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Smart Grid

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Índex

Glossary

AC	**Alternating Current-** In alternating flow of electricity the electric charge periodically reverses in direction.
AMI	**Automatic Metering Infrastructure-** Infrastructure that allows the measurement and analysis of the energy consumption in order to communicate the results to measurement devices when that is required.
AMR	**Automatic Metering Reading-** Technology that automatically collects the energy consumption that is then transferred to a database for billing or troubleshoot analysis.
CT	**Current Transformer-** Device used to measure electric alternating currents and reduce current and voltage.
CVPP	**Commercial Virtual Power Plant-** Technical part involved in a virtual power plant.
DC	**Direct Current-** In a direct flow of electricity there is a unidirectional motion of electric charge.
DER	**Distributed Energy Resource-** Decentralized and modular energy production systems located near the consumption area with capacity of 10MW or less.
DFT	**Discrete Fourier Transform-** Function that converts the original domain of another function to the frequency domain.
DG	**Distributed Generation-** Decentralized energy production unit.
DMS	**Distribution Management System-** Set of applications designed to monitor and control the distribution grid in an efficient and reliable way.
DOE	**Department of Energy-** Department of the United States of America government designed to implement rules related to the energetic politic and handling nuclear material
DS	**Distributed Storage-** Decentralized storage units.
EMC	**Energy Management Controller-** Device that uses both prices and user preferences to control power usage at home. It can be standalone or embedded in a smart meter.
EMI	**Electro Magnetic Interface-** Operation disruption of an electronic device with affects it´s electric circuit due to the electromagnetic induction emitted by an external function.
EU 20-20-20	Set of legislation rules imposed by European Union with the objective of reach certain goals environmental and energy wise. The goals are the

	reduction of 20% in greenhouse gases emissions, 20% of renewable energy in the EU generation mix and 20% improvement in energy efficiency. All of these objectives must be accomplished until 2020.
FACTS	**Flexible AC Transmission Systems-** Set of equipment using power electronics for transmission control in alternating current.
FERC	**Federal Energy Regulatory Commission-** Independent agency design to regulate the energy transmission in the USA. Furthermore, it reviews proposes to build liquefied natural gas terminals and interstate natural gas pipelines.
GHG	**Greenhouse Gases-** Gases that absorb and emit radiation for the atmosphere in the thermic infrared zone causing greenhouse effect.
GIS	**Geographical Information System-** Computed system capable of doing the geographical data treatment.
GPS	**Global Position System-** Space-based satellite navigation system providing location and information about the weather in every climacteric conditions in every part of the globe.
HVDC	**High Voltage DC-** Technology used to increase power transmission efficiency in long distances using direct current coming from points producing this kind of current.
IED	**Intelligent Electronic Devices-** Microprocessor-based controllers of power system equipment such as circuit breakers, transformers and capacitor banks.
IRENA	**International Renewable Energy Agency-** Intergovernmental organization that supports and encourages governments to implement politics and investments in renewable energy.
LAN	**Local Area Network-** Set of computers and other devices which share the same communication line or the same wireless link.
LV	**Low Voltage-** As for MV, there are several values that can be considered but in this case it is assumed that LV are all the voltage values until 1000V.
MAS	**Multiagent System-** Computed system composed by multiple intelligent agents in an environment.
MCB	**Miniature Circuit Breaker-** Electric switches automatically operated design to protect an electric circuit from damage caused by overload or short circuits.
MG	**Microgrid-** Small scale power grid which can operate independently or in conjunction with the area´s main grid.
MS	**Microsource-** Low capacity generation units.

MV	**Medium Voltage-** For energy transmission purposes the medium voltage is associated with values ranging from 1000V to 36000V. Note that these numbers are different for various areas in the world.
NREL	**National Renewable Energy Laboratory-** It develops technologies and procedures in the renewable energy and energy efficiency areas and transfer that knowledge to surpass some issues related to these areas in the USA.
PCC	**Point of Common Coupling-** Point in the public electric grid where it is possible to connect a microgrid or another type of consumer.
PDC	**Phasor Data Concentrators-** Equipment that receives and synchronize data coming from PMUs in order to produce an aligned data current in real time.
PLC	**Power Line Communication-** Technology used to transfer data through the electric grid.
PMU	**Phasor Measurement Unit-** Device used to measure electric waves in an electric grid.
PT	**Potential Transformer-** Devices that allows lower the systems' voltage to a safe value in order to be transported to rating meters and relays.
RCD	**Residential Current Device-** Electrical wiring device that connects to a circuit if it detects that the electric current is not balanced between the electrified conductor and the neutral one.
REV	**Reforming the Energy Vision-** Initiative created by the New York state to reformulate the energetic industry through new politics and regulation to improve energy efficiency, better allocation of renewable energy and development of distributed energy resources.
RES	**Renewable Energy Sources-** Renewable energy sources are natural, with regeneration capability and inexhaustible.
RFID	**Radio Frequency Identification-** Use of electromagnetic wireless fields to transfer data to identify and track tags automatically attached to objects.
RMS	**Root Mean Square-** Statistical measurement of the magnitude of a variable quantity such as sinusoids.
RTU	**Remote Terminal Unit-** Microprocessor used to interconnect the physical world to a distributed control system.
SCADA	**Supervisionary Control and Data Acquisition-** System that operates through encoded signals in communication channels to provide control of remote equipment.

SG	**Smart Grid-** Modern electric grid using new concepts such as two way communication of energy and information to achieve certain goals like energy efficiency or reliability.
THD	**Total Harmonic Distortion-** Measurement of the harmonica distortion present in a signal and it is defined as the ration of the sum of the powers of all harmonic components to the power of the fundamental frequency.
TVPP	**Technical Virtual Power Plant-** Technical part involve in a virtual power plant.
WAMS	**Wide Area Measurement System-** Monitoring and controlling system which acquires information on several parameters to provide security and fault detection for the electric grid.
WARM	**Wireless Automatic Reading-**
WSN	**Wireless Sensor Network-** Set of autonomous sensors capable of monitor various types of parameters and conditions passing that information though all the network formed by them to a determined location where that data is studied.

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Abstract

The SG concept arises from the fact that there is an increase in global energy consumption. One of the factors delaying an energetic paradigm change worldwide is the electric grids.

Even though there is no specific definition for the SG concept there are several characteristics that describe it. Those features represent several advantages relating to reliability and efficiency. The most important one is the two way flow of energy and information between utilities and consumers. The infrastructures in standard grids and the SG can classified the same way but the second one has several components contributing for monitoring and management improvement. The SG's management system allows peak reduction, using several techniques underlining many advantages like controlling costs and emissions. Furthermore, it presents a new concept called demand response that allows consumers to play an important role in the electric systems. This factor brings benefits for utilities, consumers and the whole grid but it increases problems in security and that is why the SG relies in a good protection system. There are many schemes and components to create it.

The MG can be considered has an electric grid in small scale which can connect to the whole grid. To implement a MG it is necessary economic and technical studies. For that, software like HOMER can be used. However, the economic study can be complex because there are factors that are difficult to evaluate beyond energy selling. On top of that, there are legislation and incentive programs that should be considered. Two case studies prove that MG can be profitable. In the first study, recurring to HOMER, and a scenario with energy selling only, it was obtained a 106% reduction on production cost and 32% in emissions. The installer would have an $8 000 000 profit in the MG's lifetime. In the second case, it was considered economic services related to peak load reduction, reliability, emission reduction and power quality. The DNO had a profit of $41,386, the MG owner had $29,319 profit and the consumers had a $196,125 profit. We can conclude that the MG with SG concepts can be profitable in many cases.

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Chapter 1 - Introduction

1.1 Background and Motivations

The increase in worldwide energy consumption led to many problems such as climate change and shortage of fossil fuels. This is why governments around the world are trying to mitigate these environmental impacts encouraging the transition to a low carbon economy [1]. However, our electric grid did not change a lot since it was established many years ago, which is not appropriated if we want to materialize these objectives. This system is based on large scale utilities which produce energy to be transported in long distances where it will be consumed. The biggest issue of this scheme is related with the high dependency on fossil fuels to generate power.

The energetic sector is one of the bases of the economic growth national and global wise. This dependency of the nations on these fuels increases their importation rate which is intimately related with the international politic instability (affecting resources' prices and supply security), environmental issues and climate change. Since these factors are so relevant for economic growth they can have a great and very negative impact on people's lives. One of the solutions to attenuate the dependency on fossil fuels is the recourse to Distributed Generation (DG), mainly renewable ones. This means that the generation can be done near the consumers, instead of doing it in centralized utilities far away from them. There are already several technologies for renewable energy production which can be used depending on the region where the consumers are. All of these factors are the reasons behind the importance to change our energetic paradigm. One way to do it is to convert existing grids in smarter ones which will allow energy efficiency and a better correlation with renewable energy bringing to system operators many advantages, such as investment minimization on distribution systems, loss reduction and provision of network support services.

In recent years, thanks to several political strategies, such as the EU 20-20-20 targets until 2020 (20% reduction in EU greenhouse gas emissions, raising the share of EU energy consumption produced by renewable resources to 20% and 20% improvement in EU energy efficiency) there is an increasing level of DG sources connecting to Medium Voltage (MV) distribution networks but also to Low Voltage (LV) distribution grids. Although it is more difficult to connect DG to this one, recent developments allowed this type of connection with some restrictions. Imagining a massive integration of DG in distribution networks is difficult because there are many issues related to this connection. Voltage profiles, congestion levels, short-circuit currents and protections scheme are just some of the parameters that need to be continuously supervised. The development of Microgrid (MG) is very important to face these challenges. Developing control and operation strategies for MG is fundamental to consider the scenario of massive DG integration. A MG comprises several Microsources (MS), storage devices and controllable loads connected to the main grid or isolated. The MG concept evolved from simple LV distribution systems with DG integration. This concept not only leads to the decentralization of the power system but it brings to the consumer an active paper on the energy market. This new feature involves a restructuration of the electricity industry. The successful design and operation of a MG requires the resolution of a number of demanding technical and non-technical. This is a challenge that can be overcome by the Smart Grid (SG) concept and functionalities. It is important to study a global smart electrical system that is able to integrate MG, which is very difficult with the existing energetic paradigm because of the issues stated before.

The SG has not an accurate definition but there is a set of objectives and characteristics that a SG must have in order to get a good idea of what it is in general. There are many advantages that SG can add as an electric system and they will be presented in the chapter 2.

In this work the SG grid is divided into three major subsystems from a technical perspective. Each one of these subsystems will be characterized from a general point of view to a particular one in which it is described the different mechanisms and equipment that can be used in SG.

The methodology used is based on research of SG and microgrid surveys because there are many studies and different approaches which are available to be used in a SG environment, so the idea is to present all the possibilities for every element. Summarizing, it is possible to look at this work as a SG survey which can be used as a tool to understand how it works.

1.2 Objectives

There are several objectives that this work tries to achieve. In the first place, it is intended to give a general vision of the SG concept but also understand how it is possible to improve the existing power system to reach some objectives such as improved efficiency and better accommodation of Renewable Energy Sources (RES). Another important objective is the attempt to perceive what the relation between SG and MG concepts is. However, the main objective is to review some case studies of MG projects using SG fundaments taking into account economic optimization but also another factors such as greenhouse gas emissions. Thus, it is important to focus on RES when designing MGs. So, it is interesting to consider several architectures for a MG in order to understand what the best scenarios according to the required objectives are.

1.3 Framework

The structure of this work is based in 7 chapters starting with general concepts and finishing with precise definitions.

The first one gives an introduction to the theme and a contextualization of the problem which this research tries to solve focusing on environmental issues and the fact that the traditional electric grid is not able to correspond to the new challenges the world is facing nowadays, such as the shortage of fossil fuels and the global warming. Thus, in this chapter it is still focused the importance to change the traditional electric system, to a smarter one, taking into account new concepts such as the microgrids. For a better understanding, a general description about the current electric system is presented.

In chapter 2 a general definition of the SG is given, addressing advantages, disadvantages and a comparison with the existing power system. Even though there is no concrete definition, there are some energy organizations presenting different perspectives which are exposed here. Finally, some important characteristics that an electric grid must have to be considered a SG will be evaluated.

Chapter 3 presents all the physical infrastructures which are necessary to accomplish the objectives of a SG. This system is divided into energy, data management and communication infrastructures. All the equipment and devices of these systems are presented and described. Such as the traditional electric system the SG's energy infrastructures are composed by power generation, transmission and distribution grids. Relatively to power generation, the VPP (Virtual Power Plants) and DG are concepts focused in this chapter. In the transmission grid, the SG brings several new components. For distribution grid, it is described two ways to do it effectively. Then the microgrid and the renewable energy sources are focused as important new infrastructures.

The data management infrastructure system is the one that takes care about all the information coming from all the power generation and consumption process. The objectives of this system are set in this chapter and all the physical components are identified, starting with smart meters and finishing with PMUs (Phasor Measurement Unit).

Finally, the communication infrastructure system is explored starting with a brief definition of it and the role played in the SG. A presentation of several communication technologies is given and divided into two groups: wireless and wired technologies. Each one has several advantages, disadvantages and applications that are explored in this chapter.

The 4th chapter is about the software and the strategies of energy and information management for SG. There are four goals that should be accomplished by this system and they are all enumerated in this chapter. The first one is energy efficiency and demand profile which is achieved though consumption profile shaping and minimizing energy losses. The shaping process and several methods using demand response are explained. The other goal of this system is the minimization of the utility cost. There are several methods to accomplish it. The last objective is the emission control which is achieved basically reducing the pollutants emitted to the atmosphere. There are several approaches that can be adopted to this end and they are focused here.

The chapter 5 presents several protection issues related with SG and provides some technics to overcome them. There will be more issues related with security than in the traditional electric systems mainly due to cyber-attacks. To achieve a good protection system it is needed a dynamic approach. It is important to have several methods of failure prediction, identification, diagnosis and recovery which will be described in this section. The microgrid concept and the components such as smart meters and PMUs are crucial to a good protection system. Finally, the security and privacy of costumers will be studied since, as it was stated before, it will be easier for hackers to disrupt consumers' data. The biggest issue is related with the metering and measurement devices and that is why that equipment is focused here.

Chapter 6 is all about microgrids. First, a general definition is given, comparing AC and DC microgrids, advantages, disadvantages and the differences between VPPs and concepts such as CERTS and MICROGRIDS. The components in microgrids for the management system, communication infrastructure and protection system are presented. Then the process for a good microgrid design is explored, recurring to software that maximizes the profit for the microgrid owner and it is given a case study with several scenarios to prove it. Two case studies are presented. One of the studies shows that the microgrid design, by itself, is enough to make it profitable. The other, considers several financial aspects to improve the profit.

Finally, knowing that microgrids face several regulatory issues, some legislation and governmental incentives to overcome them and help the microgrid owner to have more profit are presented.

The last chapter gives several conclusions obtained through all the research done to do this thesis.

Chapter 2 - Smart Grid Concept

2.1 Definition

It is known that the traditional electric power grid produces electricity in power generation facilities and distribute it in a unidirectional flow to end users. This system has been subjected to many technical, economic and environmental issues in recent years because the energy consumption has increased drastically. Furthermore, the modern society has new needs in terms of energy consumption and market liberalization, but the electric grid did not manage to follow those needs. This is why it is important to move for a new or upgraded system that is more reliable and manageable, keeping the cost effectiveness, security and interoperability.

The new electric power system known as SG is a promising solution to solve these problems. Unlike the traditional grids, the SG is able to generate transmit and distribute electricity in a two-way flow of electrical power and information from facilities to consumers and vice versa.

There is not a unique definition or description for SG, but several important organizations gave it a concept [2]. For example, the U.S. Department of Energy (DOE) suggested the definition of SG as “An automated, widely distributed energy delivery network, the Smart Grid will be characterized by a two-way flow of electricity and information and will be capable of monitoring everything from power plants to customer preferences to individual appliances. It incorporates into the grid the benefits of distributed computing and communications to deliver real-time information and enable the near instantaneous balance of supply and demand at the device level”

It can be said that a SG is an upgrade of a traditional distribution network and a two-way communication network for information, sensing and monitoring on energy consumption using smart devices. A common SG has several power generation sources and consumer entities, unlike the traditional one, in which all of them are connected by a network [2].

There are some features that can help define a SG, since these characteristics exist in the majority of SG applications and are crucial to differentiate it from the traditional grid. The two-way communication allows the consumers to control their energy usage providing them with more choices. The sensors installed on the distribution grid and the use of intelligent systems enables the power station to evaluate the grid status and respond to any issue faster and more efficiently. Finally, the SG enables a better incorporation of the decentralized power generation through the use of improved communication and metering technologies which allow the consumers to take part on the energy system, with all the benefits related to that, such as diminishing losses and emissions.

There are many advantages that come from using SG. Improved reliability, increased physical, operational and cyber security resilience against terrorist attacks and natural disasters, easier reparation including remote repair and self-healing, increased information available to consumers regarding their energy use, increased energy efficiency and reduction of peak demand are just some of the benefits [3].

In order to understand how these advantages will be achieved it is needed to understand how SG works, the devices and the mechanisms it uses. In this work the SG is explored in a technical view point, so it is divided into three subsystems: infrastructure, management and protection.

Chapter 3 - Infrastructure System

3.1 Introduction

The infrastructure system involves the energy, management and communication infrastructures present in SG. In other words, this system is related with all the physical parts underlying the SG.

As stated before, SG must support two-way information and electric flows. In terms of information it is common to use this two-way flow, but in terms of electricity is different. If we look at the current electric system, the electricity is moved only in one way from the power plants to costumers. In SG it is possible for consumers to generate energy from renewable sources like wind turbines or solar panels, for instance, and put it into the grid. Furthermore, it will be possible to use electric vehicles for peak shaving.

The possibility of a backward flow of electricity requires new infrastructures and devices that are not available in the current grid.

3.2 Energy Infrastructures

The energy infrastructures are related with power generation, distribution and consumption.

In current electrical grids, the electricity is produced in large power plants. There is a spinning electrical generator that rotates using, in most cases, a steam turbine. The steam can be created by burning coal, oil, natural gas or by nuclear combustion. The power leaves the generator and goes into a transmission substation at the power plant where the voltage of the electric power is increased using large transformers. This higher voltage allows the transmission for long distances on the transmission grid. In order to be useful in private homes or factories the voltage needs to be stepped down to the distribution grids. This process takes place in a small power substation which is composed by transformers, a bus that split the distribution power off in multiple directions, circuit breakers and switches. The power leaving this substation enters the distribution grid. When the power arrives to the service location the voltage is reduced again to be used in homes and facilities [4]. In Fig 1, it is represented an example of the traditional power grid.

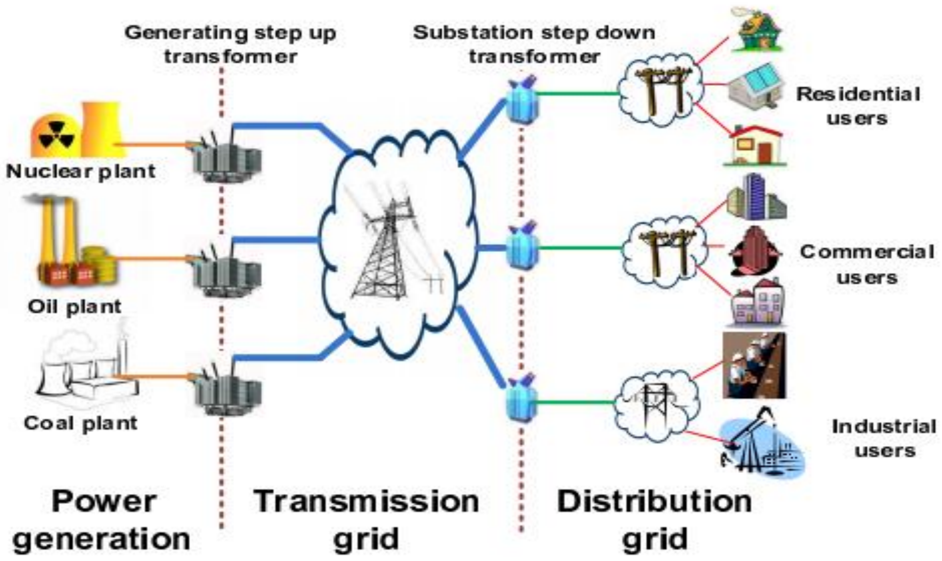

Figure 1 - Traditional Power Grid.

These are the main infrastructures used in the traditional electric grid. The SG´s infrastructures can be divided in power generation, transmission grid and distribution grid too. However the electric energy generation and the flow pattern are more flexible since it is a two-way communication.

3.2.1 Power Generation

The power generation process used nowadays comes from 1830 when Michael Faraday, a British scientist, discovered that the motion of a loop of wire or a disc of copper between the poles of a magnet can generate electricity.

