# Chapter 8
# Current Trends and Challenges in Sustainable Generation, Transmission and Distribution of Electricity

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**Abstract** This chapter addresses the technical aspects of electricity in the whole overview of energy sustainability treated in this book. Whereas in other chapters the reader can find general aspects regarding market dynamics, energy harvesting, alternative sources of energy and policy aspects; here the Authors concentrate on discussing the new technological challenges associated with modern electrical systems. We discuss the technical challenges involved in the development of a new generation of power grids, also known as smart grids. We summarise some of the main emerging issues derived from the integration of renewable energy from the electrical engineering point of view. We also elaborate on the technical challenges in decentralised energy generation; the new scenarios in the transmission of electricity that foster developments such as high-voltage direct current systems; and issues in distribution networks with a high penetration of renewable energy.

## Abbreviations

| | |
|---|---|
| AC | Alternating Current |
| DC | Direct Current |
| DG | Distributed Generation |
| FACT | Flexible Alternating Current Technologies |
| HVDC | High Voltage Direct Current |
| ICE | Internal Combustion Engine |

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| | |
|---|---|
| IGBT | Insulated-Gate Bipolar Transistor |
| LED | Light Emitting Diode |
| MOSFET | Metal–Oxide–Semiconductor Field-Effect Transistor |
| MPPT | Maximum Power Point Tracking |
| PLL | Phase-Locked Loops |
| PMU | Phasor Measurement Units |
| PV | Photovoltaic |

## 1 Introduction

Over the last decades, the development of a new paradigm for energy generation, transmission and the distribution of electricity has become a pressing research question, and a policy issue, related also with technological and commercial themes. Issues such as the urge to reduce $CO_2$ emissions, the development of lower cost semiconductor and photovoltaic devices, the compelling advantages of renewable energy generation and the undesirable power losses in complex transmission lines, is increasingly motivating the development of distributed energy generation systems based on renewables. However, the intermittent nature of renewable energies is reflected in the characteristics of the voltages/currents (e.g. amplitude and frequency) provided by transducers, prompting regulation of such variables to satisfy the nominal requirements of the loads and the grid (Ali 2013).

Moreover, a decentralised, sustainable and reliable electrical system is an issue that is prompting technological development in all voltage levels, e.g. low voltage at residential photovoltaic generation, medium voltage at medium in distributed generation in the form e.g. of solar plants and high-voltage, e.g. in the form of largescale windfarms and high voltage direct current (HVDC) converters for transmission lines (Ali 2013). In this chapter we discuss the current shortcomings and opportunities in generation, transmission and distribution from the electrical engineering point of view. We examine the current ways as well as their limitation and promising technologies that, when mature, can overcome the current scenarios of increasing demand of sustainable energy.

## 2 Generation

Electrical energy has been generated for more than a century by means of rotational machines. Traditionally, the generation process involves energy conversion from a primary energy source such as gas, coal or wind; to a mechanical force that is finally used to rotate the shaft of an electricity generator. The electrical energy generation process is the first stage of the electrical energy supply chain and is usually carried out in power plants by commercial energy companies (Murty 2017; Von-Meier 2006).

Nowadays alternating current (AC) electricity is mostly produced using three-phase generators known as alternators or synchronous machines (Murty 2017; Stein 1979). An alternator has a three-phase winding fixed in the stator while the electromagnetic field is produced in the rotor by a direct current (DC) coil that is feed through a set of rings and brushes. When the rotor is spinning, a rotating electromagnetic field is produced, the coils in the stator cut the magnetic flux, producing an induced voltage is induced across its terminals. The induced voltage mainly depends on the magnetic field strength of the rotor windings, the number of turns of the stator coils, and the speed of the rotor.

A power plant can have several generators connected in parallel, operating simultaneously. Also, several power plants can be connected to the same power system. To make this happen, the generators must have exhibited the same voltage, frequency and phase sequence. The process to connect a generator to the electrical grid is known as synchronisation. One of the benefits of using synchronous generators in power plants is that once the generator is synchronised, it remains tied to the grid frequency and voltage since in steady state its angular electrical and mechanical velocities are equal (Murty 2017; Stein 1979).

The electric power by a power plant is generated at large scale in the order of Megawatts (MW). This type of facilities is usually located at the border of cities due to land requirements, the required resources and the contaminant emissions and waste. There are different types of power plants and their classification mainly depends on the kind of fuel that they use to produce electricity (Nasar and Trutt 1998). In the following we discuss a simplified classification.

## *2.1 Thermoelectric Power Plant*

This type of power plants is the most common. In cogeneration plants, thermal energy that remains after an underlying process, can be used for other productive processes, which allows taking advantage of the energetic resources. There exist three main classification for thermic power plants (Murty 2017; Von-Meier 2006):

- By primary energy source.
  - Fossil fuel: coal, gas.
  - Nuclear: Uranium 235, plutonium 239.
  - Biomass: sugar cane bagasse.
- By primary machine.
  - Steam turbine.
  - Gas turbine.
  - Internal combustion engine (ICE).
- By utilization purpose.
  - Base demand.

– Peak demand.
– Load tracking.

### 2.2 Hydroelectric Power Plant

This type of plants takes advantage of the potential energy of the. The water flow is used to move turbines coupled to electric generators. These power plants have much lower energy production capacity than thermoelectric plants (Ali 2013; Barton and Infield 2004).

