< 100 kWh	Minute to 1 hour	< 100 kW	5 ms	80% – 85%	20 years
Battery	< 200 MWh	1 – 8 hours	< 30 MW	30 ms	60% – 80%	2 – 10 years
SMES	0.6 kWh	10 s	200 kW	5 ms	95% – 98%	40 years
Supercapacitors	0.3 kWh	10 s	100 kW	5ms	95%	40 years

terminals, the same electrochemical reaction occurs in reverse discharging it. They have fast dynamic response and efficiency between 60% and 80%, depending on the technology employed. Batteries lifetime depends on how fast and how depth they discharged [23].

Superconducting magnetic energy storage (SMES) is based on storage of electrical energy in the magnetic field created by the flow of a DC through a coil made of superconducting material kept at cryogenic temperatures. Charging and discharging times are very low enabling this device to supply high amounts of energy in milliseconds at negligible losses. Additionally, its efficiency is very high, normally between 95% and 98%. The main disadvantage is the need of a cryogenic system to raise its low energy density level. From the point-of-view of cost, the electronic-based power converter portion is about 60% of total cost. Applications include load level, spinning reserve, enhancing transient and dynamic stability, voltage support and power quality improving [23].

Supercapacitors, also known as ultracapacitors, are electric energy storage systems with high energy and power densities. The potential is applied across the cell which allows energy density being from 10 to 100 times of conventional capacitors. An important characteristic is the possibility of charging and discharging completely about a million of such cycles without loss of life. This represents 1000 times more than battery cycle. The supercapacitor in parallel with a battery is an interesting association. While supercapacitor delivers the peak load, battery charges it 90% of the time. This assemble permits battery lifetime being 50% longer than without supercapacitor. Their fast charging/discharging times make them useful to high-frequency load peak demand. It can thus provide power during voltage sags, and momentary interruptions. With an expected lifetime of 25 years or more, supercapacitor performs an efficiency of 95%.

Once the different technologies are briefly presented, a comparison among energy storage systems is displayed in Table 1. It is possible to realize that different energy storage technologies serve applications depending on the amount of energy to be stored, the rate at which this energy will be transferred and the response time. In the table is represented applications where the storage device must respond quickly and be able to supply in short periods of time e.g. ultra capacitors or SMES, and there are those in which the discharge can last several hours e.g. Pump Hydro and CAES. [23]

1.8. Information and Communication Technology

The traditional electrical power system structure is centrally operated. In such a way, the flow of energy and communication is unidirectional. There is no interaction between utilities and consumers. Conventional meters can perform only one-way communications.

The increasing presence of distributed renewable generation sources represents a challenge to power system operation. Power flow may be bi-directional depending on the intermittent behavior of these renewable sources. In order to deal with these circumstances with efficiency and reliability, it is necessary to make use of advanced information and communication technologies to enable correct energy management. These technologies also include automation, sensing, and metering services to accomplish their main tasks.

In this new scenario, the operation must be implemented by the cooperation of quite some control devices by collecting data at the distribution level to ensure protection and control duties. This way, several means of communication are so employed. Commonly communication network links include phone lines, pilot wires, optical fibers, microwave, radio, LAN/WAN/Internet (TCP/IP), etc. Choosing the appropriate means is a matter of cost and availability always focusing the best to the system operation.

Nowadays the attention is turned to a renewed electrical energy industry framework where main aspects include social benefits, lower energy costs, and greater flexibility to accept new distributed renewable energy sources. Additionally, a new structure of information and communication technology is necessary to enable energy demand and generation more predictable and controllable.

The above discussion points out towards the smart grid concept. It refers to a modern electricity delivery system in a way that it monitors, protects and automatically optimizes the operation of the systems in which it is connected [24]-[26].

1.9. Microgrids

Active distribution networks are defined as networks in which power flow is bidirectional. With the increasing penetration of distributed generation, the generated power amount the distribution system may be higher than the load. In this case, the excess of energy is exported from distribution to the transmission/sub-transmission system. Because the previous definition, distribution networks without distributed generation and just unidirectional power flow are called passive networks[27].