Until a few years ago this process relied mostly in fossil fuels to produce electricity. However the use of renewable sources is increasing due to environmental and economic problems related with fossil fuel combustion.

In SG, there are two concepts related to power generation. First, there is DG which takes advantage of distributed energy resource (DER) systems to produce electricity. This is only possible because SG allow the two-way flow of electricity and information. The other important concept is called Virtual Power Plants (VPP) which manages a large group of distributed generators.

The DG can loosely be defined as a small-scale electricity generation. It is a set of small sized electric power generating units at or near a consumer. It is possible to say that DG is referred to power generation at the point of consumption. This fact allows cost reduction, complexity, interdependencies and inefficiencies associated with transmission and distribution.

There are different technologies that can be used for a small-scale electricity generation as shown in fig.2 [5].

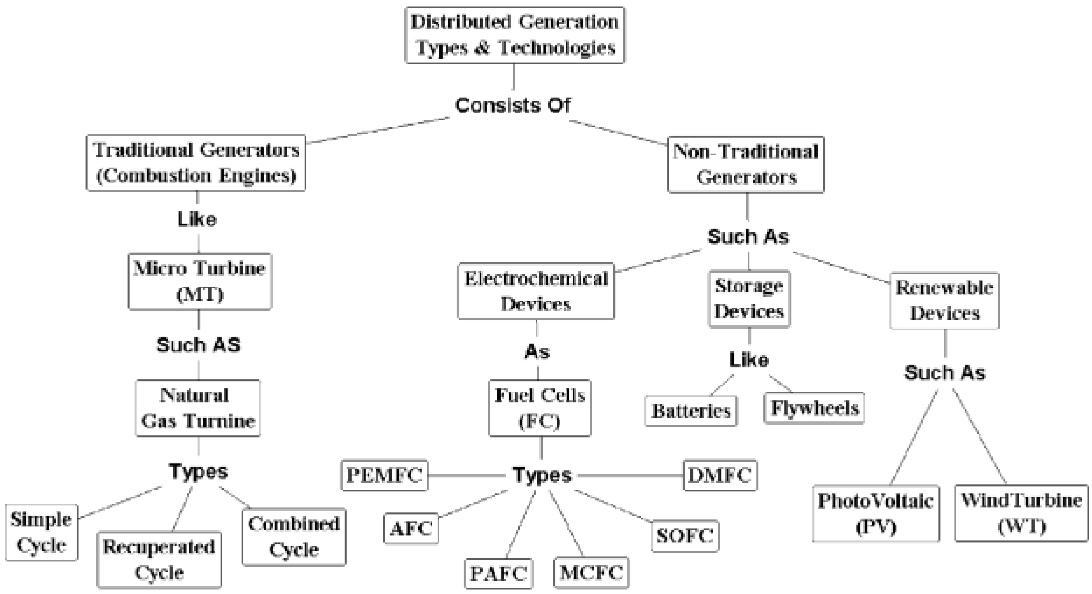

Figure 2 - Types of DG technologies.

Unfortunately with a high number of DER there are some challenges that need to be surpassed such as the intermittence of renewable sources which are weather dependent, their fluctuating output is considered non-dispatchable. Furthermore, the DER units working isolated due to different ownerships make their capability restricted to satisfy the local needs but not the whole grid.

There is a way to address these issues which is aggregate a number of generation units in a VPP. All the DG generators will be managed by the VPP that can be defined as a cluster of dispersed generator units, controllable loads and storage systems, aggregated in order to operate as a unique power plant. The VPP has an energy management system that controls the power flows coming from the generators in a two-way communication which means that the VPP not only receive the information coming from the generation systems in terms of current status, but it can also send signals to control the objects. This feature is very interesting because the VPP can operate to accomplish different objectives such as minimize the generation costs, reduce emissions or maximize the profit [6]. In fig.3, it is given an example of a VPP structure.

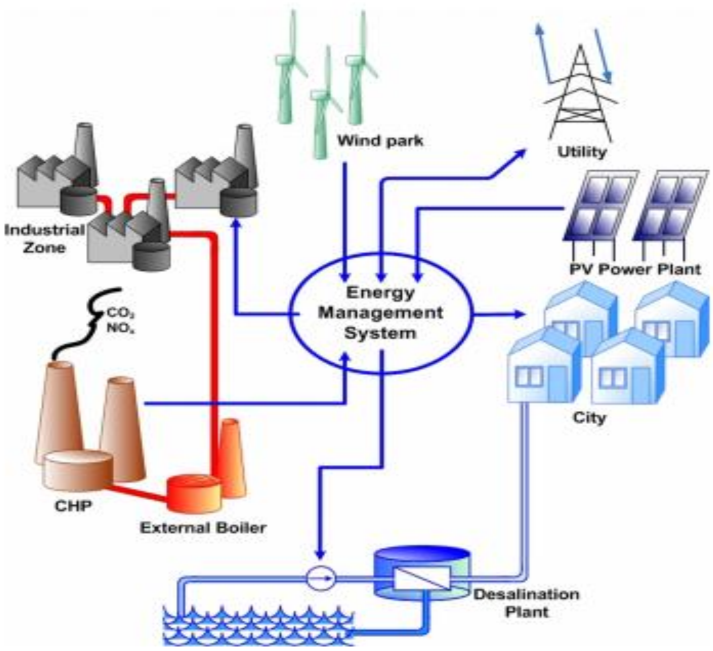

Figure 3 - VPP Structure.

It is possible to consider VPP as a way to integrate different DER into SG's framework in both technological and market/commercial terms. VPPs are classified as Technical (TVPP) and Commercial (CVPP). The TVPP ensures that the power system is operated in an optimized and secure manner, taking physical constraints and potential services offered by VPP. The CVPP considers DERs as commercial entities offering the price and amount of energy that it can deliver, optimizing the economical utilization of VPP portfolio for the open electricity market. The purpose of the CVPP is to schedule and optimize DERs utilization taking into account the energy offers and needs, while the TVPP manages the operational employment of particular DERs in technically wise [7].

The way in which the communication is done between the VPP and the DER systems will be explain next in the management and communication infrastructures sections. The objective of this section was only to provide the basic concepts and infrastructures behind the power generation in SG because it is completely different from the traditional way.

3.2.2 Transmission Grid

The electric transmission grid has evolved since it was created. It started with local low DC voltage networks to high voltage with three phases and finally interconnected networks with various levels of voltage and complex components. It is important to have these concepts in mind reading this work. It is important to implement fast online analysis tools, wide-area monitoring, measurement and control in order to satisfy the energy demand and improve the reliability of networks [8].

An electric transmission grid is the fundamental part to deliver electricity from the generation points to end consumers. In SG it has to satisfy new needs related to environment, market and infrastructures. This is why the new smart transmission grids must follow a different path from the traditional ones, which contributed largely to climate change and other issues. These objectives are accomplished with new technologies and materials.

The smart transmission grid is composed by a digital platform in order to allow a fast awareness and reliable sensing, measurement, communication, control, protection and visualization and maintenance of the entire transmission system. It must be flexible so it is possible to expand to future developments. The state of operation knowledge is important to allow a self-healing and the interoperability of the system.

The smart transmission grid is composed by three parts: control centers, transmission network and substations.

The idea behind the smart control centers is based on the existing control centers adding them new functions such as monitoring, analytic capability and controllability. The current monitoring process is done through estimators that are based in collected data via Supervisory Control and Data Acquisition (SCADA) and Remote Terminal Units (RTU) but in SG this information is collected by state measure modules which are more efficient. This equipment will be studied in detail in the information subsystem. The results from state measurement will be combined with Geographical Information Systems (GIS) for visual display on control center screens in real time.

The smart transmission networks in SG are expected to be more efficient and safe than the current ones. In SG, the transmission in long distances is done using high capacity AC and DC facilities. New transmission lines with 6 or 12 phases improve the transmission with reduced electromagnetic fields. The reliability and flexibility will be accomplished with Flexible AC Transmission Systems (FACTS) and High Voltage DC (HVDC) devices. These technologies relieve transmission congestions. HVDC are widely used lines to provide a controllable and economic alternative to long distance AC lines. Finally, the smart transmission network is composed by solid-state components such as transformers, circuit breakers and other devices that offer better reliability and life span.

The smart substations must provide monitoring, operation, control, protection and maintenance on the equipment installed there. From an operation viewpoint these substations must digitalize all the tasks. The operator should be autonomous but coordinated with other substations. The traditional electromechanical Current Transformer (CT) and Potential Transformer (PT) will be replaced by optical CT and PT which allow wide bandwidth, high accuracy of measurement and low maintenance costs. Each substation has its own Local Area Network (LAN) and a communication network via router to connect all the substations [8].

The smart transmission grid can be seen in fig.4. In this figure it is possible to see how it is correlated with the other infrastructures in the SG.

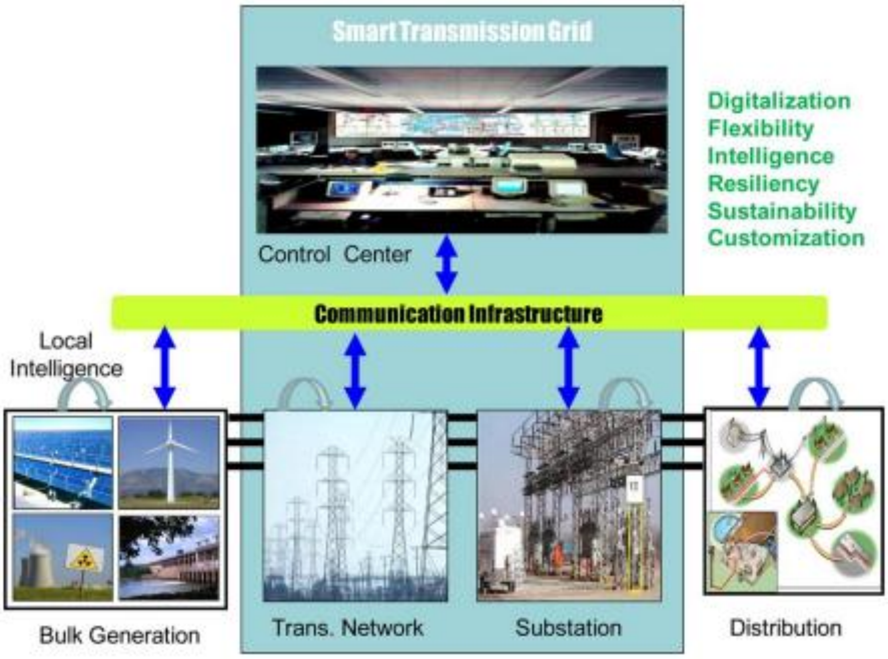

Figure 4 - Smart transmission grid topology.

3.2.3 Distribution Grid

As it was stated before the power generation in SG will be distributed using many renewable sources. This means that the households won't be just consumers but producers too. This fact comes with many benefits but it has a problem related with the balance between what is produced and demand which requires regulated renewable energy production. To solve this, it will be used in-home distribution systems that allow reduction on energy consumption and balancing production with demand, in every home [9]. There are two systems that can be used in SGs.

The first one is a circuit switching system based on AC power distribution. The goal of this system is to concurrently deliver electricity via single power distribution network in-home when renewable sources are installed in addition to commercial power. It is known that the quality of the energy produced by renewable sources is worse than the one that is commercialized nowadays, this is why batteries are coupled to this distributed systems, to compensate the fluctuation. On top of that, it is necessary to use convertors and invertors to match the quality of the commercial power. However, there are some devices with incorporated batteries that do not require high quality energy, so it is acceptable to directly connect a load to a source depending on what is necessary. To accomplish this source-and-load matching, quality and the amount of generated power must be known. To overcome this obstacle, it will be used Power Line Communication (PLC). The system is composed by two components: an information terminal and an AC power router. Each one of these components has a PLC modem and a microprocessor (CPU) with a Linux operating system. The information terminal gathers all the information from sources and loads. The CPU decides what the best source for a certain load is and transfers it to the router [10].

There is another distribution system that can solve the problems stated above. It is a packet dispatching in DC distribution system that uses power packets, represented in fig 5, through transmission IP-based Networks.

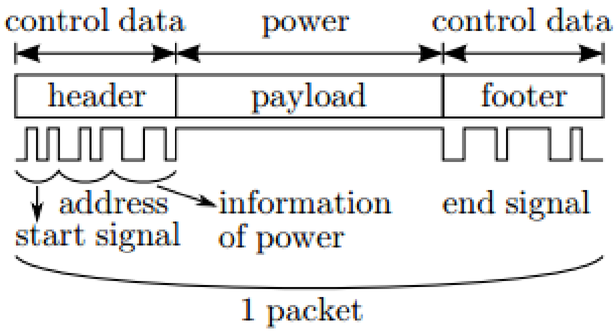

Figure 5 - Power packet representation.

Power packet representation.This system is composed by multiple sources and loads, each one with an individual address, a mixer, a router and a single distribution line connecting the mixer and the router, as it is possible to see in fig 6. Supplied power from sources is divided into several units of payload that are attached with a header and a footer forming a power packet. The header is composed by a start signal that marks the beginning of the packet, the load and the sender addresses. The footer has the end signal. The amount of energy per packet is regulated switching the length of the payload. A power request to a certain address is given when the payload is empty. The function of the mixer is to gather the payloads and send them to the distribution line, the router receives the packets the controller sorts them according to the addresses on headers and sends them to loads [10].

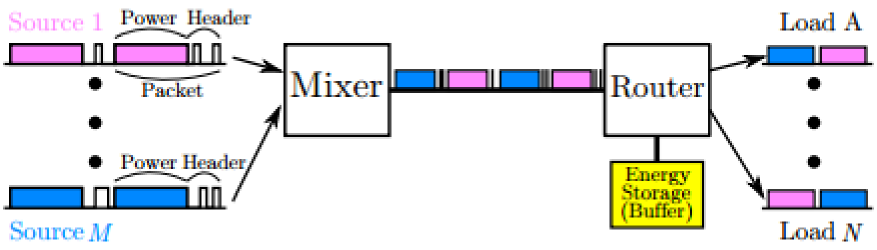

Figure 6 - Packet Dispatching System.

3.2.4 Microgrid

One of the cornerstones of the SG is the new paradigm called microgrid which development is promoted by DG. A microgrid is a group of electricity generation, energy storage and loads that is connected to a traditional centralized grid (macrogrid).

A microgrid can be a part of an intelligent global electric power and defined as an extension to the distribution grid, being located downstream of the distribution substation and formed by DER, different type of electricity and/or heat consumers. The DER units on the microgrid englobe DG and DS (Distributed Storage) which have different characteristics and capacities depending on loads and energy usage on that system. DER units are divided into two groups depending on their interaction with the microgrid. Thus, they can be connected through rotating machines or through electronic converters to provide a connecting media with the system. Control and operation strategies of the two groups of DG and DS are completely different from each other. For this reason, control strategies and dynamic behavior of a microgrid is very different from the conventional power system, especially in islanded mode. Furthermore, control strategies and energy management are dependent on the type of DER, load requirements and operation scenarios expected, in contrast with pre-defined and well stablished strategies in grid-connected mode [11]. Figure 7 shows the components and a general architecture of a microgrid.

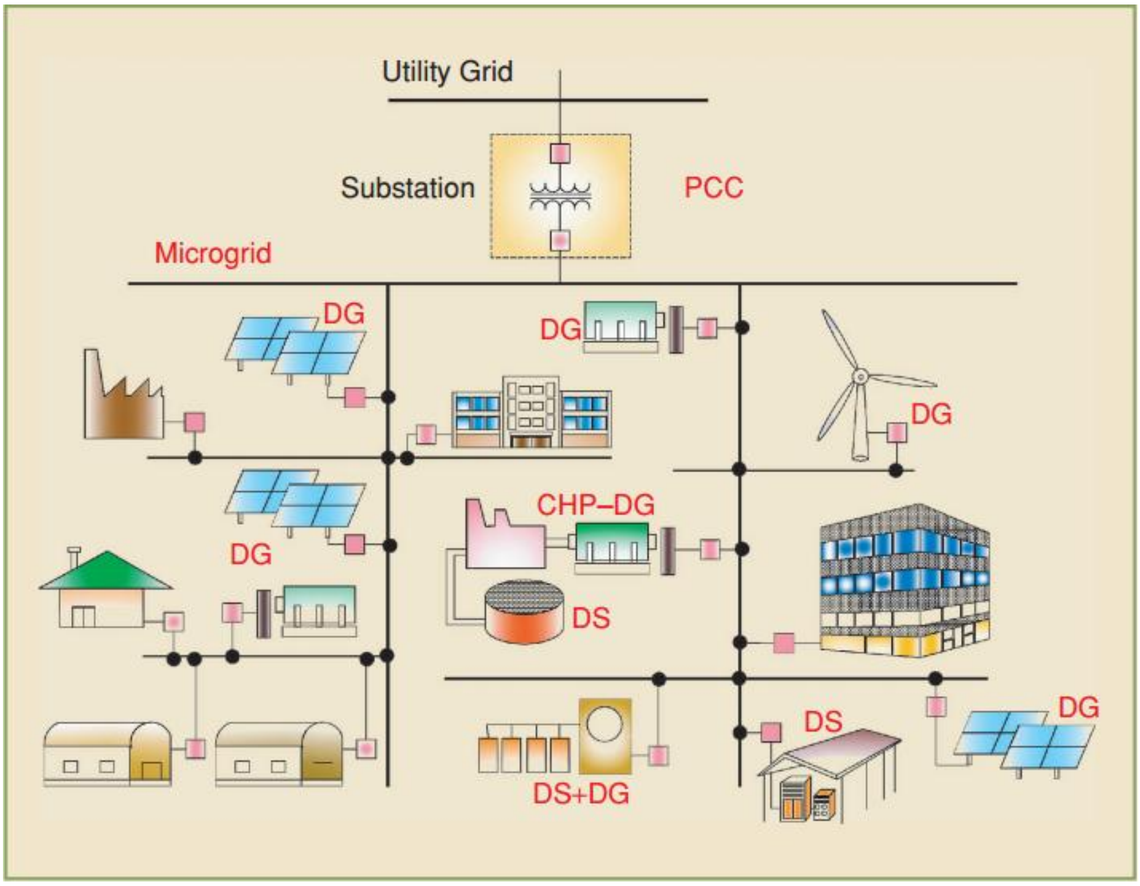

Figure 7 - Microgrid Architecture.

3.2.5 Renewable Energy Sources

The International Renewable Energy Agency (IRENA) launched a roadmap for renewable energy, in 2012. The objective was to double renewable share in global energetic mix until 2030, going from 20% to 40% in that period of time.

In developed countries, the best way to increase the renewable share is to transform the electric sector through updates and modern extensions. That modernization is technically possible and must provide new solutions to accommodate different types of renewable generation. In particular, SG is capable of incorporate characteristics of this type of generation, such as, variability, DG and high initial cost. As it is known, some renewable depend on external conditions, such as weather, to produce electricity. However, production must always meet demand and that is why it is necessary that the system absorb this variability. Furthermore, renewable generation has a high investment cost than other generation technologies. Although renewables are cost-effective in some situations, particularly in developing countries, there is not enough investment in them.

The SG can address these three challenges and offer additional benefits facilitating the transition to renewables. In this section, it will be seen how it can be accomplished.

Starting with variability, SG can integrate renewables with a great variability of resources. For example, imagining a PV system and a set of industrial and commercial users on an interruptible rate, all tied together with SG communication and control technics. If the PV system drops due to a cloud, the SG stops the service to those consumers in the interruptible rate, because this is a rate in which service can be interrupted without penalty. When the cloud passes, the service resumes.

Relatively to DG, the advantages of SG were already exposed in this work, so it is already know that SG can help developing this type of generation.

Finally, SG is able to address capital requirements encouraging private investment in DGs. Traditionally, electric utilities are the ones with the responsibility to invest in power plants to produce electricity but with the increase of DGs any person or organization can invest in energy generation systems. SG allows this, enabling utilities to manage and incorporate many small and/or individual plants in the electric system. In a more radical vision, in which the SG is compared to the Internet, where governments had the responsibility to provide the grid, nowadays, the private sector is the one providing that service [12]. In this vision, the generation almost all distributed, the consumers could be able to make direct market, bilateral deals with producers and the utility paper is relegated to distribution only.

3.3 Data Management Infrastructures

The SG not only relies on advanced generation equipment but also in the improvement of sophisticated monitoring, analysis, optimization and control from the generators location to the transmission and distribution grids. Some aspects such as interoperability of data exchanges should be addressed from a management technology perspective. The data management system is used to support generation, modelling, integration, analysis and optimization in the context of the SG.

In this section, this system will be demonstrated such as the infrastructures and devices which generate information from each entity in a SG. This equipment can be classified as information metering and measurement. The information provided by the previous devices is very important and is used for many purposes that will allow a better operation of the whole SG.