### 2.3 Wind Power Plants

Wind power plants, usually known as wind parks or wind farms, are large land spaces in which wind turbines are installed. The turbines are based on electric machines coupled with a mechanical transmission and a set of blades, which are moved by wind. In these parks, energy is directly generated without using combustion. The location of wind parks is one of the most important issue, consequently, places with high wind resource potential offer better conditions for electricity generation (Boyle 2012; Nelson and Starcher 2015; Wengenmayr and Bührke 2012).

### 2.4 Photovoltaic Power Plant

In a photovoltaic (PV) park, sun light is converted into electric energy (direct current) by means of semiconductor devices that are clustered and interconnected in which is known as a photovoltaic panel. In a PV park, hundreds and even thousands of PV panels are connected forming different series–parallel arrays. Additional power electronics converters are required to inject the power generated by the PV arrays to the grid. As in the case of wind farms, for a good amount of electricity generation, it is required to locate the park in a good solar potential region (Boyle 2012; Wengenmayr and Bührke 2012).

### 2.5 Current Trends

Most of the electricity generated around the world is produced using thermic processes. It can be considered, that the most efficient option in this case is the combined cycle plant. In Mexico most of the electric energy is produced by combined cycle plants. This plant uses a gas turbine combined with a steam turbine, both coupled to an electric generator to produce electricity. The use of gas and steam turbines allows to increase the overall efficiency of the power plant compared to traditional thermoelectric plants. Solar and wind installations produce a significant amount of electricity without burning fuels, however these technologies are not completely mature and still require research efforts (Boyle 2012; Nelson and Starcher 2015).

As the electric energy demand increases, new technologies for electricity generation and challenges arise. Recent policies related to the environmental impact caused by burning fuels have also re-shaped the way in which part of electricity around the world is generated. That is also the case of México, where new policies have established the required increase of electric energy production by means of renewable resources.

The new trends in electricity generation includes the use of solid-state power converters to connect electric energy sources to the grid. That is the case of most of the renewable sources like photovoltaic (PV) and wind energy. In the case of PV installations, power converters accomplish two important tasks. First, they are required to exploit the maximum power capability of the solar panels; this allows operating the system with overall increased efficiency. Second, power converters are required to change the parameters of the electricity coming from the solar panels, this is because PV panels generate DC current, which requires conversion to AC to be compatible with the grid (Blaabjerg et al. 2004, 2006).

The two mentioned tasks can be implemented in two power conversion stages. The first one known as DC-DC converter is the responsible of integrating the maximum power point tracking (MPPT) capability. The second stage is known as DC to AC converter (i.e. inverter) which transforms DC to AC, and is responsible of the synchronization process and injection of electric power into the grid. In some cases, all these tasks are performed by a single DC–AC stage, this allows to reduce the operating cost and increase the efficiency of the system (Blaabjerg et al. 2004; Katiraei and Iravani 2006).

In this type of converters, the synchronisation process is carried out by algorithms, usually called phase-locked loops (PLLs). These algorithms must run continuously in order to guarantee the synchronisation between the grid and the power converter (Lawder et al. 2014). This is the reason why this type of generation, based on power converters, is called non-synchronous generation. Indeed, the development of PLLs is one of the current challenges involved in the design of grid tied power converters. The reason is that in order to be able to synchronise the generated AC voltage, the PLL is required to sample the AC grid voltage, which in some cases is polluted with harmonics or is affected by unbalances and other perturbations, which complicates the synchronisation process.

Another relevant trend is distributed generation (DG). This is the term used to designate the injection of electric power into the distribution grid, close to the consumers or load centers location. Most of the times the DG energy comes from intermittent renewable energy sources like PV installations or wind turbines, although DG also includes the energy generated by means of thermic cycles like internal combustion engines (ICE) (Blaabjerg et al. 2004, 2006; Katiraei and Iravani 2006).

In the last years, the DG has had a considerable proliferation into the distribution grids and it is expected that this tendency will keep for the next 30 years. This propagation of distributed generators obeys several factors, some of them are listed here:

- The development of new technologies related to renewable sources and power converters.
- The advent of policies related to the use of clean sources to generate electricity and the deregulation of the markets.
- The restriction to build new transmission lines or to increase the power capability of lines already built.
- The increase in the power demand and energy consumption.

There are several advantages in distributed generation. In some circumstances, the distributed generation can help to overcome some problems related to power quality and voltage profile in a distribution feeder. Furthermore, depending on the control algorithm of the power converters, DG can provide some ancillary services like reactive power support. The use of distributed generation can decrease technical loses related to transmission and distribution lines up to 30% due that the generation of electricity is near to the consumption. From the utility point of view, distributed generation could replace the investment in transmission and distribution infrastructure (towers, lines, rights of way, etc.). In this sense, the installation of distributed generation systems becomes an attractive option to decrease losses in the electrical grid. A distributed generator with optimal location could contribute to reduce loses in a range of 10–15% (Kim et al. 2013; Lawder et al. 2014; Vazquez et al. 2010).

Furthermore, DG can provide auxiliary services, helping to keep a stable and continuous operation of the grid, e.g. DG can be used to stabilise variations in the grid frequency caused by the reduction in generation capacity or increase in the power demand. However, there are also some shortcoming in DG.

In the case of México and other developing countries, the DG have not been widely spread, although new grid codes contemplate the propagation of this type of electricity generation

One of the biggest challenges that DG has, is the high cost per installed kW, compared with a traditional large power plant. The price of the fuel used by some DG technologies (diesel machines, fuel cells, turbines, etc.) is also high compared to power plants. The reliability of the grid is also a concern, due that some type of distributed generators cannot be controlled from the same site that controls the rest of the grid. This can produce variability in the power delivery and additional reserve power could be necessary.