Active distribution network requires control, supervision and communication infrastructures between the different levels of the systems, to obtain a safe and economical operation. One way to achieve these requirements is associated with the smart-grids concept. Although there are several definitions available, according to [28] smart-grid should be understood more than just a specific technology or equipment. Smart-grid conception is associated with intensive use of information and communication technology in the power grid, through the possibility of communication between the various components of the network, allowing control strategies implementation and network optimization more efficiently than those currently used.

Combining active distribution networks comprising distributed generation and storage devices in a smart-grid scenario result in the microgrids concept. Microgrids are networks composed of a cluster of loads, energy storage systems and distributed generation units in a local distribution network[29]. The connection to the transmission network is made through a point of common coupling (PCC). By controlling the active and reactive power flow, the network can import or export energy to the grid[30], which is a particularity of an active distribution network.

1.9.1. Structure and Operational Modes

The formation of small electric autonomous networks does not literally represent a novelty about electricity supply. Since many years ago, small networks are used to deliver energy in remote areas, where connection to the main grid is not feasible, mainly for technical and economic issues[31]. However, the current conception of microgrids was first presented in [29]. In the new design, microgrids are represented by distribution systems (or at least a part of the system) in which distributed generation sources and energy storage devices are connected, besides communication and control systems. Based on [32], Figure 1.2 shows a typical low-voltage AC microgrid structure.