Finally, it will be explored the data management infrastructures that allow data modelling, information analysis, integration and optimization of the gathered information.

3.3.1 Metering and Measurement

The smart metering is a mechanism that must be used in SG to control behaviour and obtain information form users' devices and appliances. An advanced metering infrastructure (AMI) system is regarded as a logical strategy to realize SG. This system is built upon automatic metering reading (AMR) which is the technology of automatically collecting diagnostic, consumption and status data form energy metering devices and transferring that to a central database for billing, troubleshooting and analysing. As it goes for every component in SG, AMI differs from traditional AMR because it enables two-way communications with the meter. This meter can provide information in real time and on demand allowing system operations and customer power demand management.

The equipment that will allow the smart metering is the smart meter which is an electronic device capable of providing consumers, suppliers, distribution network operators, generators and regulators a wide range of useful information allowing new energetic services and contracts.

Traditionally, the energy consumption in households is measured by electromagnetic devices called Ferraris meters. Basically, these meters are composed by an aluminium disk that spins in a magnetic field with velocity proportional to consumption. Even though, Ferraris meters are robust, reliable and cheap they require human intervention to collect, communicate and store the information. Furthermore, it is not possible to gather detailed information such as the energy consumption in a certain hour in a specific day. Finally, these meters are not able to register electricity interruptions or deviations in nominal voltage and do not allow acting upon consumption.

The smart meters are more accurate than the electromagnetic ones, have low energy consumption and can be combined with digital displays and electronic local storage units that provide a better knowledge to users about their consumption. With these meters it is easier to monitor different variables like reactive power or power factor. These variables can be used to improve consumers' behaviours, redefine tariffs and define new incentives/penalties. The benefit of smart meters reaches everyone from consumers to suppliers. The consumers will be able to manage their consumption, save money and get a better quality of service. The suppliers will have more pricing options, less complains on billing and a better management on their portfolio. The distribution network operators will be able to quickly identify fault locations, faster restore and an improved detection of network losses and theft. There are still benefits to the public interest such as energy efficiency, increased penetration of renewable energy and improved security of supply [13].

3.3.2 Monitoring and Measurement

Another important function in SG vision is the monitoring and measurement of grid status. The most important equipment is the sensors and phasor measurement units (PMU).

Sensor or sensor networks have been used as an approach to monitoring and measurement in different applications, in order to detect mechanical failures in power grids such as conductor failures, tower collapses, hot spots and extreme mechanical conditions. Wireless Sensor Networks (WSN), in particular, due to its lower cost is able to provide feasible and cost-effective communication and sensing platforms to remote monitoring and diagnostic [14].

In traditional electric systems, plant evaluation is realized through wired systems formed by communication cables and sensors. This architecture is expensive to install and maintain since cables are even more expensive than the sensors. So, it is logic, that a way to lower these monitoring system costs is to eliminate communication cables adopting a wireless structure for this purpose. However, before WSN appear in recent years, these systems were very expensive. The deployment of wireless communications allowed a large scale integration of multifunctional sensors and actuators, which resulted in WSNs deployment. WSNs characteristics, including a sensor-rich environment, high reliability, self-organization and inherent intelligent capability make them ideal structures to a low cost management to achieve a better planning decision. In these systems, wireless multifunctional sensor nodes are installed in critical equipment of SG, which monitors critical parameters to each equipment conditions [15]. Potential applications of WSN in SG vary from Wireless Automatic Reading (WARM) to remote system monitoring and equipment fault diagnosis.

WARM systems offer many advantages to electric companies, including, reduced operation costs associated with the fact that there is no need for human presence on reading and pricing or for asset protection through advanced remote monitoring [16].

In the current electric system, safety and reliability are considered the most important characteristics once system breakdowns caused by different factors, such as, component failures, environmental aspects or bad operation can cause huge economic losses and public concern. It is known that these system breakdowns can be, relatively easy to avoid or at least be alleviated if the components and protection devices were better monitored and coordinated which does not occur nowadays. This happens because existing solutions are very expensive to be applied in large scale. For this reason, WSNs being considered a cheaper offer can be a good solution to this problem. The efficient equipment monitoring in SG, through sensor nodes provide complete information on component conditions, like generation units, transformers, transmission lines and motors in a remote manner. Using an online monitoring system it will be possible to detect and isolate a system contingency and avoid cascading effects.

There are some technical challenges imposed by SG applications that WSNs must overcome. In any electric system, there are harsh environment conditions, such as highly caustic or corrosive conditions, high humidity levels, vibrations or dirt and dust, making sensor nodes to malfunction or produce obsolete information. Another challenge is related with reliability and latency requirements because there are a wide variety of applications in SG having different specifications in terms of reliability, latency and network throughput. Finally, there are resource constraints, since the design and implementation of WSNs are constrained by three types of resources which are energy, memory and processing. In general, sensor nodes have limited battery energy supply. This is why communication protocols for WSNs are mainly tailored to provide high energy efficiency [17].

Blackout occurrence in the majority of electric systems originated the deployment of PMUs and Phasor Data Concentrators (PDCs) in a hierarchical structure. Data provided by PMU is accurate and allow a complete analysis to realize the event that cause blackout, help analysing sequence of events to determine their exact causes and malfunctions present in the system. This is the main application of these devices, nowadays, but with the deployment of Wide Area Measurement System (WAMS), new applications have been discovered, highlighting system monitoring, protection and control [18].

Traditional monitoring systems rely on RTUs and state estimators in SCADA system. RTUs measure voltage and current Route Mean Square (RMS) values of the bus where it is connected. Measured values are sent to state estimators in the Main Control Center (MCC) so that the phase angle and power flow values get computed. However, these state estimators are slow which cause delay to occur during calculations. Furthermore, state estimators are vulnerable to several errors thanks to weal modelling of traditional power electric systems. For these reasons, it is important for SG to have an improved monitoring system. For that, PMUs must be used. These devices, when placed on buses measure voltage phasor values (magnitude and angle). Yet, it is possible to know currents flowing through all branches connected to that bus. Measured values are then sent to a GPS which allows the synchronization of the measured electric quantities in every PMUs connected in the power grid. Since the voltage and current phase angles are directly measure in all buses it is possible to get a better state estimation using PMUs [19].

A phasor is a complex number that represents magnitude and phase angle of an alternative quantity which, in this case, it is sinusoidal waveform representing electricity. The phasor module is the peak or RMS value of the waveform. The sinusoidal waveform and the respective phasor are represented in fig.8.

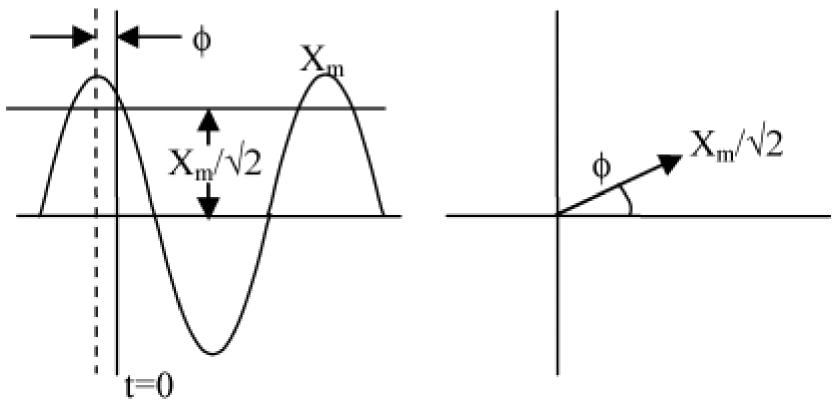

Figure 8 - Simple sinusoidal waveform and its phasor representation.

PMU is a digital device capable of measure voltage and current phasor values with respect to a global time reference. Function diagram of PMUs can be seen in fig 9.

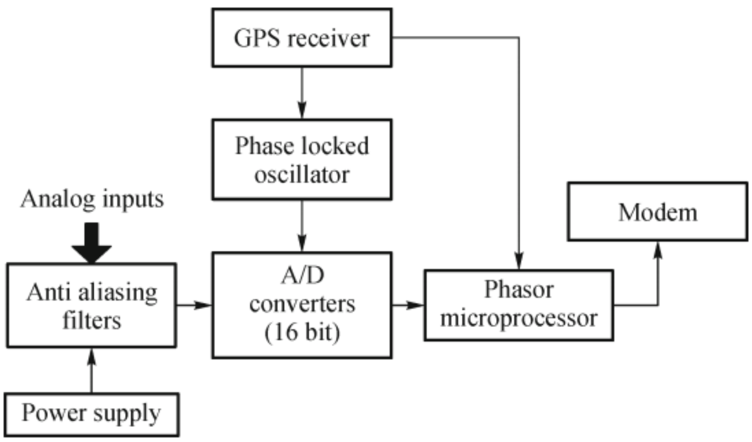

Figure 9 - Function block diagram of PMU.

The analog signals inputs from transformers enter directly in the anti-aliasing filters without using any kind of interface. Anti-aliasing filters restrict the signal bandwidth in order to satisfy the sampling theorem. The output signal coming from the anti-aliasing filters are converted to digital values using analog to digital converters (A/D converters). Phase locked loop assure that sample synchronization with the reference signal of GPS. Converted signals are, then, fed in the phasor microprocessor where the phasor values are estimated using Discrete Fourier Transform (DFT). These computed phasor values are incorporated in a current message and sent via communication network to the WAMS. The synchronization provided by GPS signals assure that the measurements of all PMUs are done at the same time.

PMUs allow SG to have a more efficient and accurate monitoring system operation. The measurements from these devices allow an easier and faster power value calculation than in the traditional electric system based on state estimators. In fig. 10, it is possible to verify the link between GPS, smart meters, DGs and control centers to form a metering and measurement structure. In this case, there are four buses but it is only needed two buses for a complete monitoring of the system [19].

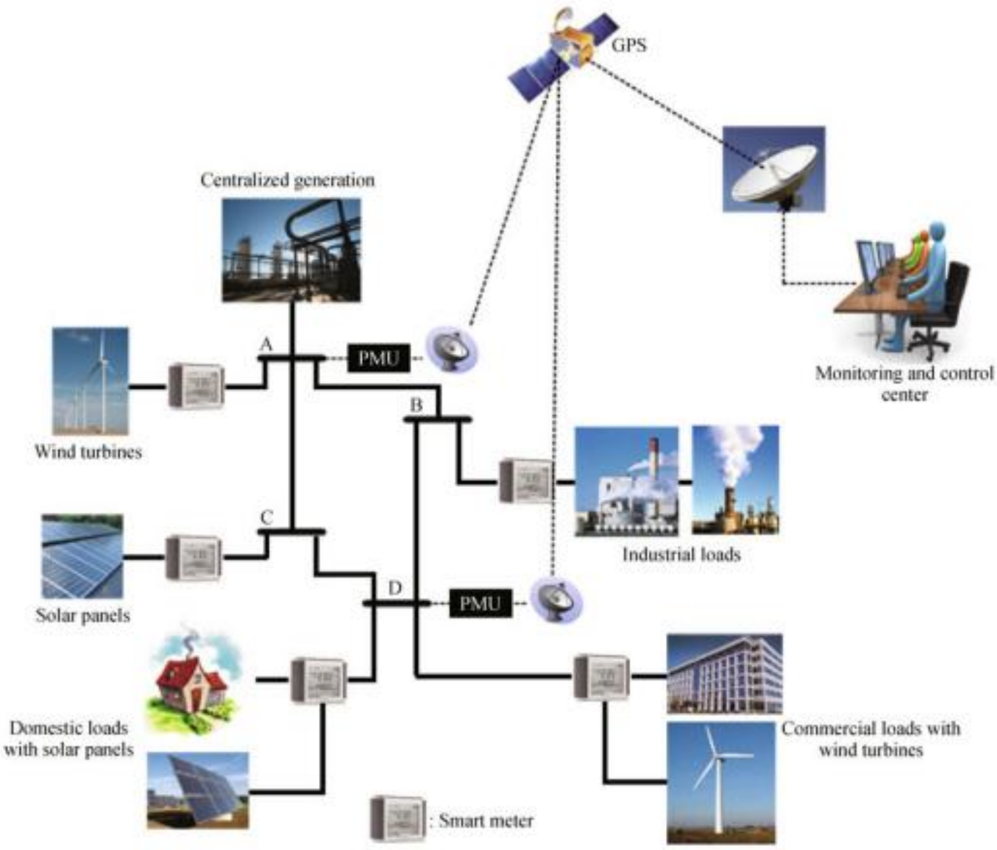

Figure 10 - Example of a four bus SG representation.

In order to find this optimal placing of the PMUs which objective is to find the minimum number of these devices to monitor the entire grid, it can be used the Integer Linear Programming (ILP). This mathematical optimization method allows having an optimal outcome for a given mathematical function subjected to some restrictions. The goal of placing PMUs is that every bus gets reached by at least a PMU. For this placing to be done efficiently it is necessary to have a communication system in each bus to transfer data from PMUs [19].

3.4 Communication Infrastructures

In previous sections it was already explored some of the infrastructures and equipment that will be used in SG. Now, the focus is the communication infrastructures which are responsible for the connectivity between all the systems, devices and applications that were identified before.

The communication system is a key component of the SG infrastructure. There is a huge amount of data from different applications that will be generated and it is necessary to analyse and control it because of the integration of advanced technologies and applications to achieve a smarter electric grid. This means that is crucial to define the communication requirements and find out the best communication infrastructure to realise all the SG´s objectives since there are various technologies that can be used.

There are some requirements that a communication infrastructure need to follow. As it was stated before, energy generation, transmission and distribution requires two-way communication, inter-operability between advanced applications and end-to-end reliable and secure communication with low-latencies and sufficient bandwidth. Moreover, this system must be secure in terms of cyber-attacks and system operability. Finally, the communication system must be scalable. This means that the system must be able to easily accept the new smart meters, smart sensor nodes, smart data collectors and renewable energy resources joining the communication network.

The communication technologies are divided into two groups: wireless and wired. Some of these technologies will be described in this section but before that, it is important to establish objectives and requirements that they must follow to be considered applicable in SG. These requirements are important since there is a great debate related with the specific technology that must be used in each SG application domain. However, there is a general agreement on the need for a communication network capable of supporting a two-way information flow between the different entities in the electric grid. Furthermore, there are some requirements that are consensual and should be taking into account for communication systems used in SG. The most important one is the quality of the service because there is critical data that must be delivered promptly. The system must be highly reliable, but since there are a great number of devices connected, this task is hard. Moreover, the system must be pervasively available and have a high coverage so it will be able to respond an event anywhere in the grid, in time. Finally, it should guarantee the security and privacy, factors that will be studied ahead [20].

With these requirements in mind, it is now possible to describe some of the communication technologies and infrastructures which are applicable in SG.

3.4.1 Wireless Technologies

Wireless technologies are present on our quotidian. Some of them are already used for electric system automation.

These communication technologies offer a great number of advantages over the wired ones. Some of them are the lower initial installation cost, rapid deployment and mobility which make these technologies more suitable for remote application. However, these technologies are more susceptible to Electro Magnetic Interference (EMI), offer limitations in bandwidth capacity and maximum distances among communication devices and there is the possibility to occur eavesdropping which can threaten communication security since radio waves in wireless communication spread through the air.

There are two ways to explore this kind of technology. The first one is using an existing communication infrastructure of a public network. The other is to install private wireless networks.

In this section, it will be explored the most important wireless communication technologies, their advantages and disadvantages, their architecture and their possible applications.

- **Wireless Mesh Network (WMN)**

A wireless mesh network is one of the most important technologies since it has many advantages over the other wireless networks.

WMNs are composed by two types of nodes: mesh routers and mesh clients. As any conventional router, mesh routers have gateway/bridge capability, but they have other characteristics essentials to support mesh networking. Through multi-hop communication it is possible to achieve the same coverage with a mesh router with low transmission power. Furthermore, a mesh router is equipped with multiple wireless interfaces which improve the flexibility of mesh networking. Despite these differences the hardware used in mesh routers and conventional ones is similar. All these advantages bring benefits to WMNs such as low up-front cost, easy maintenance, robustness, reliability and better service coverage.

There are different architectures that can be adopted to realize WMN. Here, it will be explored the one with more advantages which is called hybrid WMN and is shown in fig 11. The mesh clients can access the network through mesh routers as well as directly meshing with other mesh clients. While the infrastructure composed by mesh routers provides connectivity with other networks like Internet, Wi-Fi, WiMax, cellular and sensor networks, the routing capability of mesh clients provides higher connectivity and coverage in WMN. The infrastructure can be built using different types of radio technologies. The mesh routers forming this infrastructure are auto-configurable and self-healable. The gateway functions of mesh routers allow this network to be connected to the Internet. The bridge function permits the WMN integration with existing wireless networks. The conventional mesh clients can connect to mesh routers via Ethernet links. The ones which have their own mesh routes can connect directly to the infrastructure and communicate with it. If different radio technologies are used, the mesh clients must communicate with their base stations which have Ethernet connection with mesh routers [21].

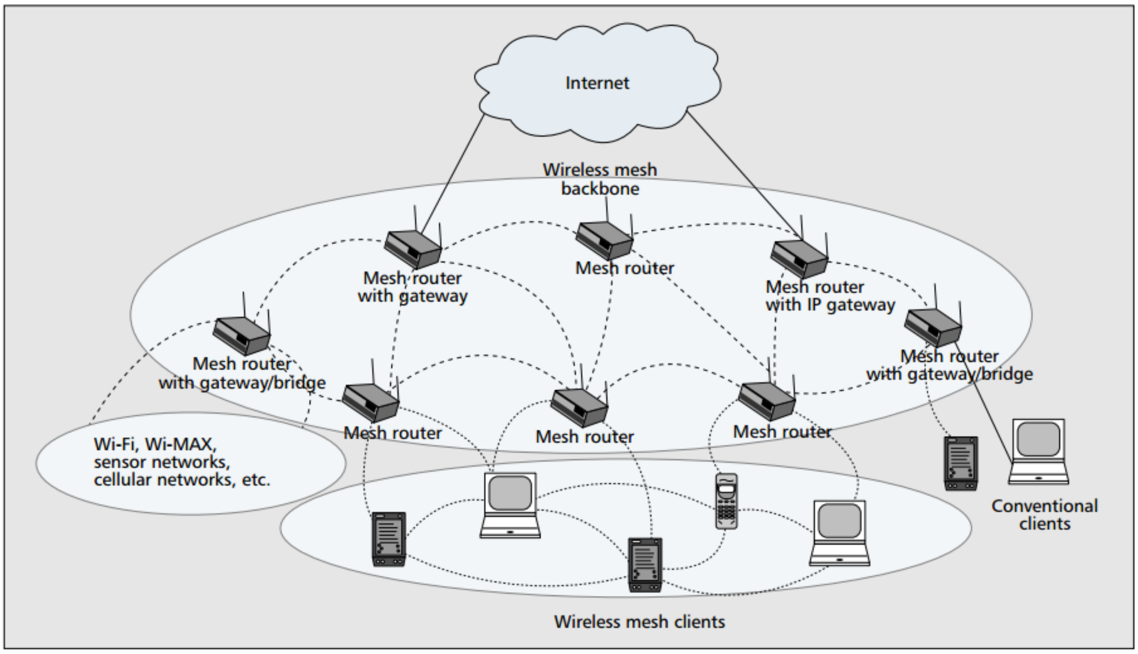

Figure 11 - Hybrid Wireless Mesh Network architecture.

Summarizing, WMNs bring many advantages to SG such as increased communication, reliability and automatic network connectivity, since it is self-organized and self-configured. Furthermore, these networks enable both long distance and high data rate communications. In SG there is a large amount of data coming from smart meters, sensors and PMU's which require a large coverage and high data rate communication network.

-Cellular communication systems

Existing cellular networks are a good option for communication in SG too. This is a solution that is very interesting because it is not needed to build a new communication networks since it is possible to use the existing ones owned by communication service suppliers, preventing utilities from spending operational costs and additional time for building a dedicated communication infrastructure.

The network topology consists in cells formed by multiple wireless power transmitters. Data travels from cell to cell without any interruption, forming a point-to-point architecture. This infrastructure is able to receive data via Ethernet and transmitting it through the cellular network allowing wired devices to become wireless. This technology offers high coverage and no maintenance costs since it is used by service communication suppliers.

Cellular network characteristics are perfect for monitoring and metering remote DER but it is a good option for communication between smart meters and the utility which can be achieved by using 2G, 3G, 4G, WiMAX and LTE technologies. This is possible using a SIM within a cellular radio model integrated in smart meters [20].

This communication system has a lot of advantages. Some of them were already exposed like the fact that an initial investment in infrastructures is not required. But there is more. Due to data gathering at small intervals, a huge amount of data is generated requiring high bandwidth to transfer it which is no problem for cellular networks. In terms of security, this system is ready to secure data transmissions with strong security controls. Other advantage is related with the fact that the use of mobile phones brought the need to increase the coverage of cellular networks and nowadays the infrastructures coverage reaches a really wide area. All these advantages highlight cellular networks as a good candidate for SG applications such as demand response management, advanced metering and outage management.