## *2.6 Energy Storage*

Energy storage installations have been recently proposed to overcome the disadvantages of distributed generation based on renewable sources like PV and wind DG.

The most commonly used energy source is the electrochemical battery which has a relatively high energy density. Battery technologies like lithium-ion have become popular for grid applications mainly due to its low failure rate, high energy density and high number of charge–discharge cycles (Barton and Infield 2004; Lawder et al. 2014; Vazquez et al. 2010).

Energy storage installations are not only able to inject active power into the grid, but also can provide reactive support in case of perturbations or failures of the grid. An in most of the DG, energy storage installations require static power converters, in this case, the converter must be able to allow bidirectional power flow to charge and discharge the batteries (Barton and Infield 2004; Byrne et al. 2018; Roberts and Sandberg 2011). Power converters control the charge of the battery bank, first transforming the AC current into DC current (rectification) and second, regulating the charging current. When the power needs to be transferred from the battery bank to the grid, a DC-AC conversion process needs to be performed by the power converter. In this scenario, the converter needs to control the active and reactive power injection into the grid accordingly with the control requirements (Barton and Infield 2004; Byrne et al. 2018; Roberts and Sandberg 2011).

## 3 Transmission

The large-scale development of a transmission network has adopted high-voltage alternate-current as the predominant mechanism for long-distance transmission of electricity. This is not a sheer coincidence, since in such large-scale projects their efficiency, practicality and costs play the main role in the selected technology (Grainger et al. 2003). Taking this into account, the most robust generation scheme involves AC synchronous generators, which besides the issue that they can be easily synchronised with the grid, they are also naturally endowed with inertia, due to the commonly large mass associated to the rotor of the machine. The latter characteristic permits to store kinetic energy that can be eventually used to account for the unbalance between generation and consumption. This inertia provides additional time for the generator to maintain a set-point of delivered power. Then its coupled turbine, commonly moved by a fossil fuel-based process, increases or decreases the mechanical torque injected to the generator compensating velocity deviations. Moreover, the AC profile of the generator permits the use of transformers, which are able to achieve high voltage levels that permit to minimize the value of RMS (Root-Mean-Squared) currents through transmission lines. This is highly desirable, since losses associated to the Joule effect are a square function of the effective (RMS) current. Consequently, losses are also minimised (Grainger et al. 2003).

Looking at their counterpart, a DC generator is also a matured technology. Moreover, DC synchronisation is not an issue as in AC, and the losses by Joule effect can be equally mitigated by using high voltages. However, DC generators are not as efficient as synchronous generators. Unfortunately, they involve extraction of power from their rotor, which requires brushes that are eventually degraded, prompting a continuous maintenance. Moreover, although even nowadays we count with several ways to boost DC voltage via power electronics converters, they are simply not as cheap, efficient and reliable as an AC transformer (Grainger et al. 2003).

Consequently, their AC profile, inertia and the natural synchronisation of synchronous generators made them a compelling option for the development of a tailored transmission network, which took place in the twentieth century. This is considered as a major achievement in technology which permitted the development of industry and residential energy supply in every country around the world. The world-wide adopted configuration of the transmission network has been so successful that it is easy to fall into the delusion that there are no new challenges in electricity, rather than changing fossil fuel-based generation by renewables, using the same robust infrastructure. However, this is not the case at all. The challenges associated to the transmission of electricity are a major pressing issue nowadays.

For instance, in most of the countries, the electrical infrastructure installed during the twentieth century requires a major upgrade, maintenance and even replacement. This is a major issue considering that the demand of electricity is much greater than the one anticipated when firstly developed, which also results in congestion and increases the technical losses. Moreover, the location of certain energy resources prompt countries to adopt very long distance or submarine transmission lines that have a very low efficiency in AC (Grainger et al. 2003).

We can notice not only glimpses of limitations in AC transmission, but significant alerts that prompt us to look for short- and mid-term solutions. The limitations are now discussed.

### *3.1 Impedance*

Impedance is a frequency domain quantity represented by a complex number. Consequently, it is only present in AC, accounting for a more general definition of opposition to electric current than resistance—involving also inductances and capacitances. In the case of a transmission line, its equivalent electrical representation involves series inductances, due to the inherent ability of conductors to generate magnetic fields when electrical currents flow through them; while capacitances appear in shunt connection due to the potential difference between the ground and the line itself, which implies the presence of an electric field. The higher the impedance, the higher the RMS current through the cable, which increases the Joule effect losses as well. Consequently, at very long distances, the impedance increases significantly, which has a major impact in the efficiency of the line, yielding high technical losses (Grainger et al. 2003).

Another case where the impedance plays a major role is in submarine lines. These types of links are very compelling in the case of e.g. offshore wind farms or due to other geographical reasons as in some peninsular areas. Notice for instance the case of the states of Baja California and Baja California Sur, where a submarine line would enable a suitable interconnection of those states to the Mexican electric system via

Sinaloa. However, though compelling, in the case of an AC link, a submarine cable involves a much higher capacitance than in conventional aerial lines.

## 3.2 Stability

Another important issue and limitation in AC transmission systems is the amount of power that can be transmitted between two nodes, which is strongly associated to stability. In power systems, the point-to-point transmission in watts, from a node 1 to a node 2, is given by the well-known equation (Grainger et al. 2003):

$$P_{1\to 2} := \frac{V_1 V_2 \sin\delta}{X},$$

where $V_1$ and $V_2$ are the voltage magnitude at nodes 1 and 2, respectively; $X$ is the reactance of the transmission line, i.e. the imaginary part of the impedance; and $\delta$ is the phase difference between the voltages of nodes 1 and 2.