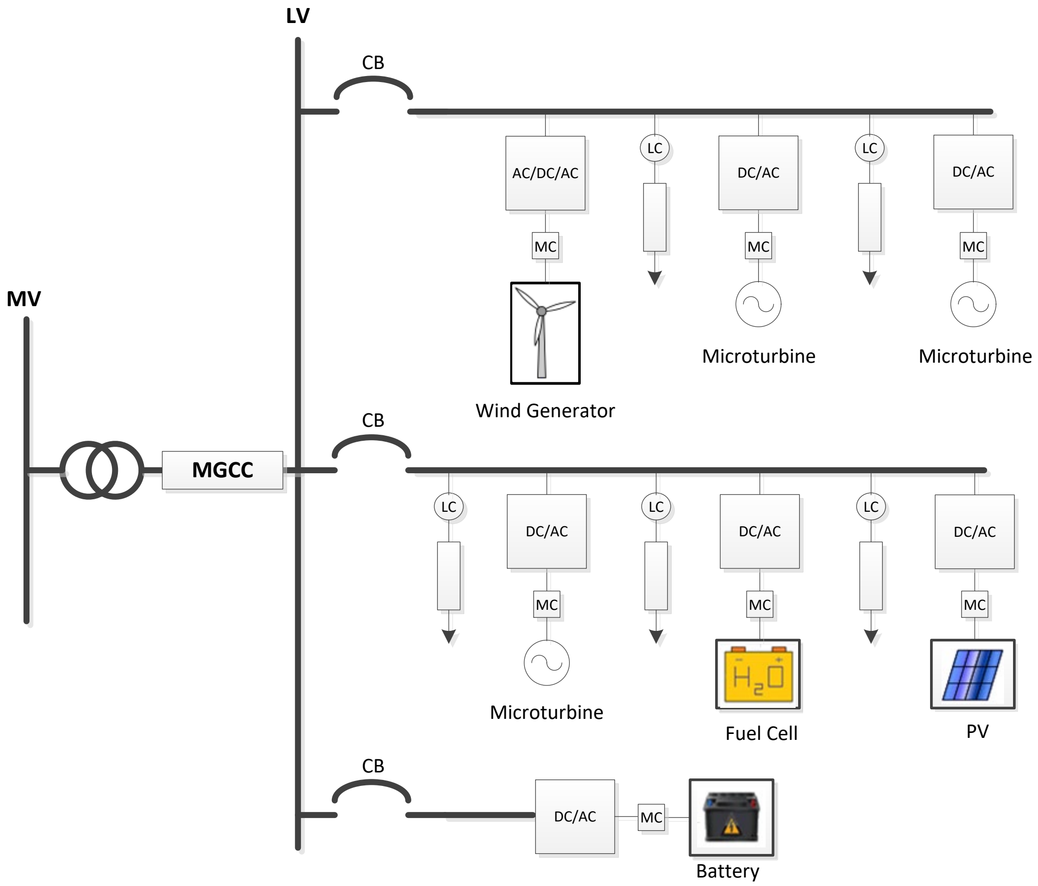

Fig. 1.1 Typical microgrid structure

According to Figure 1.2, two feeders and an energy storage device are connected to the low-voltage (LV) side. Dispatchable and non-dispatchable energy resources delivering power in AC or DC are represented. As the structure considered for the microgrid transmits power through AC, power electronic converters are used to adjust the DC sources and perform the DC/AC transformation.

Connection to the main grid in the medium voltage (MV) side is made through the point of common coupling. A circuit breaker allows decoupling the microgrid to the main grid in cases of disturbances, changing the operation to islanded mode. There may be other intermediate circuit breakers, which allow sectioning other system parts.

Microgrid control is performed hierarchically. Micro-source controller (MC) and load controller (LC) are responsible for connecting and controlling distributed sources and controllable loads to the branches. MCs and LCs operate at the local level while the microgrid central controller (MGCC) operates as a central management device. Distribution management system (DMS) must be able to exchange information with MGCC to achieve improvements in distribution system operation. Main controller's functions are listed below [27],[28],[33]:

- *Microgrid Central Controller:* Performs centralized control and is responsible for managing the energy bought/sold, to minimize emissions and power losses, maximize operational efficiency of the microgrid and provide islanding logic or supply restoration via electrical power utility. Also, MGCC is responsible for maintaining the voltage and frequency within a range of specified values. Optimal operation is achieved by sending control signal settings to MCs and LCs.

- *Microsource Controller:* By using local information, MC should be able to control the voltage and power flow in response to load changes or disturbances. Quickness in response and ability to adjust regardless of source connected type are other main features.

- *Load Controller:* Perform control in controlled loads by connection/disconnection of certain equipment in certain predetermined periods. LC also relieves unfavorable operating condition of Microgrid.

The controls listed above allow safe and flexible operation. Microgrids operation can be performed in a manner connected to the grid or in islanded mode. To achieve these purposes, the microgrids are provided with equipment and control systems suitable for whatever the mode of operation, such that the electricity is delivered to customers in an uninterrupted and quality manner. The main features of the operating modes are listed below:

- *Grid-Connected Mode:* Due to connecting to the main grid, the microgrid deficit power must be supplied by the main grid. Also, the excess power must be sent to the main grid, supporting the grid through an array of ancillary services, such as voltage regulation and reserve power. The microgrid operates by sending/receiving power according to the load and generation conditions. The main grid determines voltage and frequency.

- *Stand-Alone Mode:* Microgrid islanding operation can be intentional or unintentional [31]. The intentional islanding may occur in scheduled maintenance cases or when the network power quality may jeopardize the microgrid´s operation. On the other hand, unintentional islanding occurs due to faults, contingencies or other non-scheduled events. Islanded operation mode allows the continuity of supply, which represents cost savings and reliability improvements. However, it requires, for example, that the generation capacity in the microgrid is higher than the critical loads. In this operation mode, distributed generation sources determine voltage and frequency.

The transition between operation modes should be performed smoothly and not result in system instability. Reconnection or disconnection process must be autonomous, i.e., the microgrid should be provided with intelligent algorithms to identify the most appropriate time to perform the transition between operating modes. Furthermore, in some cases where the available generation is just enough to supply the priority loads, it is necessary to perform load shedding of some non-priority loads during the transition.

1.9.2. AC vs DC Microgrids

During the first electrical systems formation, one of the most complex tasks was to define what would be the optimum mode of electricity transmission. Thomas Edison argued that electricity should be provided in DC, while George Westinghouse and Nicola Tesla guarantee that supply AC was more advantageous. This dispute between competing systems was known as Current War. Nowadays, AC systems are predominant mainly due to the system´s ability to change the voltage level throughout the system, allowing the power to be sent from one place to another with minimal losses. In contrast, DC systems required the generation centers were located near the load.