However, there are some disadvantages that need to be considered. The services of cellular networks are shaped by customer market which can result in network congestion or decrease in network performance. This effect can be really important if it is considered that some applications in SG need continuous availability of communications. Another problem that must be considered is that sometimes cellular network providers may not provide guaranteed service, which normally happens when there is some kind of natural disaster [16].

-Satellite Communication

The satellite communication offer interesting solutions for remote control and monitoring on substations. This technology is a good alternative to cellular communication systems in rural areas where those infrastructures are not accessible and there are some substations. Satellite communication is a technology which is already relatively developed and is used for GPS and backup to existing substations. When there is a congestion problem or failures on communication links, the critical data is routed to satellites.

The advantages of this technology rely on the fact that it has global coverage and fast installation. If there are no communication infrastructures in rural areas, satellite communication is a cost-effective solution because it is possible to connect the remote substation to a satellite network only by acquiring technical equipment without the need for cable installation which would cause this process to be more expensive and difficult.

However, there is some negative points which difficult the use of this technology. It is easy to conclude that the satellite communication delay is higher than the terrestrial links. Furthermore, the satellite channel characteristics vary with atmosphere properties, like the fading effect and weather conditions which degrade the performance of the whole satellite communication system. Finally, as it was said, this technology presents a cost-effective for remote substations but if there is any kind of communication infrastructure in that area, the satellite communication will be the more expensive. In other words, this technology is only cost-effective for these substations because it is not needed to build new infrastructures. This means that a high initial investment is needed for satellite transceivers [16].

-ZigBee

Zigbee is a wireless communication technology which is ideal for smart lightning, energy monitoring, home automation and automatic meter reading. This means that Zigbee and Zigbee Smart Energy Profile (SEP) were realized as a suitable communication standard for residential networks in SG. This technology is low on power usage, data rate, complexity and deployment cost.

The communication between smart meters, intelligent home appliances and home displays is very important to realize the idea of SG´s energy management. When Zigbee is incorporated in smart meters it is possible to communicate with Zigbee integrated in devices and control them. This function allows demand side management. Zigbee SEP provides utilities to send messages to home residents which receive their energy consumption in real time.

ZigBee is considered as a good option for metering and energy management and other SG applications because of its simplicity, mobility, robustness, low bandwidth requirements, low cost of deployment, its operation within an unlicensed spectrum and easy network implementation. The Zigbee SEP is a good solution to control and reduce load, demand response, real time pricing and advanced metering support for gas, water and electricity utilities.

However, there are some constraints on Zigbee utilization such as its low processing capabilities, low memory size, small delay requirements and interference with other appliances which share the same transmission method, license-free industrial, scientific and medical (ISM) frequency band ranging IEE 802.11 wireless local area networks (WLAN´s), Wi-Fi, Bluetooth and Microwave. In order to avoid this effect it is necessary to use interference detection schemes to provide a reliable performance and energy efficient [20].

3.4.2 Wired Technologies

Current communication technologies, usually, are wired. Normally, it is used copper cables or optic fiber. Even though, these two technologies have a space in electric applications, such as system automation, they are being replaced by wireless technologies which present more advantages. However, the majority of electric utilities prefer wired technologies because they have them as being more reliable. In certain situations, these make sense because wired communications have some benefits associated with them. For these reasons, in this section, it will be present some wired communications, which can be used in SG applications.

-Optical Fiber

Optical fiber is a communication system that was first introduced many years ago. This technology has many advantages over copper-based communication systems which are the most used.

Optic fiber lines are strands of optically pure thin glass that can carry information over long distances. They are arranged in bundles called optical cables and used to transmit light signals. In optical fiber communication network, there is a transmitter which produces and encodes the light signals, the optical fiber conducting the light signals, an optical regenerator if it is needed to boost the light signal for long distances and an optical receiver which decodes the light signals.

In order to achieve electric system automation, optical fiber should be taken into account since it can provide high data rate. In addition, its immunity to electromagnetic and frequency radio interference make it a good solution for high voltage environments like substations. Furthermore, this system is able to communicate in long distances with fewer repeaters which help to compensate the attenuation and distortion effects. This fact is noticed in the infrastructure cost.

However, even though this technology presents some advantages in technical terms relatively to other wired communication systems, optical fiber networks are still expensive for electric utilities, although, the huge bandwidth allows substations to share the information with a great number of users, which helps recovering the installation cost. There are other factors that allow a cost-effectiveness of optical fiber networks. One is the fact that this system is already widely deployed in communication network backbones. The other is that the cost is spread over a large number of users. As a result, optical fiber networks offer high performance and reliability when substation requirements are taken into account [16].

-Power Line Communication (PLC)

Utilities use PLC technology for decades in remote metering and load control applications. PLC is a technique that uses the existing power lines to transmit high speed data signal from one device to another.

There is a debate in what should be the use of PLCs in SG. However, comparing to other wired communication technologies, PLC offer an advantage in installation cost since the lines are already there. In Europe, for example, PLC lines are already widely developed and they are used in AMI. The distribution network seems to be the one that better suits PLC characteristics and the one in which SGs will have a more important impact to support microgrids, DG and consumers' participation.

There are some evidences that PLC can connect substations in point-to-point configuration and transformers to meters in point-to-multipoint configuration. Traditionally, substations are not connected between them so it is interesting to use existing infrastructures to do it. This is very important because there is different kind of communications that need to be done between substations, such as those related to grid status. Another application in which is interesting to use PLC is in AMI because it does not present the congestion problems that occur in wireless technologies. Finally, one of the most important and distinguishing characteristic of a SG: demand side management. To achieve this it is needed to connect utility to applications in each home. PLC is a good solution to direct and indirect load control due to the lower path loss at lower frequencies.

Despite all these advantages and applications, PLC has some technical problems. One of them is the fact that the power line transmission medium is a harsh and noisy environment making the channel difficult to be modelled. The low bandwidth characteristic restricts the PLC technology applications. Furthermore, the number and type of devices connected to power lines and the wiring distance between transmitter and receiver affect the quality of the transmitted signal. The sensitivity of PLC to disturbances is a disadvantage to data transmission. However, there is always the possibility to form a hybrid solution to overcome these problems and provide a full connectivity [16].

Chapter 4 - Management System

4.1 Introduction

All the SG's infrastructures were already exposed. Now it is time to focus the information and energy management created and transmitted in those infrastructures.

As it was previously stated, the two-way flow of energy and information is the base to realise all the functionalities that distinguish SG from the traditional electric system. From this functionality it will be possible to achieve some objectives such as energy efficiency, operation costs reduction, emission control and balance between demand and supply. To achieve these objectives, it is necessary to develop new management applications and services that complement the information and communication systems.

A good example of management capabilities is the SG's demand response characteristic, which is a very important concept. In the traditional electric system, utilities try to match supply with demand. However, this process can be very expensive, impractical or even impossible in the long run because consumers' demand can vary really quickly in time, which requires a fast answer from generating plants. This quest to match the supply with demand may fail, resulting in blackouts and even cascading failures. Appling demand response as it is desired in SG, it is possible to match demand to the available supply conditions using control technics or convincing consumers, through various methods, to reduce their electricity consumption.

In SG, this capability and others that will be exposed in this section are possible adding a smart management system to information infrastructures such as smart meters. In the demand response example, it is possible to turn off some devices during peak loads to reduce it, using the smart meters abilities and smart management [22].

In this section, it will be explored this smart management system, classifying the technics according to their objectives and then with their methods and tools.

4.2 Objectives

4.2.1 Energy Efficiency and Demand Profile

Energy efficiency in SG will be accomplished in two ways. One of them is through demand profile shaping and the other is minimizing energy losses.

Demand profile shaping will increase energy efficiency because it can help matching demand with available supply. This will be done using all the smart meters' applications described above. The smart meters, united with a good communication infrastructure, transfer information from consumers to utilities, that can change, schedule or reduce demand in order to achieve a new form on demand profile (normally it has many peaks), obtaining a smoother one. Knowing that the traditional electric system is dimensioned for peaks, when the demand peak is lower it is possible to smooth the demand profile, reducing overall utility cost, improving reliability and energy efficiency. All of these objectives are accomplished with demand side management which is a conjunct of programs to control energy consume at users' side of the meter. These programs are developed by utilities to use energy in a more efficient way. The consumer needs an energy management controller (EMC) that uses price and preferences to control energy use of consumers at home. There are many ways to realise demand side management and to reach energy efficiency. In this section it will be exposed some of those alternatives to get a smoother demand profile and some ways to minimize energy losses.

The new load controller technologies help reaching a smoother demand profile. These technologies are already present in many devices that we use at home, micro generation and storage. Basing in historical energy utilization by residents and external factors like weather, it is possible to forecast a consumption pattern in each home. These patterns will then be used by a utility planner to explore the potential to achieve certain goals, such as better energy efficiency. The result is a planning for next day consumption and generation. This is done utilizing the load controller technologies and an algorithm that decides what appliances must be turn on/off, when and how much energy flows from and for buffers and when and what generators will be switched on. This algorithm must take into account the consumers' comfort in conflict conditions, which will prevent prevision and planning errors.

Another method that can be used exploring the EMC capabilities is one that takes advantage from the different electricity costs throughout the day. It is possible for utilities to optimize energy usage from appliances taking into account the energy cost and the lower consume in off-peaks. This means that utilities can choose when an appliance must work knowing consumers' preferences in order to shape the demand profile transferring some energy consumption from peak hours to off-peak. This is only possible for flexible appliances, in other words, appliances that are not used with urgency, such as washing machines and others [23].

The next method uses all the concepts explored above and adds market strategies. In this case, the utility can schedule the use of appliances in every home on a neighbourhood, for instance. In this method, utilities provide homes with a basic energy level and then allow them to compete for additional energy levels to match their needs, in a bid scheme. However, there is a maximum level of energy that can be used in that area or neighbourhood.

An algorithm named CAES (Consumer Automated Energy Management System) reduces energy costs at home and smooth demand profile. This algorithm is an online learning application which estimates the impact of future energy costs and consumers' decisions in energy cost in long term, scheduling the energy usage in home's appliances. CAES continuously learns and adapts to individual consume preferences and modifications in price. The consumer decides which appliance needs to work and does an energy reservation selecting the device and pushing the start button. CAES then schedules when the appliances will work and the amount of energy supplied to those devices. This algorithm lowers the energy consumption, smooth energy usage in long term and reduces high energy peaks [24].

In terms of minimizing energy losses, which is the most important topic to qualify the performance of a distribution network. Traditionally, this minimization focuses on optimizing the network configuration. In SG the main focus will be the optimization of operation and accommodation of DG plants.

Using a multiperiod AC optimal power flow (OPF) it is possible to determine an optimal accommodation of DG in order to minimize energy losses in the distribution system. Adding, control schemes such as coordinated voltage control and dispatchable DG power flow in OPF's formulation the losses are even more reduced [25].

There is another method to accommodate DGs in an optimal manner. This method is based on the creation of a probabilistic generation-load model that combines all the possible operation conditions of DG, mainly renewables, with their probabilities. The planning is formulated by a mixer integer nonlinear programming (MINLP) with a function to minimize energy losses. This method was already used on a rural distribution system, with different scenarios, including all possible combinations of DG. The results showed annual energy losses minimization in every case [26].

4.2.2 Utility Cost and Price Stabilization

Improving utility, increasing profit and reducing costs are other objectives of the management system. These objectives can be achieved through various perspectives such as individual bill or profit, single energy bill or aggregate utility of a group of users [22].

Starting by the individual consumer perspective, there is one way to materialize these objectives through an optimization model to adjust the hourly load level of a certain consumer in response to hourly electricity prices. The goal is to maximize the consumer utility subjected to minimum energy consumption in a daily basis. This model takes advantage from the fact that in SG is possible for the user to receive information in real time. In this case, they receive the price information few minutes before an hour adjusting their consumption for the corresponding hour. This hourly energy adjustment is done within a diary planning in order to guarantee a minimum energy level. The model generally results in significant saving in energy cost [27].

Another way is to couple the communication network of SG with the energy distribution grid to improve the use of scarce energy sources. In this model, the communication delays are integrated in an electricity demand market model so that the energy demand affects the allocation of communication infrastructure and vice versa. The power demand is monitored and predicted using smart meters. This information allows a dynamic pricing which will impact the user's behaviour with the objective of reducing their consumption or start using their alternative sources to help the distribution system in a local level. This system monitors and predict power demand in every home so it is possible for the supplier to allocate the resources available and control demand in order to establish an appropriated electricity price, which will be lower, because, as it was stated above, it will function as a feedback mechanism for consumers to reduce their consumption [28].

It is possible to reduce the energy cost of a set of consumers too. There are some methods to do it. One is to scheduling the requests from consumers to use appliances at different times during a fixed interval based in energy dynamic pricing in that interval. This scheduling is interesting to implement in cooperative networked consumers who have a single bill such as those who work in the same commercial building. This method minimizes the energy cost for consumers as it goes against all the constraints in scheduling.

Considering billing as an essential tool to develop strategies of demand side management, there is an algorithm of real time pricing that focuses in interaction between smart meters and the energy provided through control message which contain the consumers' energy consumption and real time pricing. In this model, there is a single energy supplier and various subscribers or users. As in the majority of models of energy management in SG, it is assumed that these subscribers have an Energy Consumption Controller (ECC) within the smart meters. The ECC controls the energy consumption and coordinate each consumer with other users and the supplier. First, it is analytically modelled all the subscribers' preferences and their pattern of energy consumption in order to select utility functions. Then, the algorithm automatically manages the interactions in all the ECC (integrated in smart meters) and the energy supplier.

This algorithm finds the optimal energy consumption for each subscriber to maximize the utility of the aggregate of all users in the system in a fair and efficient way. Using all the information gathered from the smart meters, the supplier can encourage an energy pattern for all the subscribers proposing interactions in real time [29].

Now, from an electricity industry perspective, there is an optimization model that enables the DER management in SG's operation. In order to get a complete use of operations offered by a group of DG's, the controller in each unit participating in the energy market must take some decisions and coordinate the actions from different units. In this context, the MAS (Multiagent System) is applicable to the autonomous management of all DG units. The MAS is a system composed by multiple intelligent agents that are considered as autonomous entities. The most important element in MAS is the agent which is a physical entity that acts on the environment or a virtual one which is capable of taking decisions, without human intervention, because it acts taking into account a stipulated objective. As it was stated before, the SG allows small producers to generate and sell electricity at a local level using all the characteristics discussed until now. Markets have proved to be an interesting mechanism to coordinate selfish agents. Agent-based markets have a considerable impact in improving efficiency and energy network stability. In this case, it is determined an optimal generation scheduling of DERs and an agent-based architecture in the auction process. First, generation bids are calculated taking some variables into account such as fuel cost, clime and energy quality. Each seller proposes his bid to the market before the auction. The price that each producer asks for a quantity of energy depends on his attitude. This means that a seller who risks proposing a higher bid has less probability for that quantity to be sold. This process maximizes the profit of sellers and buyers because it was the producer that stipulated the price of selling taking into account all the factors that influence that price [30].

4.2.3 Emission Control

Recently, emissions reduction is a theme widely approached in the majority of developed countries due to environmental and public health problems related to them. Various SG stakeholders are concerned with this fact and are trying to find effective ways to reduce greenhouse gases emissions to atmosphere. In the traditional electric system, the energy production relies on fossil fuels such as coal, oil and natural gas. One of the biggest tasks in modernizing the energy generation is to find ways to reduce the chemical emissions of pollutants like carbon oxides, nitrogen oxides e sulphur oxides. Normally, there are four approaches to reduce emissions. The first one is the search for new types of fuels with low emission potential. The second is related with the introduction of new technologies to improve the existent equipment in generation facilities. The third approach is the exploration of renewable energy potential. The last one is the modification of the existing power dispatch strategies. Of all these approaches, the first and second ones revealed financially costly, need a long cycle of stabilization and have a negative impact on job market in some geographic areas. The third and fourth approaches provide quicker and efficient solutions [31].

It is important to note that all management models that were exposed before help in reducing emissions since they focus in improving energy efficiency and reducing costs.

Chapter 5 - Protection System

5.1 Introduction

As it happens in traditional electric grids, SG will have certain concerns about security of the system as a whole. However, SG presents more problems in this field because on top of the normal concerns related with user errors, equipment failure and natural disasters, there are additional new problems such has cybernetic attacks, disgruntled employees, industrial spies and terrorist attacks.

5.2 System Reliability and Failure Protection

Reliability is a characteristic, in this case, of a system, to accomplish a determined task during a certain period of time. This is a very important topic in any kind of electric system because blackouts or failures at any level result in high financial losses to electric companies. SG is not an exception but this is a more reliable system than the traditional one. There are many aspects that can harm the SG's reliability. Despite of increasing generation capacity, external independency and resolving some environmental problems, renewable sources can damage the reliability because of their variability and intermittence. As it was said in previous chapters, demand response and storage are important aspects to solve problems in economic field and to increase system reliability because it helps in peak mitigation and load variability. A mix of all these factors would be ideal to increase the reliability in a deeper level [32].

Recently innovative architectures such as microgrids have been proposed to virtualize a local generator as a constant load, source or zero loads to grid, simplifying the impact in the global grid and offering a good possibility of connection of DG in the grid without sacrificing reliability. This happens because when these architectures are implemented, loads are served locally which means less flow to global grid infrastructure. Besides that, using local generation, cascading events decrease even when generators are introduced. However, this effect is less important if the number of generator introduced is too high [33].

5.2.1 Failure Protection Mechanism

In this section, it will be approached two topics related with failure protection.

The first, has to do with the anticipation on events which can result in failure, in other words, this is a mechanism that prevents and predicts failures in electric system.

Then, when the prediction mechanism does not act properly and there is a failure on the system, it comes the identification failure part that diagnose and recover the electric system to work normally again as soon as possible.

5.2.2 Failure Prediction and Prevention

The traditional electric system has always adopted a reactive strategy. This means that both distribution operators and devices react to instability conditions in the grid and do not have a preventive attitude. When a fault occurs, there is electrical and mechanical damage in transmission and distribution lines. This is, sometimes, the cause behind extensive outages, substantial expensive equipment repair and replacement, and unsafe conditions for the general population. Nowadays, distribution operators have no means to evaluate the network condition and that is a reason to adopt that reactive strategy. It is already known that failure modes of distribution lines often develop over days or weeks before a catastrophic failure or outage occurs which means that the distribution system operates in degraded state several days before the problem really happen. In SG, this issue can be avoided, since there is real time information about the system. This approach results not only in a more reliable system but in reduced maintenance costs. The system goes from a reactive strategy to a preventive, target maintenance, enabled by intelligent monitoring systems [34].

One effective way to prevent failure from happening in SG is preventing weak points or the region of stability existence.

Monitoring and control in a wide area is one of the key aspects in SG. As it was seen before, these capabilities are acquired by using PMU. However, the information gathered by these devices is not used to predict instabilities nowadays. Voltage stability is one of the biggest issues that electric utilities must face even though there are many factors that contribute to transmission grid operation, such as the infrastructure ageing, deregulation and the craving for a more economic system operation. PMU can be used to monitor the electric grid, identify the stabilization system limit and alert the operator for an eminent crisis [35].

5.2.3 Failure Identification, Diagnosis and Recovery

In SG, there is a predictive approach enabled by autonomous intelligent monitoring systems as it was said in the previous section. However, even with this predictive strategy sometimes can happen some kind of failure and this is why it is needed a good identification, diagnosis and recovery system. Next, it will be explained various methods to realize this propose in order to rapidly resolve an issue in the electrical system, focusing PMU and smart meters' importance in this system and the self-healing characteristic of SG.

When there is a failure, the first thing to do is quickly locate and identify it to avoid cascading effects. In SG, the use of PMUs is high-priority, so it is a good idea to use the information transmitted from it to detect interruptions in lines and identify parameter errors in the network. PMUs allow data to be available in real time which is very interesting to know the global network operation. Different applications were addressed to PMUs since their diffusion on electric grid, such as status estimation applications, dynamic security assessment and visualization. Furthermore, the knowledge of transmission line, transformer and generator statuses is another key aspect of situational awareness in the power grid that PMUs are able to perform.

There is a method to use PMU data to improve the knowledge of system operators of line outages. This method is based on taking advantage of the angle measurements coming from PMU in real time to detect those line outages on the system. Even though this method can be used by any source of synchronized angle data, PMUs are the best solution since they are the only devices present in all SG and capable of providing geographical dispersed, synchronized and accurate phasor angle measurements [36].