This equation has a stability regime that is surpassed when the angle difference between the emitter and receiver points reaches 90°. In words, an unstable regime implies a change of sign in the formula which leads to an equivalent positive feedback for the receiver, then deviations, e.g. in frequency, are amplified instead of being mitigated. For this reason, the transmission of power is usually operated in a much more conservative point, e.g. 60°. This issue undermines the possibility to satisfy the increasing power demand in certain areas where the transmission lines are “congested”, i.e. operating close to the 60° limit.

## 3.3 Asynchronous Interconnection

As previously discussed, an AC power system requires synchronisation, i.e. a uniform frequency for all the interconnected generators. However, in many cases it might be of interest to interconnect systems with different frequencies. For example, interconnection among countries. However, it is simply unfeasible to require synchronisation of the whole electric system of different countries to be able to share electricity, since now the dependence when taking decisions and risk of stability issues, will be completely shared.

This situation does not permit to develop a wholesale electricity market that could take advantage e.g. of time differences. For instance, notice that in the case of Mexico and USA, the peak hours of the major cities do not coincide, since their time is shifted due to geographical reasons. Consequently, the price of electricity varies considerably, which may permit a more competitive price at peak hours that could benefit both countries.

### 3.4 Asynchronous Generation

A paradigm shift from fossil-fuel to renewable energy generation is not an easy task. As previously discussed, renewable energy generation is in general asynchronous and requires power converters as an interface with the grid. Moreover, renewables are not endowed with the natural inertia of synchronous generators, which prompts the operation of the utility to act in a much faster way to deal with generation and consumption imbalances.

### 3.5 Solution Scenarios

A plausible solution to the limitations of AC lines in modern scenarios of increasing demand and pressing need of integration of renewable energy, is the combination of AC and DC systems. For instance, while AC presents several shortcomings, it is undeniable that the best way to step-up voltages for transmission purposes is via transformers. At this point it does not matter that this is a passive component that in the future could be replaced by an electronic counterpart, but nowadays, it is the most mature, cheap and efficient way to yield and interface between generation and transmission systems. On the other hand, power converters in the form of rectifiers and inverters could serve as yet another interface to transmit power in DC at long distances. This is the case of LCC (line commutated converters), which are based on mercury-arc valves of thyristors. Other modern power electronics interfaces between AC and DC at high voltage levels (HVDC) involve back-to-back IGBT-based (Insulated-gate bipolar transistor) converters, which permit to achieve an AC to DC conversion, then transmit electricity through a long-distance DC-line and transform back from DC to AC at the other end of the line. There are some operating interconnections of this type of HVDC converters in the world, though the most predominant is still the LCC configuration, due to the costs and reliability of IGBT-based stations. The latter are promising technologies since they permit major flexibility and control on the grid, e.g. voltage regulation and they permit to revert the power flow at any time. Installation of HVDC lines also conjugates well with renewables, since they are usually located in remote places and require rapid evacuation due to their intermittency.

## 4 Distribution

By the end of nineteenth century the first power plant installations appeared. Before that, electricity was generated in situ where it was needed to avoid the complex infrastructure required to take the electric energy from one place to another. Power systems have been there for more than a century and their use increased rapidly. Today these systems are vital for the development of economies in which new electricity applications have raised additional requirements in the production, transportation and distribution of electric energy (Murty 2017; Stein 1979; Von-Meier 2006).

Distribution systems are the last part of the electrical system chain and are concerned with delivering the electricity from the distribution substation to the final users. Usually, responsibility for these grids lies with the utilities; electricity companies that must guarantee the electricity supply to all the grid users.

In México, the electricity distribution is usually carried out in two stages: medium voltage (voltages from 6 to 35 kV) and low voltage (voltages from 220 to 440 V). The medium-voltage stage takes place from the output of the substation to the pole transformers or to medium-voltage users who require high power (Nasar and Trutt 1998; Stein 1979; Wengenmayr and Bührke 2012). This circuit is often known as a distribution feeder or primary feeder. The distribution substation is the link between the transmission power system and the distribution system. The low voltage distribution stage is the circuit that is connected to the pole transformer's secondary winding. Most of the residential users are connected to the secondary distribution feeder. This electricity power supply could be in one phase (127 V) or two phases (220 V).

In general, the electricity distribution system can be divided into six parts: Subtransmission circuits; distribution substation; primary feeders; distribution transformers; secondary feeders, and, consumers services (Murty 2017; Nasar and Trutt 1998; Stein 1979; Von-Meier 2006).

Distribution substations usually service a load area, which is a subdivision of the total distribution network. In the distribution substation the main equipment are the power transformers, on-load tap changers, switch gears, and connection buses (Murty 2017; Nasar and Trutt 1998; Von-Meier 2006).

The effectiveness of distribution systems is measured in terms of the following criteria:

- Voltage regulation to avoid unwanted voltage variations, which are usually known as swells (voltage increase for several cycles), sags (voltage decrease for several cycles) and flickers (sudden voltage variation).
- Continuity of service, which implies a minimum number of interruptions in the electric supply.
- Flexibility to allow the expansion or modification of the electricity system caused by an increase in users or demand.

For a distribution system, it is important to keep the capacity close to the real load requirements, this permit having a more affective investment use. The cost of the electricity distribution is an important factor in the total electrical energy supply cost and in many cases; it is more than the 50% of the total investment cost (Nasar and Trutt 1998; Wengenmayr and Bührke 2012). One of the main challenges of electricity distribution is related to design, build, and the operation of the distribution system to provide an adequate electricity service to a load center at the minimum cost (Nasar and Trutt 1998; Wengenmayr and Bührke 2012). Due that, load centers present different topographies, load densities and users, thus for each distribution circuit a custom design is required.