The main obstacles to adoption of DC for large systems are overcome in the case of microgrids, bringing the AC vs DC discussion up again. Distributed generation sources such as photovoltaic panels, fuel cells and battery banks operate in DC mode and are located near the loads. Various loads such as computers, TV's and LED bulbs are supplied with direct current. Figure 1.3 shows the typical AC and DC configurations to highlight the main differences between both systems [34].

In an AC network, DC sources such as PV and fuel cells are converted to AC using DC/AC converters while AC sources are coupled directly using power electronics interfaces. DC loads are connected via AC/DC converters. In DC microgrids, AC generating sources and loads are converted to DC using DC/AC converters. However, the conversion process results in losses. The DC/AC inverter is approximately 85% efficient, AC/DC rectifier 90% and DC/DC converters 95%. At first, these previous data indicate that the fewer conversions type AC/DC better is the use of energy [35].

Another advantage of DC networks is related to simpler power electronics interfaces, resulting in fewer points of failure. Also, imbalances are not present in these systems. Despite these advantages, some challenges hinder the adoption of DC systems as unanimity in microgrids. Issues related to power system protection, the lack of standards for transmission in DC and lack of people with experience in this type of system represent some of the challenges.

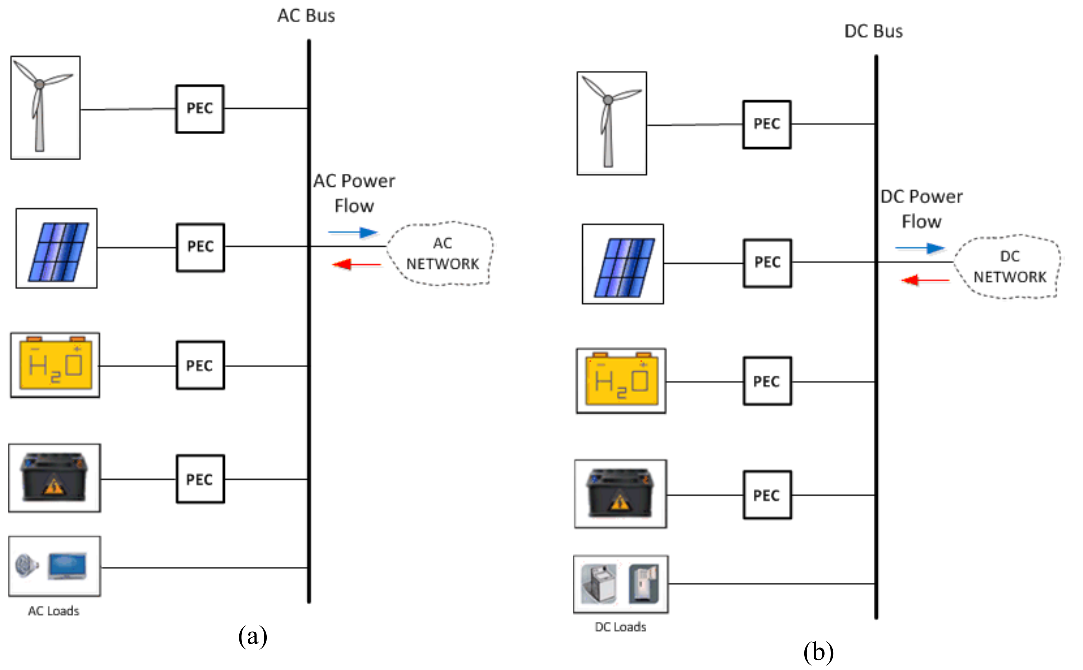

Fig. 1.2 Dispersed generation in (a) AC microgrid (b) DC microgrid

An intermediate solution is the formation of hybrid microgrids. The main objective is to develop networks minimizing the number of converters, i.e. reducing the losses associated with conversion. Figure 1.4 shows an example of a hybrid microgrid configuration. In hybrid networks, AC generation sources and loads are connected to the AC side of the network; DC generation sources and loads are connected to the DC side. The connection between the AC and DC sides of the network is made through a bidirectional converter, which can act both as an inverter drive and as a rectifier relying on the power flow direction [36].