There is another method using PMU data which is based on Petri Net (PN) modelling to diagnose failures in SG both at power and communication system levels. This method allows failure detection in data transmission and identifies failures in distribution grid even when there is high penetration of DG. PN is a mathematical model which represents, describes a global process and models its evolution, in terms of its new status after occurring new events. As a mathematical tool a PN can specify the status evolution equations with algebraic relations that govern the system behaviour [37].

The ability to self-healing when there is a failure in the system is one of the novelties introduced by SG. A good way to do it is dividing the energy grid in autonomous islands, as it happens for microgrids. As it was stated in microgrids section, they are able to islanding in order to continue working normally even when there is an outage. This is an intentional reconfiguration for an emergency. The objective is to stop the disturbances propagation avoiding wide area blackouts. If this reconfiguration is done properly these disturbances impacts will be minimal and cascade effects will be successfully avoided [38].

Failures in SG are not exclusive at transmission and distribution systems. These failures can occur in several devices, being the most important of them the smart meters because they contain data that can easily be corrupted or deleted. Processing and recovering that data is very important since it has vital information for normal day-to-day operation and system analysis. Smart meters gather the information about the consumer energy consumption. This information is used to generate a load curve which is a time series where load values are collected at a certain time frequency and is perhaps the most important information in an electric system. Analysing the load curve improves the operation, analysis, visualization, energy saving, global system planning and decision making. For all these reasons it is very important to have great data quality coming from smart meters. However, is possible that some of that data is missing or corrupted resulting from problems in the meters themselves, communication failures, equipment outages or lost data. These problems origin differences between what is represented in the load curve and the real consumption patterns. Traditionally electric utilities detect and correct corrupted data manually through ad hoc, which is an approach that does not work perfectly, because it is impossible to analyse that huge amount of generated data coming from smart meters. There are statistical models that allow automatically detection of corrupted data and replace them by better estimated data. There are two types of corrupted data. The first one is called locally corrupted data which represents a data point that deviates markedly from the local patterns of the time series. The other is named global corrupted data and it is a data point that deviates markedly from the global patterns of the time series [39].

5.2.4 Security and Privacy

5.2.4.1 Metering and Measurement

Despite all the advantages already approached in this work, that SG can provide to all entities involved in the electricity market, problems related to security and privacy start showing up in projects already putted in practice. Hackers or cyber-terrorists are new variables that appeared with the diffusion of intelligent technologies in SG. These people are able to compromise data gathered by smart meters and manipulate energy costs. They can change the consumption information at a global level affecting the whole electric system.

In this section, the problems related with privacy in the AMI system will be explored, focusing in smart meters, PMU and sensors. There are some solutions being studied in order to help mitigate these problems but for now, detection is the most important characteristic to combat them. However, hackers are able to adapt to these new barriers which may turn this effort in a hard task.

Data should be confidential to be available only for authorized entities. Furthermore, the integrity and the availability of this data must be guaranteed so that it is authentic, without any kind of modification and available at any time. These requirements can be affected by several types of threats. In this section, these must have security characteristics and their threats will be explained related to the AMI infrastructure, especially smart meters, communication structure and control centers. It will be present some solutions to mitigate those threats.

AMI infrastructure presents several issues security wise. Starting by confidentiality, it is relatively simple for a hacker to access data about how much energy is consumed by an individual user and his consumption patterns. Thus, this information must prevail confidential, so prevention against smart meters physical theft to gather data is very important. AMI network allows not only communication between consumers and utility but between users too. This is why, this infrastructure needs prevention mechanisms to avoid costumer-costumer interaction using suitable architectures to accomplish that objective or through security measures.

Relating to security integrity, it starts in meters since they are stuck on a wall outside each home, there is no way to completely avoid the corruption on that device. Furthermore, their computer chips can be breached and data added or erased. AMI communication network is subjected to such attacks too and it is very important to detect them because when that happens it is possible for utilities to repair the damage relatively easy. AMI control centers, have security issues related to data integrity too because human errors can happen, which is normal, but the biggest threat comes from the fact that disgruntled employees are able to modify or replace data similarly valid since they know exactly what can cause more damage and is more difficult to detect. On top of that, from this area, it is possible to send commands to change prices, control load requests, reset meters or switch on/off loads and generators.

Finally, the problems related to availability. Smart meters may have some failure in any physical or software component which can be caused purposely to stop metering. Again, detection is a fundamental process such as assessments of the probable causes. This detection is automated for physical or cyber intrusions. There are some problems related with availability in AMI network because there are many failure spots or radio interference, cut cables, path degenerations or bandwidth loss. In control centres the availability problems occur in the design process since this AMI system is still a new concept [40].

As it was stated before, some SG projects have been presenting some issues relating to consumers' privacy because smart meters send detailed measurements from users to utilities. As result it is possible for hackers to access important information to know a user lifestyle getting information on meal times, working and home occupation hours. To address these problems it will be explained some methods to guarantee users' privacy.

Data provided by smart meters have privacy issues since there is the need for high-frequency measurements which can expose private information. There is a method that allows energy data measurement anonymity to increase user privacy level. To accomplish this it is incorporated 2 IDs in the smart meters instead of 1 ID as usual. One of them will be the High Frequency ID (HFID) which is anonymous and a Low Frequency ID (LFID) which is attributable. The HFID confidentiality is achieved because neither the utility nor the installers have information about that ID. However this fact has an authenticity problem because it is impossible to know if the information received by the utility is authentic. That is why it is needed a 3rd party coming into play which can be the manufacturer, the smart meter itself or another trustful entity. Assuming it is the manufacturer. This is the only party which knows the connection between the HFID/LFID pair. However, it must be privacy politic because the manufacturer can't access, process or store data from the smart meter [41].

Data and resources aggregation is a very important function for SG. There is a method to aggregate data in a distributed manner instead of centralized collector devices. In order to protect consumers homomorphic encryption is used to ensure that intermediate results are not revealed to any device on route, maintaining an effective and efficient aggregation process. Homomorphic encryption represents a group of encryption functions that allow certain algebraic operations in plaintext to be done directly in ciphertext. This kind of encryption is already used in privacy-preventing operations like voting where the operands (inputs) are no divulgated [42].

5.2.4.2 Information Transmission

It was already shown that communication networks used in SG are an aggregation of multiple networks with various communication levels and coordination between power providers, operators and costumers. That complex network must be design to ensure data security since they are easy targets for cyber-attacks. Even though it is not possible to classify all type of attacks due to their complexity and sophistication, they can be divided into three different groups knowing their goals. They are the network availability, data integrity and information privacy. Relating to network availability, the attacks are classified as denial of service (DoS) because they try to delay, block or corrupt information transmission. It is expect that the majority of SG use IP-based protocols and TCP/IP which are vulnerable to DoS attacks, so it is needed efficient and sophisticated measurements against them. A good example of this kind of attacks is when and attacker uses legit methods to intentionally delay message transmission which need to be at a certain point in the right moment. This is possible through physical connection to information channel legit but useless traffic generation in order to delay power monitoring transmission and control devices. These attacks can occur in wireless networks and that is why it is important to create measures to counter the attackers since these kind of networks are the most used due to all the advantages suggested in the wireless communication networks chapter. The other group of attacks are the ones who compromise data integrity and information privacy. These attacks are considered more sophisticated than the ones related to network availability. The target is consumers' data or network operation information such as pricing information or voltage reading. The goal of the attackers is to modify that information in order to corrupt data exchange in SG. In terms of information privacy, the attacks only acquire desired information such as the account number of an individual user and their energy usage. It is not expected that this kind of attacks modify that information although it is useful to accomplish other types of attacks. Although, the attacks aiming privacy have a negligible impact to SG as a whole, those aiming data integrity may produce catastrophic consequences such as outages. Mitigation measures to avoid these attacks can be achieved having various perspectives in mind. It can be done through protocol authentication which is an important tool for problem identification in any network communication. Strong authentication schemes are required for consumers and electronic devices to assure communication with security. It is still possible to counter these attacks using intruder detection which must be an ability of SG to detect the attempt of an intruder to access computational systems. Finally, Firewall and Gateway design use will be a good and simple manner to block undesired or even suspicious flows generated by malicious nodes [43].

Chapter 6 - Microgrid

6.1 Introduction

In this section, the use of microgrids as promoters of SGs will be explored. First the general idea of the concept introduced in chapter 3 will be more detailed. Then, a comparison between the VPP concept and the microgrid will be discussed. The different components and architectures but also their advantages and disadvantages will be studied. These are the introduction section themes. Then, like it was done for a large scale SG system it will be seen how the management, protection and communication systems work on this type of architectures. Finally, and the most important section of this all work is the economic analysis involving microgrid optimal designing and management taking into account the regulatory environment and incentive programs to realize microgrid projects as business opportunity.

So let's start with the concept. The microgrid concept appeared as being a great solution to integrate DERs in large-scale in LV grids without compromising the whole system.

Despite microgrid seemed to be a new concept, the first electric systems already supplied consumers through generators near the consumption location. Furthermore, energy storage was used, mainly, with batteries to balance generation and supply in small scale. DG deployment brings some challenges and requirements that must be followed.

There are two different types of concepts related with microgrids: The Consortium for Electricity Reliability Technology Solutions (CERTS) in United States of America and the European approach "MICROGRIDS – Large Scale Integration of Microgeneration to Low Voltage Grids". The original concept belongs to CERTS. It assumed an aggregation of loads and microsources as being a unique system capable of providing heat and power. Thus, this concept relies more in microsources in order to achieve the flexibility and to assure the operation as a unique aggregated system. This flexibility allows the global system to recognize the microgrid as a controlled unit that ensure local needs on reliability and security having plug-and-play simplicity for each microsource. This approach allows DGs to continuously function isolated from the grid when there is any issue and reconnect again after that.

The European microgrid concept was developed in MICROGRIDS project. In this case, the microgrid is considered an association of electric loads and small generation systems in a LV distribution grid. This means that loads and sources are physically close so that the microgrid can correspond to all the needs in a small scale urban area. It is assumed that there are storage systems, management and control systems and CHP. The operation is considered normal when the microgrid is connected to the MV being totally or partially supplied or injecting power on it. The emergency mode is when there is some kind of failure on MV system. When that occurs, the microgrid isolates and operates in an autonomous mode similar to geographic islands electric systems [44].

Thus, after reviewing these two concepts it is possible to briefly define the microgrid as a power system that involves LV grids with small generation sources, controllable loads and storage systems which can be connected to the global system or autonomously operated. There are many definitions of microgrids. Accordingly with DOE the microgrid can be defined as: "A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate both grid-connected or island mode". The majority of the definitions involve a collection of loads, generation units and storage connected as a unique system [45].

A holistic concept called smart microgrid considers the business part, technological needs and all the users involved with the objective of providing a quality grid that meet the consumers' needs. In this approach, all the services and advantages of the SG concept, which have been explored through all this work, are implemented.

It is possible to note that microgrids and VPPs have similar concepts because both are DG management systems. However, there are some differences. Microgrids can be connected or not to the grid while VPPs are always connected to it, being compared to a generation plant. Thus, microgrids require storage systems and VPPs can operate without them. Microgrids rely on energy management and innovation hardware since VPPs only need smart meters and IT. Finally, microgrids consist in a set of resources in a delimited area but VPPs are a mixture of different kind of resources in a geographical area [46].

Usually, microgrids are associated with AC systems but DC microgrids are an interesting possibility because DER connection is done through power electronics interface. Furthermore, other problems related with AC microgrids helped the deployment of DC microgrids. Thus, microgrids can, nowadays, be operated based on principles of AC or DC power systems.

Generically, in AC microgrids, all the generation units, such as wind turbines, are directly connected with an AC bus line and then with the main system via power converters for their stable coupling. In this case, the Low Voltage AC (LVAC) can be connected with the utility through a power transformer. DC generation units, such as photovoltaic arrays, fuel cells or energy storage devices are connected to the LVAC bus line recurring to a DC/AC inverter. Relatively to loads, AC ones are directly connected while DC loads need an AC/DC converter.

DC microgrids have a similar configuration, as it is possible to see in fig 12, but DC generation units and storage devices are easily connected to the grid while AC units need an AC/DC power converter [47].

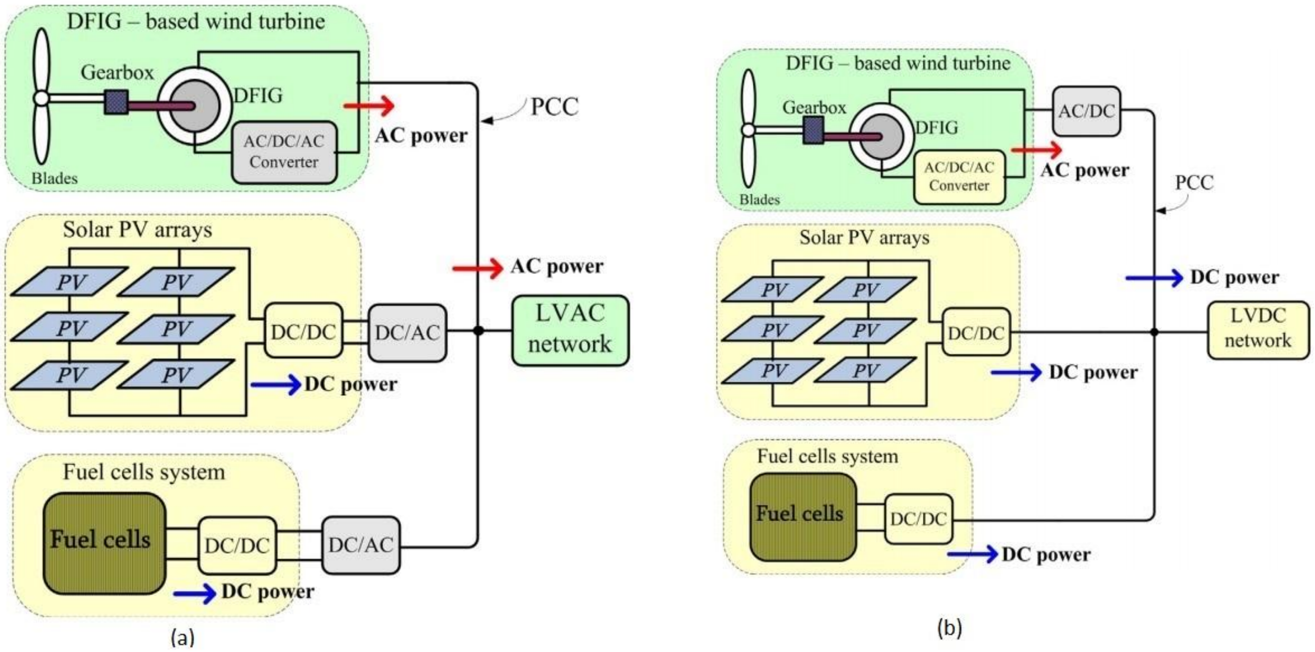

Figure 12 - Microgrid's DG configuration: (a) AVDC network; (b) LVDC network.

Microgrid deployment brings many advantages for the global power system technically, economically and environmentally wise. However, there are challenges to overcome and several issues, especially in management and operation. The advantages of microgrids are noted in operation, power quality, markets and environment.

Starting by the issues avoided in operation, related with the reduced distance between generation units and loads. Microgrids allow the reduction of:

- Distribution feeder overload
- Losses on the distribution process
- Investment in expanding transmission grid and large-scale generation systems

Relatively to power, quality is improved because:

- Supply and demand meet almost perfectly
- Impact of large-scale transmission and generation outages are reduced
- Voltage profiles are improved

In markets there are some advantages which can be achieved such as:

- Providence of ancillary services
- Reduction on energy price in power market with economic balance between network investment and DG utilization

Finally, environmentally wise microgrids will allow a smaller use of large thermal power station bringing benefits like:

- Consumer awareness toward a more rational use of energy thanks to the proximity to microsources
- Reduction of greenhouse gases (GHG) emissions

Unfortunately there are some challenges and potential drawbacks facing the development of microgrids that will be explored next:

- Technical issues related to lack of experience and technical knowledge to operate and control a significant number of microsources
- Cost of microgrids is a big disadvantage
- Standardization is another issue because there are not yet available standards for addressing power quality, operation and protection issues
- Lack of legislation and regulations for operation of microsources in many countries [44]

6.2 Architectures/components

There are two typical architectures of microgrids associated with CERTS and european MICROGRIDS project.

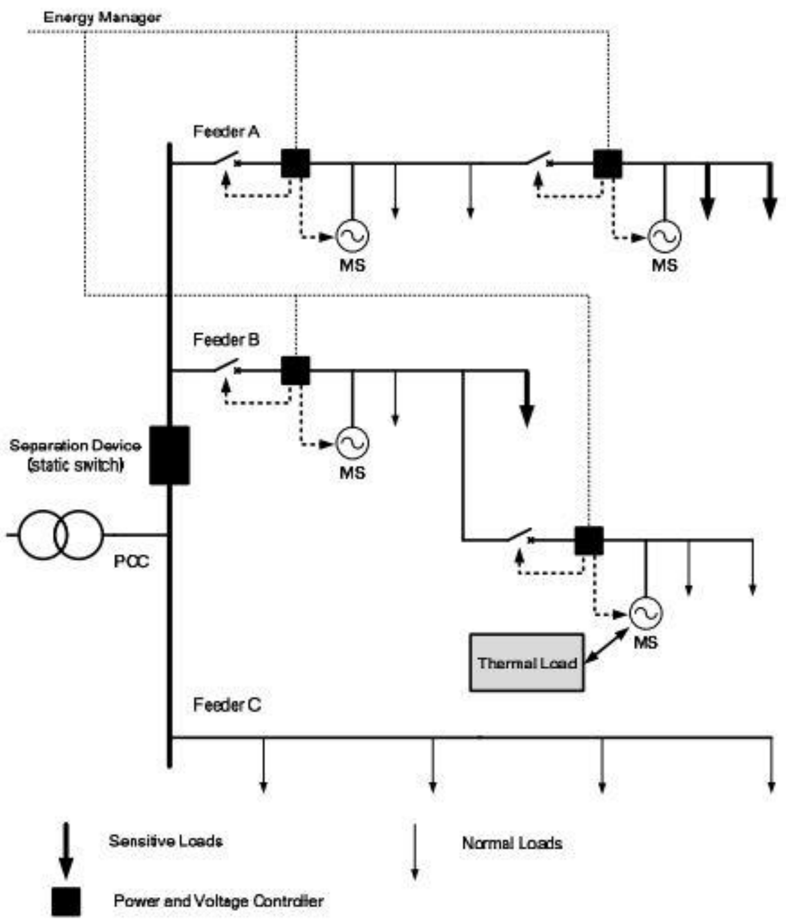

Figure 13 - CERTS microgrid.

The CERTS microgrid's basic structure is represented in figure 13. It includes interface requirements, control and protection for every microsource as well as a voltage control, power flow, load sharing during islanding, protection, stability and operation as a whole. Its capability to function connected to the grid or islanding are important functions too. In this case, there are three feeders represented (A, B and C), a set of loads (arrows) and a set of microsources. A point of common coupling (PCC) is situated near the transformer defining the separation between the grid and the microgrid. Here, there are some requirements that need to be satisfied, like, for instance, the IEEE P1547. In order to represent different situations in a microgrid, feeders A and B have micro generation while feeder C has no generation units. Other components present in microgrid are the circuit breakers, power and voltage flow controllers in each feeder. These controllers situated near microsources allow that the Energy Manager, which is like a central control system, regulate the power flow in feeders and bus voltage through control signals sent by the controller, so it is possible to obtain a more efficient microgrid operation. Another component present in this kind of microgrid is the Separation Device (SP) which allows the isolation, in this case, of feeders A and B in a way that disturbances in sensible loads are minimized. When this occurs, feeder C is supplied by the MV grid, because there are no sensible loads in that feeder. In this architecture, there are three functions that distinguish it from other types of microgrid architectures. The first one is the microsource controller (MC) capable of providing a fast answer to disturbances in the grid without recurring to a communication infrastructure. This function is the operation base for this architecture because it allows voltage and power regulation in a feeder when loads change their operation points. Furthermore, it assures that each microsource recuperates its load share when the system islands. Every one of the functionalities state before are accomplished in a matter of milliseconds. The second fundamental function in CERTS microgrid is the Energy Manager which provides system operation through dispatch of power and set points to each Microsource Controller. The orders are given according to pre-defined criteria which can be loss reduction, system efficiency improvement or contractual agreement satisfaction in PCC. In that case, these actions are practiced in minutes. The last important function, can be divided in two types, the reaction to failures which occur in MV network and failure in the own microgrid. The objective of the protection system is to reset reliability levels in critical loads or in other sections of the microgrid. When a failure starts on the grid the reaction taken must be the isolation of the critical loads in the microgrid to protect them. When a failure occurs in the own microgrid, it is needed to isolate that area which contain that failure [48].