The voltage level of a primary feeder is the most important parameter because it has a direct impact in the design of the distribution circuit, its cost, and operation. Some of the factors to be considered when selecting the voltage level are:

- Length of the feeder.
- Load of the feeder.
- The number of substations.
- The capacity of substations.
- Maintenance cycles that will be required.
- The physical infrastructure required (poles, wires, etc.)
- Electrical protections.
- Type of isolators.
- Energy losses.
- Policies and grid code.
- Voltage drop in the lines.

Usually, primary feeders located in low-load density areas are limited by the length and load due to the permissible voltage drop. On the other hand, in high load density areas, like industrial and commercial zones, the length of the feeder is limited by thermic restrictions. In general, for a given permissible voltage drop, the length and load are functions of the voltage level of the feeder. Distribution circuits can be classified by the type of load they serve. The load can be defined as the characteristics of energy consumption. There exist three types of loads which are discussed following.

### *4.1 Residential Loads*

They are basically for apartment buildings and houses in urban areas. These loads are low voltage-low power and in most of the cases are supplied as single or two phases. Residential loads are predominantly resistive with a very low reactive power component.

### *4.2 Commercial Loads*

Most of the times, they are located close to the centre of the cities. They are normally three phase and consume medium power. In this case, the power density is bigger than in residential loads, but it is still mostly a resistive load.

## 4.3 Industrial Loads

These loads have the biggest demand and they are usually supplied at medium voltage (or even high voltage). They have an important component of reactive power due to the large number of motors and other inductive-type loads (Nasar and Trutt 1998; Stein 1979; Von-Meier 2006). Usually, these loads have reactive compensation systems and load management due to their hourly-based tariff.

## 4.4 Location and Reliability

Distribution networks may also be classified by their geographic location.

The most common are the urban networks which have the following characteristics:

- Ease of connection to the electricity grid.
- High load density.
- Three phase distribution transformers are usually used.
- There exist single, two and three phase loads.
- There is small distance between the primary and secondary circuits.
- Necessity to coordinate the electrification networks with, phone, and water services.

Rural networks are not always economically feasible; however, they are needed for agriculture and cattle raising. Another common justification for rural electrification is the social benefit and the increase in quality of life for poor communities. The main characteristics of rural networks are:

- Low load density due to disperse users.
- Mostly single-phase loads.
- Higher cost per kW and kWh compared to urban installations.
- Wooden poles can be used.
- Additional requirements such as “right of way” need to be considered.

The last classification for distribution networks has to do with reliability. There exist three levels of reliability considering the suspension of electrical service. First level loads; any interruption of the electricity supply to these loads can have a severe impact on the health of people, industrial equipment or national security, and hospitals are at the top of the list. In the case of severe failure of the electrical network, sensitive loads need to keep energised. In second place could be the institutions related to government and the military facilities (Von-Meier 2006). Second level loads. In this group are industrial installations that can be damaged in the case of an outage. Some examples would be the textile industry or chemicals production factories. Third level loads can withstand more than half an hour without electricity without having serious consequences. This is the case for residential and commercial loads. When a contingency in the electricity network occurs and loads need to be disconnected, the first option is to disconnect the third level loads. Decisions about the substation location needs to be based on the reliability of the system and economic issues. The reliability of the distribution system is an important quality indicator and careful plans need to be made in order to ensure the availability of electrical energy (Nasar and Trutt 1998; Stein 1979; Von-Meier 2006; Wengenmayr and Bührke 2012). As the technology related to the production and consumption of electrical energy has increased, important challenges related to the analysis, planning and operation of distribution networks have arisen. We can separate the challenges related to the distribution grid into two main categories.

- The first one has to do with new ways of electricity generation on a small scale.
- The second one is related to new types of loads that are connected in distribution circuits.

## *4.5 Distributed Generation and Its Impact in the Grid*

Distributed generation is referred to as the introduction of electrical power into the distribution network. In this type of electricity generation, the energy is introduced by the users, in locations close to the load centres (Boyle 2012; Nelson and Starcher 2015). Most of the time, this energy comes from renewable resources, such as photovoltaic energy and wind energy, although diesel generators can be also considered among others. Additionally, it is also possible to insert power from energy storage systems, such as battery banks. In recent years, the installation of small rooftop PV sources has increased as an alternative way of obtaining an electricity supply (Blaabjerg et al. 2004, 2006; Nelson and Starcher 2015). Here we list some of the issues related to distributed generation. **Bidirectional power flow**.

As mentioned before, traditional distribution grids were designed thinking of power delivery from the substation to different type of loads. On one hand, power demand varies throughout the day having some peak hours, usually early in the morning, or at the night. On the other hand, distributed power generation based on renewable sources such as PV panels, have peak generation hours close to noon (Blaabjerg et al. 2006; Nelson and Starcher 2015). As can be seen, the peak hours of generation do not match up with the demand peak hours, and this can cause a reverse power flow back to the primary feeder and to the distribution substation if the quantity of PV installed capacity is larger than the minimum consumption of the feeder. There are two main problems related with bidirectional power flow:

Distribution power protection is not prepared for bidirectional power flow; this can cause false trips and problems with the protection coordination and short circuit current computation (Blaabjerg et al. 2004, 2006; Boyle 2012; Nelson and Starcher 2015). Feeder voltage profile could be affected and maximum voltage level can be exceeded. This can damage sensitive loads connected to the grid. One plausible solution to avoid bidirectional power flow is the use of energy storage systems. This could allow storing energy in peak solar hours and release that energy in peak consumption hours. Indeed, this technique has been named as peak shaping due to its capability to re-shape the peak demand over a day (Katiraei and Iravani 2006; Kim et al. 2013).