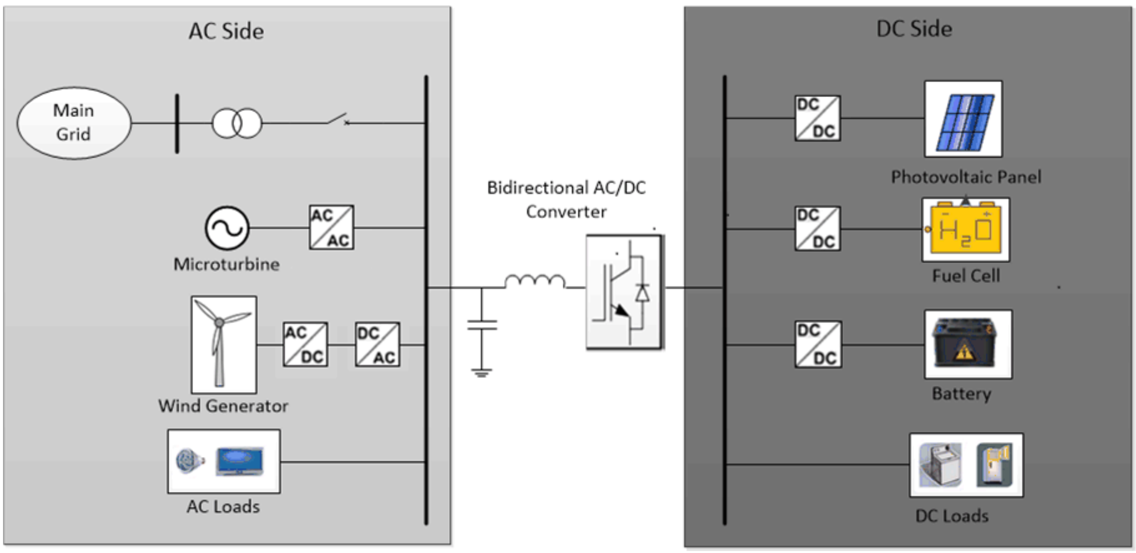

Fig. 1.3 Hybrid microgrid

1.9.3. Advantages and Challenges of Microgrids

The main characteristics of microgrids are the integration of small-scale generation sources (renewable or non-renewable), the power generation close to the loads, and the possibility to operate grid-connected or in stand-alone (islanded) mode. Based on these characteristics, microgrids development is very promising, resulting in some advantages. Some of the main ones are listed below:

Operational and Power Quality [27]

- Reduction of Power Outages and Reliability Improvement: Because of a disturbance or due to an operational criterion, the microgrid can operate in islanded mode.

- Losses Reduction: Due to a reduction in the electrical distance between load and generation and power re-dispatch, power losses can be reduced in both the transmission and distribution system.

- Enhance Reactive Power Support: Enables an improvement in the voltage profile.

- Decentralization of Energy Supply: Lower system dependency upon the occurrence of transmission lines outages or generation loss, especially when these devices are responsible for a large portion of system's generation / transmission.

Environmental:

- Encouraging Electrical Power Generation by Renewable Sources: Considering many renewable sources have reduced nominal capacities and intermittent generation, microgrids formation contribute to the use of these sources.

- Reduced Emissions of Greenhouse Gases: Created in 1997, the Kyoto Protocol aims to establish international agreements and discussions to jointly establish reduction targets in the emission of greenhouse gases, mainly from industrialized countries, and create forms of development of less harmful way to those countries in full development. Thus, microgrids with renewable generation sources imply in reduced emissions of greenhouse gases compared to systems using other sources such as gas, coal, oil, diesel or any other fossil fuel.