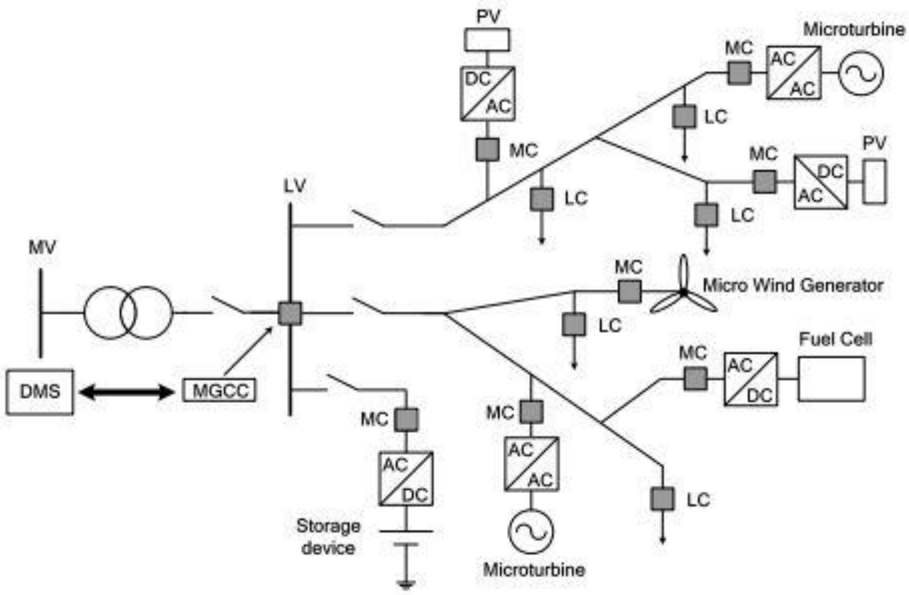

Figure 14 - MICROGRIDS project architecture.

In figure 14, the architecture of the microgrid developed in the European project MICROGRIDS – Large Scale Integration of Micro-Generation to Low Voltage Grids is represented. The components forming this microgrid are feeders supplying loads, microgeration units which are, mainly, renewable, storage devices and a hierarchical management and control systems integrated by a communication infrastructure. This operation is realized by an entity in

LV side of the substation MV/LV which is designated by Microgrid Central Control (MGCC) being considered as an interface between the microgrid and the grid. In a second hierarchical level are all the microsources and storage devices controlled by a MC and each load controlled by a Local Controller (LC). In order to control and operate this system, a communication infrastructure between all the hierarchical levels is needed. Thus, this infrastructure must connect LC and MC, the interfaces to control loads (through the application of an interruptible concept) and the microgeneration active and reactive power production levels, respectively, and the MGCC, as central controller that aims at promoting adequate technical and management policies and providing set-points to both LC and MC. Furthermore, it is expected that communication exists between the MGCC and the Distribution Management System (DMS) located upstream in the distribution grid, improving management and operation in MV grid. This is the general management and control operation of the microgrid because this section's goal is to identify all the microgrid components. Next, those activities will be explained in a more detailed way [44].

6.3 Management System

The operation of a microgrid requires a Power Management Strategy (PMS) and an Energy Management Strategy (EMS). In figure 15, it is possible to verify the PMS/EMS functions and data/information flow in a microgrid. The management and control system collects concrete or forecasted data in real-time of production, load and market to control the output generation, utility's consumption level, dispatchable sources and controllable loads, respectively. Furthermore, this system must assign references to DER units in order to respond to possible disturbances in the microgrid, determine DER units set points to balance microgrid and enable resynchronization with the main grid when it is necessary.

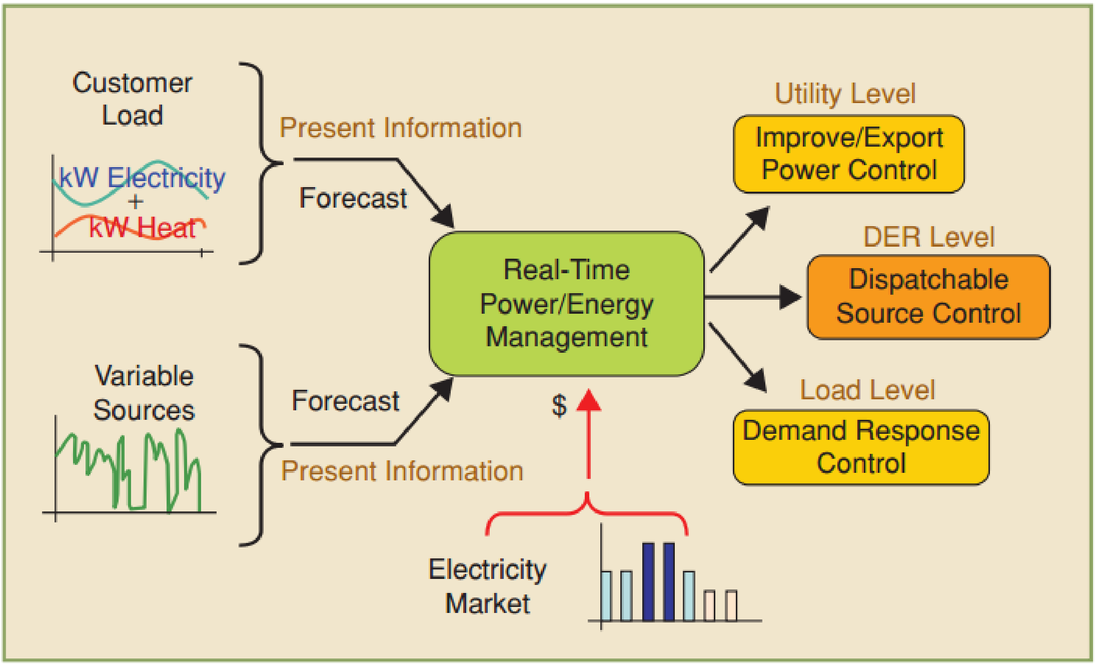

Figure 15 - Energy Management Strategy.

In gird-connected mode, DER units supply a determined power to minimize energy importation from the grid. In island mode this is not possible and the units' output power must equal demand or recur to a load-shedding process to do it.

In order to accomplish all the objectives and functions exposed previously, there is a supervisory control which can be centralized or decentralized named MGCC. As it was stated before, it includes three hierarchical levels. In decentralized operation, each LC receives set points from MGCC and takes decisions at a local level which can be taken without recurring to the MGCC. However, in a centralized operation LCs follow commands coming from MGCC during the grid-connected mode but they have the autonomy to optimize local power exchange between DER units and switch to fast load tracking methods subsequent to transition to an autonomous mode. In a decentralized approach, control decisions are taken by the DER's LCs. These decisions have objectives, such as, power optimization to meet the local demand, and maximizing power export to the main grid based on market prices. Furthermore, LCs must assure a safe and smooth operation.

In a more detailed way, when it is used a centralized control method, the MGCC optimizes the exchanged power with the macrogrid. Thus, is it possible to maximize local production taking into account the market price and security issues through set point messages to controllable loads and DER units. The MGCC takes decisions in a determined time interval. Let's suppose that it decides what to do for the next hour or hours, every 10 minutes basing its decision in market prices and capabilities of each unit. The LCs adjust the generation and demand, and prepare bids to the next period knowing the signals coming from the MGCC.

In the decentralized control method the objective is to give autonomy to DER units and loads. For that, LCs can be seen as an intelligent entity capable of making its own decisions. In this case, the main task of each controller is to improve the microgrid performance instead of trying to maximize profit. For this reason, the system must include economic functions, environmental factors and technical requirements, as black start, for example. Having all these aspects in mind, a good solution to achieve the objectives is the utilization of MAS, in which every agent uses their intelligence to determine future actions influencing its near environment. In this structure, seen in figure 14, it is possible to identify the three hierarchical levels. The highest level is the MV level and its agent is in permanent communication with the microgrid. The medium level is the management level where the agents coordinate DER/load controllers, market participation and possible collaborations with the adjacent microgrid. The lowest level is the one referring to the main elements of MAS and that correspond to LCs. At this level, the operation requires two parts. One in which LCs communicate with microgrid through set points, bids and commands. The other part is the one that allows LCs to communicate between them [49].

6.4 Communication infrastructure

In order to achieve a good management and control system it is necessary to resort a communication infrastructure to connect the MGCC and local controllers. The data transfer is basically messages containing set-points to LC and MC, information requests about active and reactive power values and messages to control microgrid switches. The fact that microgrids cover, normally, a small geographical area facilitates establishing the communication infrastructure diminishing its implementation and maintenance costs.

One of the best technological options is PLC because it is a technology that is widespread and can be explored for communication purposes, since power grid connection characteristics provide a link between all the microgrid elements. Even though PLC present great characteristics to be used on microgrids as communication infrastructure, it must be subjected to a carefully analysis as it was done in MICROGRIDS project. The tests executed in this project focused, mainly, physical characteristics from transmission channels. Thus, there are several parameters that must be taken into account when the communication technology to be used is being chosen. One of the parameters is the attenuation of the communication signal which can assume a high value when the distance travelled is large. Another relevant parameter is the level and nature of the signal interfering and that are present at the input of the receiver and generated in connected loads. When there are several signals interfering with communication one, it is very difficult for the receptor to reproduce the original information. PLC was exposed to all these tests and revealed to be a good option but there are other technologies that can be used if they are economically and technically viable.

Relatively to the communication protocol taking into account the use of PLC, the TCP/IP based transport protocol provides extra functionality, flexibility and scalability, especially in terms of system evolution. Furthermore, this protocol allows another choice for any other physical infrastructure.

6.5 Protection

As it was stated for several times before, DG units represent many operation issues, but also protection problems. The main protection issues are related with relay selectivity, overcurrent and earth-fault protection, protective disconnection of generators, islanded operation and neutral grounding. It is obvious that DG units increase complexity in the protection system due to amplitude duration changes and direction of fault current. Furthermore, the impacts on protection system related to DGs include coordination protection loss, unnecessary tripping and reach reduction. In order to design a protection system which is capable of overcome all these obstacles coming from DG utilization, it is necessary to take into consideration certain requirements such as reliability, speed, selectivity and cost. The main function of a good protection system must be the fast removable of a problem source in the microgrid, which means isolate the component not working properly, in order to avoid the expansion to whole microgrid. Other functions are securing personnel safety, continuity of supply, damage minimization and repair cost reduction. Thus, summarizing, when there is some sort of fault, the system must assure disrupt where it occurs. Recurring to selective operation of protective devices is possible to maximize continuity of service with minimal system disconnection. In a traditional distribution system the operation is realized through a radial feeder. The current flows normally from high voltage levels at the substation to low levels which are consumers' loads [50]. The protection system, in this case, is simple and uses schemes which consist in fuse utilization, reclosers, circuit breakers and overcurrent relays, at it is possible to see in figure 16.

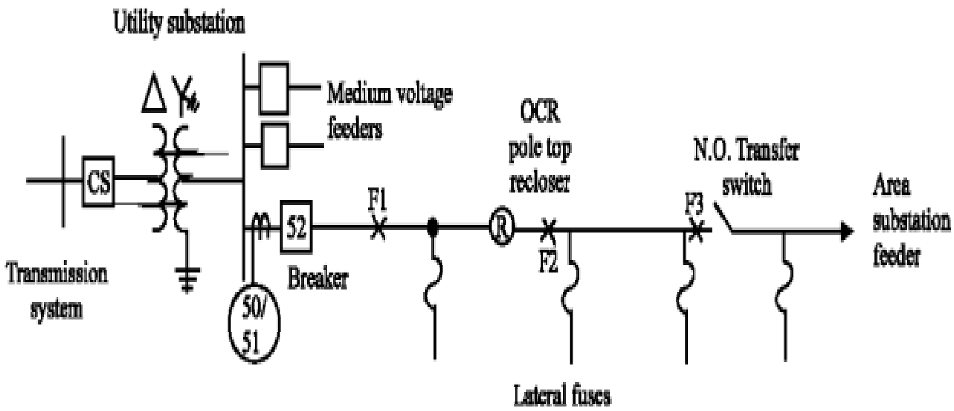

Figure 16 - Traditional distribution system protection.

These devices are coordinated to operate in selective mode based on current or time so that the device which is near the failure is the first to give a signal about it. In the traditional distribution system, the protection is unidirectional, as the whole power system, opposing to SG which is the base for microgrid. This protection is based in overcurrent relays and when there is a fault DG sources are simply shut down. This means that it is impossible the islanded operation of microgrid. Now, microgrid protection philosophy must ensure not only, grid-connected mode but also islanded mode. However, each of these operation modes presents different challenges and, because of that, maybe it is a good option to use two sets of protection systems for each type of operation. Thus, during the grid-connected mode it will be possible to use the traditional method. The problem related to this thought, is that the installation of several electronically-coupled DGs brings several precautions which are not compatible with the traditional protection system, such as DG's high contribution of short-circuit current.

There are several protection schemes which can be used such as overcurrent-based, voltage-based, current component-based, harmonic content-based, fault current limited-based and current wave-based. Relating to coordination technics there are time-current grading and optimization algorithms that assure protective device selectivity. In figure 17, it is possible to identify all these methods. These schemes are adequate to different types of operation, DG and issues.

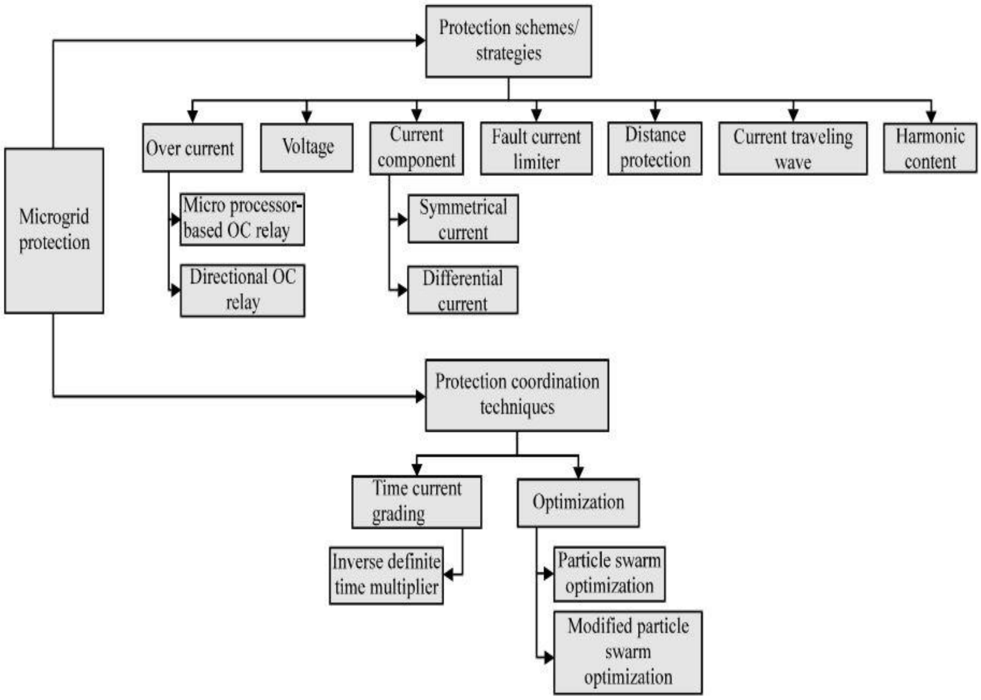

Figure 17 - Protection systems.

An overcurrent scheme uses overcurrent relays and balance earth fault protections to detect failures on the main distribution network. These devices are located at the grid side of circuits between the main grid and the microgrid, these ones having the capability of inter-tripping the microgrid. To detect faults on microgrid overcurrent protection and Residual Current Device (RCD) to protect the feeder is used. When there is a failure it is necessary to recur to a storage system when the microgrid is in island mode. After the fault the protection disconnects the damaged feeder and has the ability of inter-tripping all the microsources at the same time. When a fault occurs at the consumer side, a short circuit protection device protects the consumer from the phase-to-phase and phase-to-ground which can be Miniature Circuit Breakers (MCB) or fuses and a RCD which protects against phase-to-ground or earth faults. It can be installed at the grid side of consumers. This scheme has a drawback because this type of protection decreases sensitivity and can make circuit breakers to refuse to operate or work poorly.

The scheme based on voltage uses output voltage measurements of DG units to detect and clear faults. The output voltages are monitored and transformed in dc quantities through d-q reference frame. Any issue that exists at DG output is reflected as disturbances in d-q values. It is also considered protections zones and the use of communication between relays to help in fault zone detection and fault-free zones. However, this scheme does not consider grid-connected mode and its high impedance faults, so it is needed to conjugate it with another type of protection to operate in island mode.

In the current component based scheme the microgrid is divided into different protection zones with relays. The objective is to detect Single-Line-to-Ground (SLG) faults and Line-to-Line (LL). The differential current components are used to detect faults that occur at the upstream protection zone and the symmetrical current components detect SLG faults at the downstream protection zone and LL at all zones. This method is a good solution for microgrids that are the majority of the time in island mode and which DG are connected with inverters.

One way to avoid the cost that these new devices imply is to use current limiter apparatus set in series with power lines, in order to limit current faults generated by DG and at the same time contributing with low impedance and power loss in grid-connected operation.

A harmonic content based scheme is a good option to use in microgrid in which production is realized by inverter-based DG units. In this case these microgrids in island mode need to support a high harmonic source that is produced by DGs during faults. This method is based in the output voltage harmonic content from the inverter. The protection relay continuously monitors the Total Harmonic Distortion (THD) of the inverter terminal voltage and shut down the inverter if the THD exceeds a threshold value during a fault.

The distance based protection scheme divides the microgrid into two protection zones, with distance relays having Mho characteristics. Fault currents in the faulted phases are limited reducing the convertor voltage. Then, in relay zones, it is calculated the sequence currents and voltages through the analysis of fault characteristics. This method was tested in several types of faults and for two operation modes and it is good a solution for converter-controlled microgrid. However, the effectiveness of this method was not yet totally proved.

One of the most recent schemes is the adaptive one which uses telecommunication Intelligent Electronics Devices (IED) and it is dependent on information of current flow direction and voltage measurements in different locations. This scheme is reliable to detect fault condition based on undervoltage and to detect faulted zone based on current flow information from IEDs.

Finally, the current wave based scheme. This method relies on busbar voltages with the objective of determining if there is a fault, so current travelling waves identify what is the affected feeder. Depending on the fault type, the power frequency voltages in the busbar change in that feeder. The current travelling waves are measured by current transformers on the lines. Wavelet multi-resolution analysis is used to decompose the travelling wave signals. By comparing the travelling waves in terms of magnitude and polarity, it is possible to discover what the damaged feeder is. This protection system is able to be operated independently of the microgrid operation mode and it is immune to power flow, fault current, unbalanced load and plug-and-play generators.

Now that it were seen the different possible protection schemes and their physical structure it is important to know how those systems work software wise. The objective behind the coordination protection process is to maximize service continuously supply, minimizing or avoiding faults through coordination of protective devices. For that, it applies and set protection relays so that they operate as fast as possible in a main zone and delayed in a backup zone. A good protective coordination system is capable of realize with success two main tasks which are very important. One is the system selectivity maximization to isolate faults in the nearest protective device and avoid nuisance operations. When a fault is diagnosed, the device closest to it must be able to remove or isolate it following messages from the operator. Traditionally, it is used a time grading to overcurrent relays. However, in microgrid, DG units are used, and for that reason this system is not reliable. Thus, a possible option is the disconnection of a healthy feeder by its protective relay because DGs inject short circuit current in neighbour feeder. When the fault occurs in the main grid and microgrid border it is important to disconnect feeders or generators that are faulty. There are several methods to realize this coordination. Those are being discussed next.

Coordination using time-current discrimination is one of those methods. It uses time delay discrimination in every relay and it is possible to detect Single Line-to-Ground (SLG) and Line-to-Line (LL) faults based on symmetrical and differential current components. Three threshold values are set. One of them is implemented in all the relays to detect downstream SLG fault based on zero-sequence current component. The other is configured in relays to detect upstream SLG faults based on differential current component. There is, still, another value that is used to detect LL faults based on negative-sequence current component.

Other method of coordination is the one using a Particle Swan Optimization (PSO) algorithm. This algorithm uses directional overcurrent relays to protect microgrid consisting in synchronous-based DG. The problem coordinating relays is formulated as a Mixer Integrer Nonlinear Programming (MNLP) and it is solved using the PSO technic. With this formulation it is possible to obtain better results comparing with linear programming. This scheme also uses a central protection unit through a communication link to change the relay definitions [51].

Concluding, it was possible to verify that a protection scheme for microgrids must take into account the attributes referred in the beginning of this section (reliability, selectivity, speed and cost) but is also needed to recognize the type of relays used, operation mode and communication link availability. Thus, is it easy to conclude that there is not a system which is supports all microgrid’s functions. Relatively to coordination systems, the grading of relays is either based on time or current discrimination. Selectivity can be accomplished maintaining a time interval between relays, using PSO it is possible to obtain optimal relays settings.