Most of the distributed electrical energy is introduced into the grid by means of a solid-state power electronics converter. Due that, power converters are based on high frequency switching. If the current that is injected into the distribution network has some harmonic pollution it contributes to the distortion of the voltage waveform. Some new switching modulation techniques, converter topologies and filter designs have been proposed in order to reduce the harmonic content of the output current and it is expected that this will become and insignificant issue (Lawder et al. 2014).

**Anti-island**.

Low power distributed generators are not dispatchable; this means that they are not controlled by the utility. Instead, they inject as much power as they can, but this operation mode can come with some problems for the distribution network (Barton and Infield 2004; Byrne et al. 2018). For example, in the case of a fault in some part of the grid, protection will be triggered interrupting the energy supply to several parts of the circuit in order to isolate the failure. A grid island can be formed if distributed generators continue injecting power into the sectioned grid; in some cases, (high impedance faults) the distributed generators can even continue injecting current into the faulted section. This scenario is dangerous for grid operators that are fixing the fault, due to the isolated sections becoming energized, initiating a potential risk of electric shocks. Nowadays by norm, grid-tied power inverters are normally provided with an anti-islanding structure in order to avoid these hazardous situations (Barton and Infield 2004).

## *4.6 Low Inertia*

Rotating generators, such as those that are traditionally used in large power plants have a relatively high moment of inertia due to the rotating mass of the rotor. This inertia can be considered as an energy buffer that is able to respond quickly to load changing, thereby helping to keep the power system in a stable condition (Byrne et al. 2018; Roberts and Sandberg 2011). The increased use of non-rotating generators, such as those based on solid-state power converters, can have a low inertia effect on grids. This low inertia can cause stability problems that may lead to massive outages.

In order to avoid these problems, new control systems implemented in power converters could be able to emulate what is called a "virtual inertia" (Dehghani et al. 2019; Roberts and Sandberg 2011; Zhu et al. 2018). These new control techniques are even capable of emulating the behaviour of synchronous machines. This approach solves not only the inertia problem, but also the one related to synchronisation (Roberts and Sandberg 2011; Yi et al. 2019).

Another plausible solution is the use of energy storage systems to provide virtual inertia to the grid. As the real inertia (rotor) acts as a small high-power/low-energy source, in this case batteries or ultra-capacitors can be used as quick response energy buffers (Dehghani et al. 2019; Zhu et al. 2018).

## 4.7 New Loads in Distribution Systems

New technologies have come with new challenges for the grid. Users expect to have a continuous supply of energy whenever they connect to the power outlet. As the types of load have changed with time, new considerations are needed to be taken into account by the utility companies.

## 4.8 Non-linear Loads

One of those challenges is related to the increase in non-linear loads connected to distribution circuits. As a counterpart of linear loads, which are those formed by passive elements (resistive and reactive), the non-linear loads are based on electronic devices like diodes or transistors. Due to the increase of electronic type loads, which usually require DC current to work, the use of rectification circuits, whether diode or transistor-based circuits, are often required as a front-end component of several appliances.

The problem with rectifiers is that most of them demand pulsating current from the grid. This produces distorted waveforms that can be considered as a harmonic pollution for the grid. As the non-linear loads increases the pollution becomes more severe. Specific cases of this change of paradigm are light bulbs. Years ago, most of the light bulbs were of the incandescent type (predominantly a resistive load). Today, the fluorescent and LED lamps are the most common type of lighting in use. These types of lamps use rectifiers as a front-end circuit, which makes them a non-linear load. Nowadays, high power non-linear loads, such as inverter-based air conditioners, are required to incorporate what is called a power factor corrector (PFC) circuit. Such circuit regulates the current demand in order to avoid the harmonic distortion (Singh 2012).

## 4.9 Electric Vehicles

Although vehicle electrification could be a good option for reducing air pollution, the electric vehicle proliferation represents a challenging problem for electricity grids. Each electric vehicle (sedan type) consumes an average of 10 kWh daily (Clement-Nyns et al. 2010; Liu et al. 2013; Rezaee et al. 2013). This energy needs to be taken from the grid to charge the vehicle's battery. If a considerable number of vehicles were connected to the same distribution feeder, additional energy supply would be needed in order to satisfy the additional energy required (Clement-Nyns et al. 2010; Lopes et al. 2011; Pieltain-Fernandez et al. 2011; Rezaee et al. 2013). Furthermore, it would also be also necessary to considerable increase the capacity (power) of the distribution feeder. For example, if the 10 kWh needed to be supplied, in an 8-h changing period, an additional capacity of 1.3 kW per car would be needed. Faster charging will require additional installed capacity.

Most of the distribution feeders are not equipped to allocate electric vehicle chargers due to their limited capacity. The massive connection of electric vehicles to the distribution grids could cause overheating in electrical equipment such as distribution transformers and AC lines (Rezaee et al. 2013, Pieltain-Fernandez et al. 2011). Energy storage systems can be also beneficial in the case of electric car proliferation. Energy can be slowly stored into the battery bank and then released as needed to charge the vehicles (Clement-Nyns et al. 2010; Liu et al. 2013; Rezaee et al. 2013).

## 5 Power Electronics

Power electronics is an enabling technology, which was followed by the fast development of other technologies, such as renewable energy generation, and transmission and distribution improvements. This chapter covers some of the main aspects of all three main parts of the power system, generation, transmission and distribution.