Economics and Market

- Investment Reduction: Considering the presence of local generation, the formation of microgrids reduces or at least postpones investments in generation and transmission of energy.

- Cost Reduction: Electrical energy price takes into account the cost associated with system outages. With increased system reliability, this portion can be reduced. In the case of microgrids composed by industrial loads, continuity of power supply results in increased revenue, since some costs associated with an interruption are reduced, such as operating costs related to downtime in production and/or loss of raw materials. In the latter case, also reduces the fines paid by electric power utility company to consumers. Furthermore, application plug-and-play micro sources may contribute to a reduction in energy price in the power market.

- Ancillary Service: When operating in grid-connected mode, the microgrids can contribute to the main system providing ancillary services. From ancillary service providers, this results in compensation. Some applications and linked to energy imbalance, operating reserve, reactive power and voltage control.

Despite all the advantages, the creation of microgrids represents a paradigm shift from electrical power systems. Even with features for comparing the microgrids to small versions of electrical systems, like any new technology, they present a number of challenges that must be overcome:

Frequency and Voltage Control:

- When the microgrid is operating in grid-connected mode, the frequency is kept constant. On the other hand, in islanded mode, the microgrid should be able to control its frequency, because in this case there is no swing bus in the system. Furthermore, the transition between operating modes must be appropriately performed by the frequency and voltage requirements in order to ensure stability.

- Microgrids with high penetration of distributed generation are subject to voltage instability problems due to the bidirectional power flow and voltage fluctuations.

Operational and Topological Issues

- The optimal operation of microgrids, from the technical and economic point of view, is directly linked to the definition of the network topology, and quantity and location of distributed generation sources. Currently, the installation cost is high and should take into account the intermittent generation units, e.g., wind turbines and photovoltaic panels among others. If a distributed generation source is connected to a weak part of the system, the short circuit level can be increased, leading to voltage fluctuations and reduction in system stability.

- Development of adequate analysis and simulation models to consider the possibilities of the networks being AC, DC, hybrid, operating in a balanced or imbalanced way, in a band composed of different voltage levels.

Development of controllers tuning techniques related to equipment with power converters and control hierarchy patterns between active and reactive power.

Protection

- Bidirectional power flow interferes in the traditional method of protection adjustment. Furthermore, the microgrid can operate in islanded or grid-connected mode, requiring different protection schemes for these different operations modes.

Communication

- Communication, information, and measurement technologies are fundamental factors for the proper microgrids operation. The communication system adopted should enable fast, safe and economical two-way flow of information between consumers and electric companies and vice versa, as well as communication between different devices in the network.

Market and Economy

- Currently, renewable energy sources installation price is high. Government incentives should be created to reduce these costs.

- Regulations are needed to define the microgrid remuneration when it is operating disconnected from the main grid. As the microgrid is the only generation delivery option available in islanded mode, abusive prices can be charged if there are no fixed or limited values. Microgrid remuneration on providing ancillary services must also be regulated.

- The connection of electric vehicles on the network presents both operational and market challenges. The main reason is that vehicles can consume power(when they are charging) or generate (acting as a battery).

1.10 Conclusions

A huge reformation in the electric power system building is taking place. It points to a new agile, cheaper and rapid response structure that consider aspects such as environmental problems, deregulated markets and diverticalized operations for generation, transmission and distribution of energy. Microgrids are part of it. A microgrid is a controllable power system with local generation, consumption and energy storage. It offers a flexible way to bridge the gap between the dependence on large, centralized power systems and the efficient transition to renewable energies. Microgrids are able to accommodate quite a number of the new aspects of the renewed electric power system building (such as wind farms, photovoltaic systems, fuel cells and energy storage systems) and uses modern power electronics devices, high-voltage direct current and information and communication technology. The most interesting scenario appears when the microgrid is disconnected from the main grid, i.e. working in islanded mode. In this case, local controllers must maintain the power quality standards regarding to different parameters. In islanded mode, one or some distributed generators must act as voltage sources, in the same way that usual giant power plants connected to the grid.

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