6.6 Microgrid Design

In this thesis, rural areas for microgrid implementation are the main focus. Furthermore, renewable sources are the priority. Thus, before planning and designing a microgrid, it is necessary to define several factors such as the best renewable sources to be used, number and capacity of those sources, the amount of emissions avoided, distance to the nearest main grid point, energy excess, fuel price and types of loads. The objectives of this section are:

- Microgrid planning and design optimization based on renewable energy taking into account their characteristics and different technologies.
- Compare the overall benefits from the optimally designed renewable energy based microgrid with existing microgrid configurations.

These objectives are achieved supported by the factors referred previously and their effects on the proposed microgrid design.

Now, the procedure to plan and design a microgrid is explained. First, the system costs are defined. There are two main elements related with the costs which depend on annualized costs for the microgrid. There is software (HOMER) which optimizes the system economically wise. The programmer must insert all the investment, operation and maintenance and miscellaneous costs. The miscellaneous costs are credits that are caused by emissions, obtained power from the grid, etc.

The systems considered to design a microgrid involve renewable sources (wind turbines, solar PV array, battery bank, hydro turbines), fossil fuel sources (diesel generator), thermal systems (boilers), converters (AC/DC) and dump loads. For cost and capacity sizing of the DG, it is necessary to obtain a consumption profile where the microgrid will be inserted. To obtain the consumption in those areas it is necessary to analyse bills of all the community members when connected to the grid. In some locations there are already microgrids which use diesel generation. In this case it is possible to reformulate the system. Where there is no electrification it is possible to present a standard consumption profile for the community with electric devices power and the usage hours for every household, commercial or industrial buildings. The result for each situation is a graphic with energy consumption for every hour and a demand peak. The thermal load will be an estimated percentage of the electric one. In this work, this load will not be fully detailed. After the load characterization, solar and wind data is needed for that place. Furthermore, information on fuel prices in that region and density of pollutant gases emission is also important. Economically wise, it is considered an interest rate, the project lifetime costs which include investment, replacement and operation and maintenance costs for all the components mentioned before and that will be used in the optimization software [52].

6.6.1 HOMER SOFTWARE

The HOMER software is a simulation tool developed by U.S. National Renewable Energy Laboratory (NREL) for planning and designing of microgrids taking in consideration the physical behaviour and the energy supply system. Using this system it is possible to analyse several architectures such as DG form isolated, grid-connected microgrids etc. This software also realizes microgrid simulation, optimization and sensitivity analysis of several parameters in time [53].

For a grid-connected microgrid the mathematical formulation is explained below. Note that, for islanded microgrids, the only difference is the grid parameters which are not present in calculations for this kind of microgrid. So, first, it is considered *n* as a group of generators of the same type with an output power P with k being dispatchable ones. The total electric load is designated by P_L. From the conservation principle it comes:

$$P_L[h] = P_1 + P_2 + \cdots + P_n + P_{grid} \quad (1)$$

With P_i [h] (i= 1, 2,…,n) being the average output power of the generator i and P_{grid} [h] the power exchanged with the grid. When P_{grid} is positive, power is imported from the grid.

The operational cost (C) ($/hr) and emissions (E) (kg/hr) for each hour [h] are:

$$C[h] = C_1 + C_2 + \cdots + C_n + C_{grid} \quad (2)$$

$$E\,[h] = E_1 + E_2 + \cdots + E_n + E_{grid} \quad (3)$$

With C_{grid} [h] and E_{grid} [h] being, respectively, the cost and emissions related with the grid. Note that the cost and the emissions are only related with the *k* generators because the non dispatchable ones do not have any operation cost or they can be neglected.

The annual operational cost and the emissions of the microgrid are obtained summing C[h] and E[h] for every hour of the year. The total annual cost of the microgrid comes:

$$C_{ann} = C_{ann\_op} + \alpha_1 . \left(C_{ann_{fx},1} - \sum_{h=0}^{8759} p_1 [h]. R_1 \right) + \alpha_2 . \left(C_{ann_{fx},2} - \sum_{h=0}^{8759} p_2 [h]. R_2 \right) + \cdots + \alpha_n . (C_{ann_{fx},n} - \sum_{h=0}^{8759} p_n [h]. R_n) \quad (4)$$

Where $C_{ann\_fx,i}$ ($/kW year) represents the annual fixed cost per kW of the installed capacity of the *i'*th generator which include annual maintenance and capital cost. The installed capacity of the *i'*the generator is represent by α_i (kW) and p_i [h] = P_i [h] / α_i is the normalized output power of the *i'*th generator. R_i is the price that the utility pays for each kWh produced by the *i'*the generator which is zero for non-renewable energy.

To compare the lifetime costs of the different configurations it is necessary to express the summation of the annual costs represented before in terms of the money value at the present time which is achieved through the Net Present Value (NPV), expressed by:

$$NPV = C_{ann} . PVF \ (j, l) \quad (5)$$

With *j* being the annual interest rate (%) and *l* the project lifetime (year).

$$PVf(j, l) = \frac{(1+j)^l - 1}{j(1+j)^l} \quad (6)$$

For emissions the principle is the same. The annual operational emissions are summed for every year of the project lifetime. The results of this case study will be present later.

Now, it will be explained how it is determined the process of optimal dispatching for each configuration represented by a conjunct of generators α_1, α_2 , ..., α_n. The objective is to determine the output power P_1 [h], P_2 [h],..., P_k [h], imposing P_{grid} to minimize the following function:

$$J[h] = \theta . C[h] + (1 - \theta). E[h] \quad (7)$$

With θ being a weighting coefficient which minimizes C[h] and/or E[h].

The optimization process referred as "optimal dispatching" is subjected to the constant:

$$P_{i\_min} \leq P_i[h] \leq \alpha_i \qquad i = 1, 2, \ldots, k \quad (8)$$

P_{i_min} is the minimum permissible power to the generator *i*. For some generators this value is zero, for storage devices and the grid is a negative value.

Finally, it is calculated the system cost for its lifetime (C_{life}) for each configuration, the values of α_1, α_2, ..., α_n are changed from configuration to configuration and the process is repeated until the minimum C_{life} is achieved, being that considered the best option [54].

There are some examples of cases that can be considered:

- Diesel generation only
- Renewable energy only
- Mixed generation (renewable + diesel)
- Microgrid connected to external grid without any DG or DS (grid extension)
- Percentage of renewable generation on a grid connect scenario

Every case must be analysed economically wise to choose the appropriated configuration. However, as it was stated before, there are several factors that will influence that decision. Greenhouse gases emissions are one of those factors. For example, if the first and the second cases have similar costs, it is a good practice to implement the microgrid with renewable generation only. Another factor that can influence the decision is the distance to external grid. There is no doubt that the microgrid connected to the main grid is the cheapest solution, but depending on the distance to the microgrid this scenario can prove to be the more expensive one, since it is needed to extend the main grid which involves extra costs. The intermittence and non dispatchable characteristics of the renewable sources can increase the generated energy for the dump load or the unmet load effect because even though the system has capacity to generate sufficient energy sometimes the peak load cannot be satisfied which brings some issues to the microgrid. It is necessary to choose schemes that have a better energy usage. Finally, the fuel cost must be taken into account since there is some areas where the fuel is very cheap which can represent an economical viable option to use diesel generators. Thus, it is very important to conjugate these systems with renewable ones to decrease emissions. To finalize this section it is important to underline the fact that for microgrids disconnected from the grid, the principle is the same but without the factors related with energy exchanged with the grid. This means, that all the previous expressions are equivalent for those type of microgrids without the grid terms [55].

6.6.2 Case Study - Grid-Connected Microgrid

Nowadays, there are many communities around the world that are isolated from the electric power system. A good example is the case of northern Ontario province, in Canada, where there are several of those communities, which aren't electrified or rely on diesel generators to obtain electric power.

A study was done near that area, in the University of Western Ontario, to evaluate whether a microgrid is able to mitigate the reliance on diesel which is costly and has a huge impact on the environment. In this case, the most important factors studied were the cost and emission levels during the microgrid operation connected to the main grid. Thus, to optimize the design of the microgrid, the output power of the dispatchable generators was determined in order to know the power exchanged with the grid so the cost of the microgrid and/or the emissions were reduced. Then, it was calculated the total cost of the system to several configurations. The configuration with the lowest cost is the chosen one. The mathematical formulation explained before was used in this case study.

In this case, the power consumption is represented in figure 18.

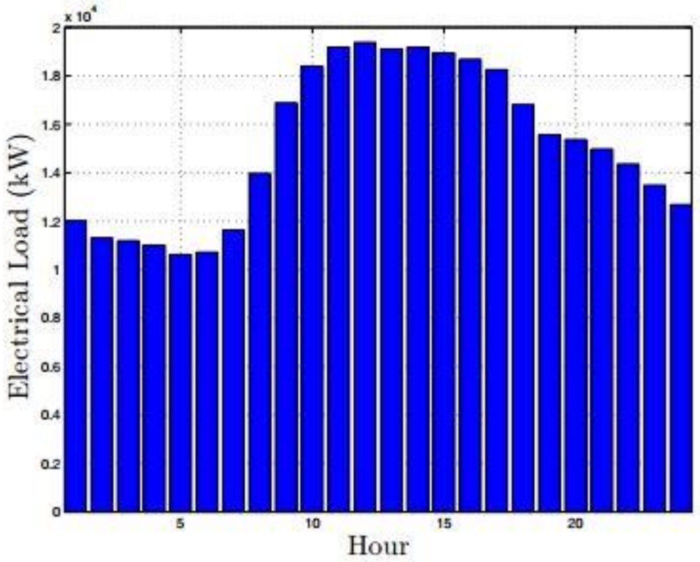

Figure 18 - Consumption profile.

In order to supply the demand, the only sources that can be used are solar and wind. Thus, it is necessary to get data from solar radiation and wind for that place. In figures 19 and 20, the normalized output power values obtained in HOMER from time series of solar and wind data for a day in that region are presented.

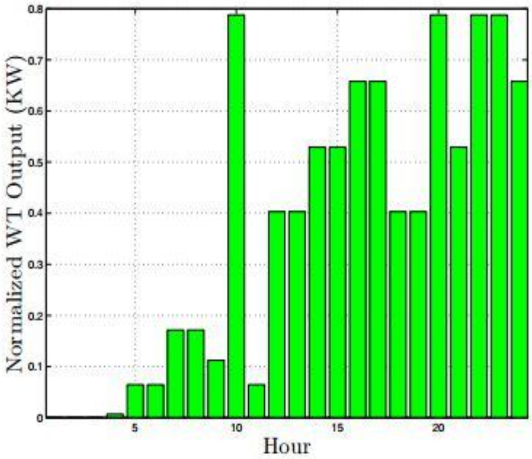

Figure 19 - Normalized WT Output.

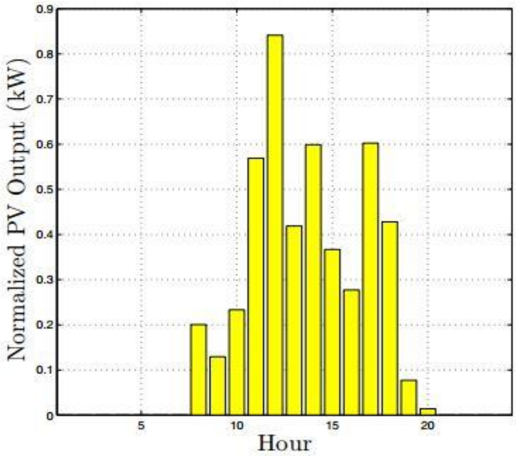

Figure 20 - Normalized PV Output.

It was decided that it was possible to use batteries and diesel generators to supply necessary energy to the campus. Taking all these sources into account, four scenarios were studied to obtain the best microgrid design:

1) Existing solution, connected to the main grid without DG or DS
2) Microgrid with 5% renewable implementation
3) Microgrid with 10% renewable implementation
4) Microgrid with 20% renewable implementation

The results from the software are demonstrated in the next table where there are represented several parameters achieved for each case. The first case is the configuration which was implemented so that will be the reference case.

Table 1 - DG capacities and system costs for the different cases.

Case	**α_1 (PV) [kW]**	**α_2 (WT) [kW]**	**α_3 (Microturbines) [kW]**	**α_4 (Batteries) [kW]**	**C_{life} ($)**	**E_{life} (ton)**	**Cost saving ($)**	**Emission Saving (ton)**
1)	-	-	-	-	143 373 536	2 393 398	-	-
2)	2 000	7 500	30	200	101 853 168	2 204 651	41 520 368	188 746
3)	4 000	15 000	30	200	60 859 576	2 015 900	82 513 960	377 497
4)	6 500	33 000	-	-	-8 138 752	1 615 607	151 512 288	777 790

In case 2), there is a reduction of 29% and 8% on cost and emissions, respectively. This difference in cost is related with tariffs to renewable energy from the government. Relating to emissions it is obvious that the reduction comes from the fact that renewable energies are implemented on the system.

In case 3), there is an even greater reduction because of the factors explained before and the higher capacity of renewable generators.

The case 4) is the one that obtains the best results with a reduction of 106% and 32% on cost and emissions, respectively. In this case, since the cost presents a negative value, it means that the owner of the microgrid has profit when this system is installed [54].

6.7 Economic

In the previous sections it was seen that a microgrid can be a reliable and profitable investment just by considering energy and cash flow optimizing its design. However, there are other interactions between several microgrid stakeholders creating financial benefits which are a bit more complicated to evaluate. Each stakeholder is seen by an entity with direct or indirect financial interests in the development of a certain project. To give a better understanding about the stakeholders involved in a microgrid project, the next table presents all of them, their type and description.

Table 2 – Microgrid stakeholders.

Stakeholder	Stakeholder Type	Description
Microgrid Customers (MGCs)	People or Corporations	Residential, commercial, or industrial loads within the microgrid
Grid Customers (GCs)	People or Corporations	Loads outside the microgrid
Independent Power Producer (IPP)	Person or Corporation	Owner of DG in microgrid
Distribution Network Operator (DNO)	Corporation	Entity responsible for correct operation of the grid
Utilities or Bulk Energy Suppliers (BESs)	System	Entities outside the microgrid who supply power to the grid
Society	People, Corporations & Other Entities	Everyone who might be affected by microgrid externalities

There are several ways to distribute all the profit coming from the implementation of a microgrid. This division depends on the ownership model, the regulatory environment (explored in section 6.8) and the market where the microgrid is inserted. Thus, before a further economic analysis it is important to understand the ownership model and the objectives from the microgrid owner which can be the DNO, the consumers or and IPP. In this work, it will be considered that the owner is an IPP.

It is obvious that each type of stakeholder has a different goal for the microgrid. The DNO focus, mainly, on the technical value that it can bring to the global system. The consumer wants his electricity price lower. The IPP has the objective of profit maximization which, usually, has positive impacts on the objectives of the DNO and consumers. Note that in the last case it is necessary that the microgrid is inserted in a free market environment [56].

The financial benefits achieved by the microgrid stakeholders are related with:

- Wholesale energy price lower than the retail one. This occurs because the last one is tagged with prices related to the grid usage, service fees, market changes, retail changes and taxes. Contrary to the microgrid where it is possible to deliver power directly to loads.
- Fluctuations in retail prices in the electric market.

In the first case the IPP (considered as the microgrid owner) is able to sell energy with a higher price than the wholesale but lower than retail. This way, both the IPP and consumers have additional benefits.

In the second case, applying SG concepts, such as demand response and intelligent controllers it is possible for the grid operator to provide energy to the grid when the prices are high and be supplied by it when the energy prices are lower. To achieve this optimization it was already seen that HOMER is a good tool. However, in order to get a more complete evaluation of all the financial benefits it is necessary to have other factors in mind because in many cases, a microgrid cannot be competitive economically wise just by exchanging energy with the grid. The study of some of those factors in such a way that it is possible to quantify them in financial terms is the main objective of this section. Then, this evaluation model will be applied to a case study in order to measure the possibility of a microgrid to be profitable for every stakeholder taking into account each of the following factors:

1) Peak Load Reduction
2) Reliability
3) Emission Reduction
4) Power Quality Services

For the first factor (Peak Load Reduction) the benefits come from the fact that microgrids reduce the load in global electric system which helps components to last longer avoiding investments on their replacement or upgrade because they do not achieve their capacity limit so easily. When a component operates in its limit it is needed to replace, upgrade or support it for an additional price that must be covered by the utility. A microgrid allows those devices to work for longer times providing financial benefits for the DNO. To calculate the profit that this delay of investment has, it must be taken into account the peak load and an estimative of its growth which allows the determination of the upgrade time with and without the reduction provided by the microgrid. The NPV of a single future investment is the present value of C_i in year Y_i at interest rate d, so:

$$NPV = \frac{C_i}{(1+d)^{Y_i}} \tag{8}$$

From the previous expression it is possible to see that in the presence of the microgrid, the DNO defers an investment C_i from Y_{BC} to $Y_{\mu G}$. Thus, the total benefit is the difference between the present value in the base case NPV_{BC} and the microgrid case $NPV_{\mu G}$:

$$B = NPV_{BC} - NPV_{\mu G} = C_i \cdot \left(\frac{1}{(1+d)^{Y_{BC}}} - \frac{1}{(1+d)^{Y_{\mu G}}}\right) \tag{9}$$

Taking into account a number of affected network components, the total investment deferral can be calculated as:

$$Inv.Def. = \sum_{t=1}^{h} \sum_{i=1}^{n} \frac{C_{i,t}}{(1+\rho)^t} \left| - \sum_{t=i}^{h} \sum_{i=1}^{n} \frac{C_{i,t}}{(1+\rho)^t} \right| \tag{10}$$

Where t is the time step from 1 to the end of the planning horizon h, n is the number of investments required in time step t, $C_{i,t}$ is the cost of asset i in time period t and ρ is the interest rate.

It is important to note that this parameter can only be calculated for microgrids relying in dispatchable generation units because non dispatchable ones do not allow peak load reduction. Thus, in order to take this factor into account it is necessary to use energy storage, hydroelectricity and/or dispatchable loads.

The second factor that can improve the financial benefits for microgrid owners is reliability. The islanding mode is capable of improving the reliability of the electric system because when there is a fault on the grid, the microgrid consumers are supplied by local DER. Thus, power interruptions will be less frequent and less durable in those areas. There are two indices considered to measure the reliability of the distribution systems and how they are impacted by microgrids. Those indices are the SAIFI (System Average Interruption Frequency

Index) and the SAIDI (System Average Interruption Duration Index). The SAIFI measures the number of interruptions that a given consumer experiences during a certain period of time and it is calculated by:

$$SAIFI = \sum \frac{N_i}{N_t} = \sum_k \frac{\lambda_k N_k}{N_t} \quad (11)$$

N_i represents the number of consumers affected by each interruption summed over the number of interruptions per year, N_t is the number of customers and λ_k is the failure rate at a load point *k*.

SAIDI is related with the duration of the interruption which the average consumer experiences in a determined period of time and it can be expressed as:

$$SAIDI = \frac{\sum r_i N_i}{N_t} = \frac{\sum U_k N_k}{N_t} \quad (12)$$

Where r_i is the duration of each interruption and U_k is the average interruption duration at load point *k*.

If we consider a microgrid as a single load point the equations simplify to SAIDI = $\lambda_{\mu G}$ and SAIFI = $U_{\mu G}$

The indices used in the previous expressions are formulated as:

$$\lambda_C = \sum_{i\epsilon f} \lambda_i + \lambda_{up} \quad (13)$$

$$U_C = \sum_{i\epsilon f} \lambda_i r_i + U_{up} \quad (14)$$

Where λ_i and r_i are the failure rate and restoration time of section *i* of the feeder, λ_{up} and U_{up} are the failure rate and unavailability of the upstream network and L_C is the average demand of load point *C*.

Just to give an idea of usual values of SAIDI and SAIFI, in USA there is 1-2 outages per year with a duration of 2 hours. From the developer point of view this reliability parameters are important because it can provide a base for a negotiation with the utility when the time comes for the initial investment, since the utility can be interested in reducing faults in the system. These faults create several problems to the utility related with public image, technical and political negative consequences and even costumers' health and safety, especially in winter.

The third parameter to be studied is the emissions reduction. The benefits from this factor are related with the load supply but also with the energy sold to the grid by DER. The reduction of emission e can be formulated as:

$$E_e = E_{e\,BC} - E_{e\,\mu G} = \sum_t^T [P_{GP}(t)E_{e\,G}] \,\Big|- \sum_t^T \big[\vec{P}_{DG}(t).\vec{E}_{e\,DG} + (P_{GP}(t) - P_{GS}(t))E_{e\,G}\big]\Big| \quad (15)$$

Where $E_{e\,BC}$ and $E_{e\,\mu G}$ are the emissions of *e* in the base case and microgrid case, *t* is the time step (hours), P_{gp} and P_{gs} are the power purchased from and sold to the grid, $E_{e\,G}$ is the average rate of emissions from the grid, $P_{DG}(t)$ is a vector containing the power produced by each DG unit in time step *t* and $E_{e\,DG}$ is a vector containing the emissions rate of each DG unit.