### *5.1 Power Electronics in Generation Systems*

The first part of a power system is the generation sub-system, in which electrical energy is obtained from different sources, traditional and well stablished power sources such as hydro-electric generation, nuclear plants, and fossil fuel-based energy generation (based on coal, gas, or other petroleum based fuels), have new competitors based on renewable energy sources, such as wind farms, and solar power in the form of photovoltaic panels and sunlight concentrators, ocean wave energy generators and tide generators. Most of those energy sources have challenges that have been overcome thanks to power electronics converters.

### *5.2 Photovoltaic Solar Panels*

Photovoltaic PV Solar panels (after decades of research) have reached a competitive cost against the traditional electrical energy generation (Romero-Cadaval et al. 2013; Yang et al. 2017), one of the two main aspects which gave solar panels this edge was the development of more efficient solar panels by itself. The second reason is related to the power electronics field, the interconnection of the panel systems to the grid permitted by improvements in the efficiency of power electronics converters enables the development of what we now call maximum power point tracking MPPT. This principle is now used in all renewable energy systems, not only for PV panels systems.

Once the energy can be introduced into the grid, the system doesn't need to bind its energy production to their load requirements, or to their battery's state of charge. Any additional energy can be injected into the grid and used somewhere else, and this maximises the profitability of the investment. All this is driven by power electronics-based converters. Another rising renewable energy generation system is solar concentrators, but in this specific field, power electronics does not play an important role.

## 5.3 Wind Turbines

The electrical energy generated from the wind was a big surprise for its fast cost reduction compared to that of PV panels. The variable nature of the wind was a major challenge for their use in energy generation (Muller et al. 2002; Pao and Johnson 2011; Pieltain-Fernandez et al. 2011; Thresher et al. 2007), while traditional sources of energy (hydro-electric, nuclear and fossil-based) rely on synchronous machines to perform energy conversion from mechanical to electrical form.

On one side, the frequency of the voltage produced with a synchronous generator, depends on the rotor speed. And the voltage-frequency of the power system must be kept constant, at 50 or 60 Hz, depending on the regional standard. The well stablished synchronous generation technology could not be applied to the new wind-turbine energy generation systems, but after several years of research, a new standard emerged which is now the doubly feed induction generator. This generator allows a decoupling between the speed of the rotor and the frequency of the generated voltage. The speed of the wind turbine can then be chosen in order to maximise the generated power, while the frequency of the generated voltage can be adjusted to allow connection to the power grid (Muller et al. 2002; Pao and Johnson 2011; Thresher et al. 2007).

The power converter used for this purpose is composed of two three-phase inverters connected through their dc-link, which is called back to back connection. Converters operate at different frequency which allows the connection of the induction generator to the power grid.

## 5.4 Ocean Wave-Based Generators

Ocean wave can be used to generate electricity, it is a promising (non-mature) technology, and many systems are under development for this purpose (Ringwood et al. 2014), power electronics is used in the development of all propositions, but the mayor challenges of wave energy generation systems are in the mechanical engineering system, to change the kinetic movement of waves into a rotating movement to be used in electrical generators.

### *5.5 Stability Challenge Due to Renewable Energy*

The power system faces a stability challenge due the increment in renewable energy generation systems (Ackermann et al. 2015). This is caused by the fact that electrical energy cannot be stored in large quantities. Consequently, simultaneous production and consumption is difficult, since the load is unpredictable. However, energy consumption profiles change only slightly from one day to another. Hence, unpredictable loads are a small percentage of total energy consumption.

Once the consumption profile is predicted statistically, there are two kinds of traditional generators (from the dispatch point of view): (i) The first type receives a fixed generation profile for the next day, called 'dispatch'; (ii) the second kind is designated for frequency regulation, they will be ready to produce power, but they can actually produce nothing. The operation of this small percentage of the generation system designated to compensate for the small unpredictable deviations, is called frequency regulation.

Generators in charge of frequency regulation represent a small percentage of the total power capability of the system, they represent a cost, the cost of the uncertainty in the load profile, but they are required to maintain the system operation.

Renewable energies add another uncertainty to the system, they have an unpredictable generated energy, cloud can reduce the energy produced in solar panels, a reduction of the wind speed, would produce a reduction of the energy generated at wind mill farms, so now an additional uncertainty appear, not at the consumption side, but at the generation side. This unpredictable behaviour requires a backup, which can be from traditional generators, or energy stored, for example in batteries. It is important to point out that systems with a small percentage of traditional generation don't have a problem, because the uncertainty can be handled by the frequency regulation, but as long as renewable energy generation systems become more popular, this challenge may become a severe limitation (Ackermann et al. 2015).

### *5.6 The Google's Little Box Challenge*

Distributed generation is another option for the generation of electrical energy, in which final users can produce the energy on site, for example with solar panels in the case of residential users. In 2014, Google launched the little box challenge LBC (Halsted and Manjrekar 2018; Sniderman 2016; White 2016), with the intention of contributing to distributed renewable energy generation development. The challenge was to increase the power density of power electronics-based inverters (which would reduce the size of converters for a specific power rating).

The challenge was to design and build a 2-kVA inverter with a power density of at least 50 W per cubic inch having an efficiency of at least 95% (Halsted and Manjrekar 2018; Sniderman 2016; White 2016). The input voltage was defined as 450 V DC. Other specification details can be found at (Halsted and Manjrekar 2018). The winner's award was 1 million dollars. This competition reflects the humanity interest in the distributed generation based on renewable energy.