The last parameter is the power quality service. The previous factors have no validation in many areas around the globe, mainly, in developing countries. However, microgrids can provide some ancillary services which can result in revenues to the microgrid owner because there are several incentive politics to this type of services. Those services can be frequency support, voltage support, black start or system restoration support, peak load support and balancing services. There are many types of incentives which can be established through compulsory provisions, bilateral contracts, tendering or a sport market, a payment for service availability or a payment based on opportunity cost. In the case study presented next it will only be considered frequency support and voltage support. These services will be valuable only for the IPP and DNO since the costumers have always the right to service quality by the DNO independently of the microgrid presence. Note that the benefits of DNO come from the deferral of investment to assure service quality. To the IPP the revenues will be studied with more detail from now on..

Let's start with frequency or active power support. To achieve this support the microgrid has to use non intermittent sources and DG units must operate below its capacity. If there is a retail market, this characteristic implies less profit in peak hours. In off –peak hours the reserve provision revenues can be higher than the electricity retail price not being generated. The primary frequency control is usually remunerated based on availability. The profit to the IPP coming from the reserve bid at any time is:

$$r_{PR}(t) = \pi_{PR}(t)x_{PR} - C(x_{PR}(t)) \quad (16)$$

Where $r_{PR}(t)$ is the net revenue from reserves during time step *t*, $\pi_{PR}(t)$ is the price for reserves at time *t*, $x_{PR}(t)$ is the reserve bid at time step *t* and $C(x_{PR}(t))$ is the additional cost of providing the reserve amount bid. The total net profit comes:

$$R_{PR} = \sum_t \pi_{PR}(t)x_{PR}(t) - C(x_{PR}(t)) \quad (17)$$

If there is a fixed quantity contract in place, the previous formulation is simplified to:

$$R_{PR} = n_{PR}X_{PR}T_f - C(X_{PR})T_f \quad (18)$$

With π_{PR} being the fixed reserve price, X_{PR} the fixed reserve quantity and T_f the length of the contract. In some regions, reserve prices are set in advance which means that the assumption of a constant rate is valid.

The total output of a generator proving frequency support $x_T(t)$ depends on the instantaneous reserve utilization factor $\lambda(t)$ (representing the portion of reserve used at time t) and the energy exchange $x_E(t)$ and it comes:

$$x_T = x_E(t) + \lambda(t)x_{PR}(t) \tag{19}$$

The maintenance cost variable for the output of a generator is a linear, usage-dependent function dependent on fuel cost and expressed by:

$$C\big(x_T(t)\big) = C(x_E(t) + \lambda\,(t)x_{PR}\,(t)) \tag{20}$$

This cost is negligible for the most practical situations because the value of λ(t) is near zero. The consequence of this is that the cost of reserve provision on top of the real power provision is negligible too which means that C ($x_T(t)$) ≈ C ($x_E(t)$) and income from the reserve provision can be found as:

$$R_{PR} = n_{PR}X_{PR}T_f \tag{21}$$

Now, the voltage or reactive power support service is studied. For many large power systems the reactive power paper is so important that utilities insist that IPPs provide reactive power as a requirement for interconnection, so, in many areas this service is not compensated. However, for regions where the reactive power support is remunerated, it is done with a fixed rate or based on availability. It is important to underline that in North America there is a growing interest in exploration of these reactive power markets. In this case, to evaluate the revenues of this kind of service the method used is similar to frequency support. However, the investments necessary to realize this service are more subtle than in the previous case. There are two types of costs. The first one is related with the generators producing reactive power because they must be a synchronous machine or be connected to the grid by electronic interface. If DG units producing DC are considered the cost of that interfaced is neglected because it is already used [57]. The second cost is related with the fact that there are limitations in providing reactive power in equipment being used because from a certain point, providing reactive power is impossible or it reduces the amount of real power that a device can deliver due to the current limitation.

6.7.1 Case Study – Economic Services

Since the cost of renewable energy sometimes is a bit high, a microgrid may not be cost effective relying only on energy price but some benefits may result from its operation and functionalities advantages.

To evaluate this, a microgrid constructed in Western Canada was studied. This is a good example because this area had low reliability with approximately two outages a year with an average duration of 16 hours. The generation is done through two hydroelectric units which serve a remote community with 3 MVA_{peak}. All the parameters are synthetized in the next table.

Table 3 - Case study parameters.

Parameter	Value	Parameter	Value
DG size	2 x 3.46 MW	Peak Load	3 MW (W)
DG Cost	$16.5M	Peak Growth	2% p.a
Microgrid Cost	$687 500	Outage Frequency	2 f/year up.
O&M Costs	2% p.a		0.32 f/year int.
IPP rate to Customer	$0.65/kWh	Average Duration	16 hours up.
Interest Rate	8%		5 hours int.
Project Life	25 years	ToU Rates	$0.108/kWh
Base Case CO_2 Intensity	200 g/kWh		$0.092/kWh
			$0.062/kWh

As it is possible to see on the table the DG installation cost was %16.5 M and the microgrid implementation cost with all its fundamental components is $687 500. In this case, it was assumed a selling value to the grid equal to purchase price. It is know that in several regions, especially in Canada, there is several subsides to DER utilization but here, the objective is to demonstrate that microgrids are viable by its own characteristics. Recurring to economic dispatch realized by authors recurring to HOMER, it was possible to obtain the benefits in the next table.

Table 4 - Economic benefits from optimal energy dispatching.

	NPV	Annual Income
IPP	-1 488 010	-139 395
Costumers	2 093 590	196 125

In figure 21 and 22, several parameters are represented based on a sensitivity analysis.

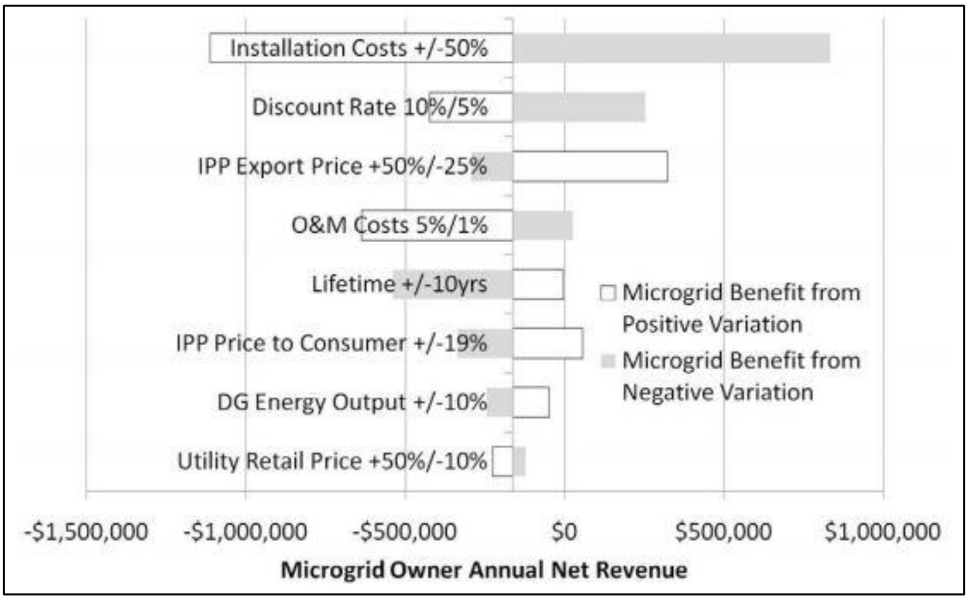

Figure 21 - Sensitivity analysis for the IPP.

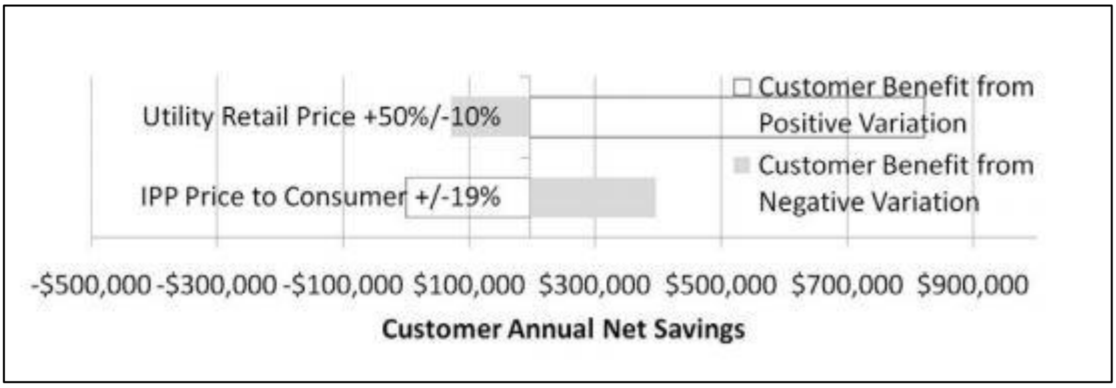

Figure 22 - Sensitivity analysis for costumers.

There are several conclusions that can be taken from analysing these two figures:

- Customers have the same electricity cost for both cases (base and microgrid).
- The IPP receives $56 730 from energy selling to microgrid customers.
- The microgrid profit for the project lifetime is highly susceptible to the variation on installation costs due to the fact that this cost influence the amortized payments and the O&M

- ➢ Although benefits for consumers are highly susceptible in retail price changes from utility, the microgrid owner is not affected by this parameter because the power imported from the grid is low.

The non-energetic benefits being studied until now were calculated using the previous formulas (8 to 22). Thanks to the microgrid, the DNO reduces its peak load from 3 MW to 0,6 MW in the first year, emissions were reduced by 5347 tonCO_2 per year and the reliability indices improved as seen in the next table.

Table 5 - Reliability indices.

Parameter	SAIFI	SAIDI	NDE (MWh)
Base Case	2.320	33.600	61.800
Microgrid	0.685	7.433	13.671

Now, that all the results obtained are explicit, it is possible to verify how much each service needs to profit so that the microgrid is economically viable. In the following table it is possible to see those values, compare them with the base case and verify what the normal values for each parameter are.

Table 6 – Required values for microgrid profit.

Parameter	Required Value	Normal Value
NDE	\$2896/MWh_{NDE}	\$1500/MWh - \$3500/MWh
Frequency Control	\$5.92/MWh	\$3.22/MWh - \$4.55/MWh
Emissions Reduction	\$26/tCO_2	\$10/t - \$30/t

The values for the “normal values” column were based on available data. For NDE that range of values comes from middle-road estimates with the lower estimates corresponding to residential customers and the higher ones corresponding to industrial and commercial customers. It is easy to conclude that the required compensation value is possible.

For the frequency control it was assumed that the average daily price for 10 minute spinning reserve in Ontario has that variation, being the lowest value the previous year and the highest the average value. This means that relaying only in frequency control it is impossible to compensate annual costs.

The emissions reduction bring benefits by either their projected environmental impact or by carbon taxes in some areas. From the table it is possible to see that the required compensation can be accomplished.

There are still two parameters which do not appear on that table. They are the deferral investment and the peak load reduction. This is because these two parameters are more difficult to quantify as financial benefits. For the investment deferral the difficulty comes from the fact that is hard to know the upgrade schedule of the utility but assuming a case in which the substation transformer needs an upgrade from 3.5 MVA to 5 MVA, it will occur in 7.75 years with a cost of 56 000$/MW at a discount rate of 8%. The result is an investment of $153 807 which means a profit of $14 412.

Relatively to the peak load reduction, the microgrid is capable of delaying an investment for 33.8 years which means a NPV of $40 885, net savings of $112 922 to the utility. If the utility compensates the microgrid owner for even the entire value of the deferred investment it is impossible to make up the total project deficit.

From the analysis of all these values it is already possible to prove that, even though the estimates are a bit optimistic, it is possible to implement not only an economically viable project but a profitable one. However, it is possible to create a business model providing several if not all these services. In this case, conjugating all these services, the investment can be easily covered. The following assumptions were taken into account:

- The energy value not delivered by the utility is 1500$/MWh and the value is shared with the microgrid owner. The DNO and the IPP both win $36 097.
- Using 50% of the capacity not used to create bids in the spinning reserve market at a 4$/MWh gives an average annual profit of $47 120 to the IPP.
- If every ton avoided emission has a compensation tax of 10$/ton the profit is $80 208.
- If the DNO shares the value of deferred investment with the microgrid owner the profit is $56 461, equivalent to $5289 amortized through the project lifetime.

Summing all these values it comes a $168 715 annual income, equivalent to a profit of $29 319 per year to the microgrid owner. The DNO benefits $ 41 386 and the consumers $196 125 [57].

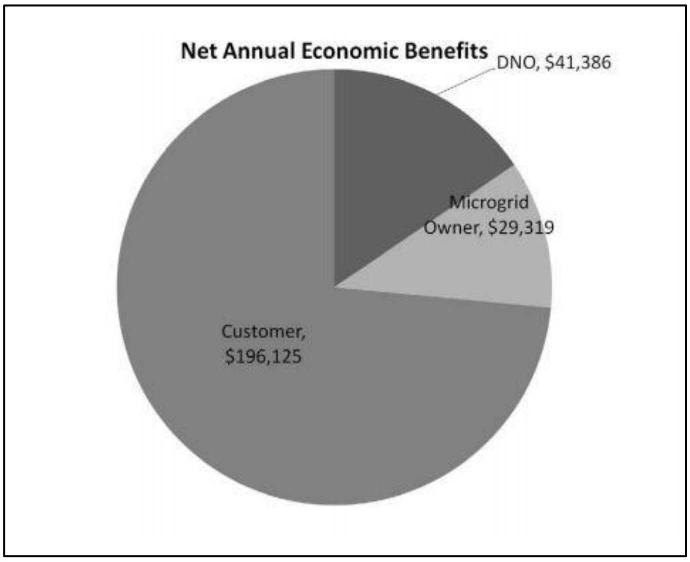

Figure 23 - Net annual benefits for DNO, Customers and IPP.

6.8 Regulatory Environment and Incentive Programs

The previous case study showed that the legislation can help the deployment of microgrids even though there are others which make it difficult such as permitting issues, market penetration, financing and fuel supply management. However, the biggest obstacle that was not explored yet, in this work is the interaction between the microgrid and the utility. Problems like interconnection standards, standby rates or sub metering rules are, usually, the most presented in this relationship. Utilities have two concerns about the microgrid. One is related with the technical part because microgrids can harm the grid reliability through interconnection tripping or failing to island or reconnect properly. The other concern is financial because utilities predict a high backup cost for microgrids. There is, still, to underline the fact that microgrids can compete with utilities in the energy distribution business. The clients being supplied by DGs abandon the utility. If this happens in large-scale, utilities see their client base being reduced drastically which can be insufficient to pay all the costs involving the distribution process without recurring to higher taxes which can influence other clients to leave the utility.

Another regulatory restriction for microgrid deployment is the fact that in several locations it is impossible to transmit wires in public streets infringing the utility franchising rights. However, taking into consideration the North American example, the laws are different from state to state and it will be seen below a case where this law is not applied. In some states where the legislation is tighter, microgrids are not totally excluded. A financial agreement with the utility is necessary so that private entities can go forward with their projects. Fortunately, some states and countries, with incentive programs to implement microgrids, can help in overcoming some of the regulatory challenges explained above.

In Connecticut the support for microgrids is done through financial and regulatory incentives. Until now, this state applied two solicitations for microgrids and there is another one being planned. These solicitations were:

- In July of 2013 were funded several microgrid projects with $18M with hosts being critical facilities such as police stations, hospitals, fire departments etc.
- In March of 2014 it was offered a $15M fund for projects promoting geographical diversity.

On top of these financed programs, several laws promoting microgrid deployment were created. One of those laws (Public Act No. 13-298) allows microgrids containing public streets to be able to do it without infringing the utilities franchise, even though those microgrids had to supply only critical facilities.

In New York, the New York Public Service Commission created a procedure which can be very interesting for stakeholders involved in the microgrid concept. It is called Reforming the Energy Vision (REV). The idea is the creation of a grid operator called Distributed System Platform Provider (DSPP) which manages the DGs in a similar way to nowadays centralized generation markets. It will be a kind of market platform where the owners of distributed sources can buy and sell energy. Finally, it would be responsible for targeting distribution grid needs, measure programs and handle payments/transactions. The utility is a good candidate to provide the service as a DSPP. This proposal is still not completely formulated and it will be reviewed, discussed and possibly changed. The New York governor also announced a $40M funding for a competition to launch at least ten microgrids.

The own USA government through the Department of Energy created a solicitation in January of 2014 to offer grants for research, development and system design of microgrids. More specifically, the objective is to test advanced commercial microgrid controllers for microgrids from 1 to 10 MW. The candidates who win the grants are responsible to work with an entity or a community in order to design microgrids capable of supply power to a small community or critical facilities. There are still regulatory aspects being studied to overcome some issues related with microgrids. The Federal Energy Regulatory Commission (FERC) does not have a docket specific for microgrids but it has opened some discussion about that issue.

In Canada the research work is being done through the Smart Microgrid Network (NSMG-ND) which is a partnership between Canadian universities, the government and the industry. This program involves not only the development but also the test, verification of technologies and legislation. More specifically, in Ontario, their long term energy plan predicts an association with the federal government to develop microgrids in their remote communities. One of the Ontario government actions, through the energy minister was the partial funding of a project with the Canadian Solar in which a test microgrid was created to share information and services with utilities, communities and companies interested in the concept. There are near 300 remote communities in Ontario, so the interest in remote microgrids is high [58].

Chapter 7 - Conclusions

This work started with a brief description about SG to introduce new concepts which can be used in traditional electric systems to improve their reliability, efficiency and integrate new consumption profiles and renewable sources.

The concept of SG is not very accurate but in every, of the many definitions, it considers 2 way flow of energy and information associated with the active participation from the costumers.

The defining characteristics of the SG recall for a change in the infrastructures used in the traditional electric system. The microgrid is one of those structures. The SG can help solve some issues such as the environment through its ease in integrating renewables. Sensors, PMU and smart meters are interesting physical equipment to be introduced in the electric system. To realize SG, a communication network is necessary connecting all the infrastructures and devices in order to share information, such as the grid status, to realize a good management for the grid as a whole. There are several communication infrastructures capable of doing it and they can be wireless or wired.

A good management system will be able to achieve different objectives such as better energy efficiency, operation costs, emission reduction and better balance between supply and demand through demand profile shaping. The utilities profit is, also, an important factor that the management system must take into account.

The security is another important aspect for SG because it reveals new possible issues in that area due to new functionalities which can be easily hacked through cyber-attacks, industrial spies or terrorist attacks. The protection, focus on system reliability and prevention, prediction and protection against faults. The fault identification, diagnose, system recuperation and the privacy and security are other factors that must be in the scope of the protection systems. The security and privacy of the consumers is related with the energy distribution process, but also, with the information gathered on all the new devices stated before. Using PMUs and using several methods it is possible to have an evaluation of the grid status in real time increasing the reliability of the system.

The management of the microgrid is done by a controller which receives real information or generation prediction and the consumption to control microsources and load through the communication systems. The PLC is communication infrastructure that proved to be a good option for this kind of systems because it was already present in tests and passed them in the European MICROGRIDS project. The microgrid protection system is more complex since

DG cause amplitude duration change and direction of fault current. However there are several methods which can be used depending on the microgrid type and its operation mode.

Finally, it will be seen the most relevant conclusion about microgrids. The concept of microgrids, like SG, is not explicit and it varies from region to region. Microgrids can function as AC or DC systems. There are many advantages coming from the microgrid implementation but there are also some challenges that must be surpassed. The HOMER software showed to be an interesting tool for microgrid optimal economic design as it was seen in the case studie. Even though the optimal design relies on an economic analysis there are other factors that must be considered such as greenhouse gas emissions. A sensitivity analysis must also be done for several parameters like fuel cost or unmet load. Based on a case study it was possible to conclude that the microgrid optimal design taking into account only the energy exchanges can be a profitable project. The other case studied proved that recurring to provided services from the microgrid it will be possible to get a higher profit. However, these services are dependent on legislation and the microgrid is seen as a competitor to the utility. Fortunately, there are already some states in the USA and some countries in the World with incentive programs to the deployment of microgrids which can help to alleviate the division between the utility and private entities wanting to invest in these systems. However, the great conclusion of this work is that there is still a lot to do to realize the deployment of SG and microgrids in large scale. Even though, depending on the region it is possible for private entities to have a business model for these systems exploring the local legislation and financed programs.

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