## *5.7 Power Electronics in Transmission Systems*

In a transmission sub-system, power electronics is the key technology for the high voltage direct current HVDC transmission (Litzenberger and Lips 2007; Marquardt 2018). Traditional alternating current transmission has its limits over long distances, due the parasitic inductance and capacitance of the lines, as the transmission line approaches 1,000 kms length. The DC approach overcomes these AC transmission limitations.

The main drawback of the DC transmission is the cost of the converters, an AC to DC converter is required at each extreme of the line. From this point of view the HVDC transmission field can be classified in two main ways: (i) the well-established and mature technology based on thyristors (Litzenberger and Lips 2007), on which almost all DC links and transmission lines are based, and, the emerging transistor-based technology, in this field. Development of the modular multilevel converter technology, allowed the construction of very high voltage converters (Marquardt 2018), and the topology improvement along with the development of high voltage transistors based on silicon carbide promises to bring high voltage converters not only for medium voltage or distribution systems but also for HVDC systems (Marquardt 2018).

Another important development of power electronics for the transmission system was the development of the Flexible AC Transmission Systems FACTS (Gemmell and Korytowski 2016; Reed et al. 2003), in which several topologies where proposed to control grid parameters such as the voltage in certain nodes, the impedance or the power flow in certain lines, as well as for the HVDC. Most FACTS devices are still based on the well established thyristor technology waiting for the enabling of topology improvements or the a new age of transistors.

## *5.8 Power Electronics in Distribution Systems*

The main trend for the power electronics field in the distribution system is the development of the electronic transformer (Briz et al. 2016). This aims to eliminate the grid frequency transformer and replace it with an electronic-based alternative.

Grid frequency transformers are of relatively large size and weight, but electronic transformers utilise a medium frequency transformer along with switching converters. The development of modern battery chargers for mobile phones, gives a good idea of how this principle can reduce the size and weight and also provide advanced functions such as voltage regulation and power factor correction.

Several electronic transformers have been tested; their main limitations are two.

(i) Their cost is higher than for conventional electrical transformers; and, (ii) pure electrical transformers have strict regulations to ensure their operation under contingencies; the tests electrical transformers pass include atmospheric discharges and inrush currents. Electrical transformers are able to operate at, for example, more than 10 times their voltage rating during an atmospheric discharge (for a relatively short time), or more than 10 times their current rating during an inrush current (also for a relatively short time). Those are extremes which cellphone battery chargers did not need to face, and they represent a big challenge which solid state transformers have not yet overcome. Electronic components cannot sustain this kind of stress, and the relatively short time periods for electrical transformers, represent very long time periods for transistors.

Even when an electronic transformer can be designed with a rating much larger than its nominal operation, that would increases the price to prohibitive levels. Again, the fast development of silicon carbide and gallium nitride transistors promise to overcome those challenges, in the near future.

The distribution system is experiencing a fast evolution, since distributed generation is being connected at the low voltage side of the distribution system then has generation and transmission functions. Another important challenge for the distribution system is the high penetration of electric vehicle chargers. These chargers have a high-power rating, and their installation requires the distribution system to be reinforced to ensure the system operates safely.

## *5.9 Wide-Bandgap Semiconductors*

As mentioned in a former section, the development of new transistors is a promising news for power electronics at all levels (Bindra 2015; Kaplar et al. 2017). These new transistors switch faster, can sustain a larger voltage and drain a larger amount of electrical current. For medium and high voltage rated applications, silicon carbide devices are expected to be substituted for the currently used silicon IGBTs, and for the low voltage applications, gallium nitride transistors are expected to replace of silicon based MOSFETs (Bindra 2015; Kaplar et al. 2017).

## 6 Conclusions and Recommendations

We examined the background to the development of the current means of generating, transmitting and distributing electricity. The current challenges as well as the trends that arise from the increasing demand of clean energy were also discussed. In particular, the role of power electronics in the development of solutions was argued for. We emphasised that the development of mature and low-cost technologies in power electronics will permit the transition to a sustainable way to consume electricity. It was noticed that the development of technology is a crucial step to achieving energy sustainability.

Nowadays, the electrical power systems around the world are moving towards more efficient and modern solutions that including High Voltage Direct Current (HVDC) systems, Flexible Alternating Current Technologies (FACTs), Phasor Measurement Units (PMUs), renewable energy sources, distributed generation, microgrids, and smart grids.

All these new technologies have promoted an increase in the overall efficiency of the electric energy supply chain.

In Mexico some of these technologies have started to be implemented, and some other are planned to be developed in the next years.

For instance, there already exist a regulatory framework for the distributed generation that considers the maximum allowed installed capacity. There is also a recently deployed grid code, which takes into consideration several of the new technologies that will be deployed in the future.

Mexico, now has the opportunity to become a user of several excellent technologies for generation, transmission and distribution of the electricity this will allow Mexico to have cheaper and cleaner electrical energy for its industrial, transportation and residential sectors.

Some recommendations are given as follows, Mexico should:

- Include the implementation of new generation technologies in the national development program for the electricity sector.
- Institute tax incentives schemes to promote the implementation of more efficient technologies for the electricity generation.
- Continue with the development and expansion of the national electricity system, to increase its transmission capacity in order to allow the installation of new technology generation plants.
- Start with the development of HVDC transmission lines to make feasible the transportation of huge amounts of energy over long distances. This will allow the development of more wind and solar farms in the south and north of the country, respectively.
- Promote the implementation of microgrids in buildings, commercial environments, factories and other urban centres.
- Implement information technologies related to the monitoring, control and fault detection in the electrical power system.

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