Faculdade de Engenharia da Universidade do Porto

Storage coordination of photovoltaic injection for loss reduction purpose

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Resumo

A energia solar está apenas disponível durante o dia. Mas este período pode não coincidir com o consumo de carga. De modo a aproveitar toda a energia diária produzida, uma central fotovoltaica ligada á rede injeta a diferença entre a energia disponível e o consumo local nessa mesma rede. Neste trabalho propomos o uso de sistemas de armazenamento capazes de guardar a energia solar quando é possível e injeta-la quando é mais necessária, nos picos de carga para melhorar a eficiência da rede.

Esta dissertação propõe uma metodologia para uma ótima coordenação da energia armazenada com intuito de reduzir as perdas, através de previsões da produção solar e das cargas e sujeito a restrições da rede. Esta metodologia foi implementada em código de Matlab o que gerou um protótipo de ferramenta capaz de assistir os produtores fotovoltaicos na gestão ótima das unidades de armazenamento em relação á previsão da produção solar e das cargas da rede.

A estratégia proposta foi aplicada numa rede teste alcançando reduções das perdas quando o sistema de armazenamento é ligado á central fotovoltaica. Foi mostrado que os métodos de alocação de perdas podem ser usados para calcular os incentivos para os produtores dispersos pela contribuição na redução das perdas.

Abstract

As solar energy is available only during the day, this not always coincides with the load consumption. In order to take profit of the entire daily energy, a PV plant connected to grid injects the difference between the energy available and the local consumption into the network. Here we propose the use of accumulators able to store solar energy when it is available and successively deliver it when it is more need during the peak load period increasing the global efficiency of the network.

This dissertation proposes a methodology for optimal coordination of the stored energy for loss reduction purposes based on load and solar power forecasts and subject to the network constraints. This methodology has been implemented in Matlab code generating a tool able to assist PV owners for an optimal management of their storage device in relation with the prevision of solar production and load forecasted in the network.

The proposed strategy has been applied to a test system achieving higher loss reduction when storage capacity is added to a PV plant. It has been shown that loss allocation techniques can be used to calculate effective incentives for loss reduction contribution offered by DG units.

Acknowledgements

I begin by thanking my supervisor and co-supervisor, Professor Jean Sumaili and Mauro Rosa for the confidence and motivation that has placed in me and all the support given.

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Abbreviations and symbols

AC	*Alternating current*
CHP	*Combined heat and power*
DC	*Direct current*
DG	*Distributed generation*
DSO	*Distribution system operator*
PV	*Photovoltaic*

Chapter 1

Introduction

1.1 - Contextualization

As the society evolves and become more technologically advanced, the need for energy and its consumption quickly rises. After the industrial revolution, the need for cheap, readily available energy made the fossil fuels an excellent choice to solve this need for energy.

However the fossil fuels become more and more a part of the energy produced worldwide, humanity is now facing the turning point where this type of resource is no longer abundant, its prices are increasing and the society is becoming more “green”, requiring types of energy more environment friendly. For all this reasons, distributed energy using renewable sources has emerged as an alternative to the traditional large power plants, expanding its penetration and integration in the power networks.

Photovoltaic (PV) technology arise as one of the diverse alternatives to fossils fuels. In the last decade, the development of new technologies and the consequence improvement of the efficiency in this type of generation make its expansion boom. Many buildings have installed PV panels on their roofs. Combined with storage device the applications of PV plants can be even further extended.

Unfortunately, the connection of this type of generators in the distribution networks can bring some technical issues as its “fit and forget” connection is applied. This approach does not give advantage for the use of storage unit, while connected to the network. So, as more and more DG units are integrated in the networks, an active management of the distribution networks is a future becoming reality. This active management would enable to control the storage unit and control the power injected to the grid by this PV/storage coordination and improve the issues related to the integration of DG units.

1.2 - Objectives

This dissertation aims at proposing a coordination strategy for the management of a PV plant with storage capacity for loss reduction purposes. The goal of this work is the development and the implementation of a tool able to suggest the optimal PV injection in order to minimize the total losses of the system. This tool must determinate the periods of the day when the produced energy will be stored and successively injected in the grid when there is more capacity for loss reduction. Loss allocation algorithms will be used for calculating the contribution of the DG plant to the reduction of the losses.

1.3 - Structure of the thesis

The structure of the thesis is divided in five chapters. The first one consists in a general introduction to the problem analyzed and in the presentation of the goal of the thesis.

Chapter two is dedicated to the state of the art. At the beginning the focus is on the composition and operation of Distribution networks, then Distributed Generation and storage devices issues are presented. One section is entirely dedicated to PV systems offering an overview on the main characteristics and configurations. After that, typical load curves are presented. Then the solution of the equations of power flow in distribution system is discussed. The last section of chapter two is related to the loss allocations methods and presents two promising algorithms.

Chapter three shows the explanation of the problem which originate this work as well its mathematic formulation. The variables are shown and the algorithm operation is detailed and explained.

Chapter four is about the case study applied to show the effectiveness of the proposed methodology. The obtained results are then presented and analyzed.

In the last chapter, the main conclusions are exposed as well as the main contributions to the problem studied. The limitation of the developed algorithm and the perspectives future improvements are located at the end of the dissertation.

Chapter 2

State of art

2.1 – Distribution networks

This section contains an overview of the structure of a traditional power system and will focus on the distribution networks and their configurations. The goal of an electric power system is to generate, transport and distribute the electric energy from the generation units to the consumers [1]. It can be divided in 3 main parts:

- Generation
- Transmission
- Distribution

In the traditional system, electricity is produced from large central generators which elevate it at higher voltages to make it possible to transport. Then, the transmission lines transport the energy to distant substations where the voltage is lowered and only after this the electricity is distributed to small consumers. However, large and medium consumers can be directly connected to the transmission network. This operation structure is shown in figure 2.1.

The distribution network can have two types of topology or simply how their lines are connected. In radial configuration lines branch out sequentially and only have one supply from a substation. This configuration is typical in rural and isolated areas where the loads are separated by long distances. In an interconnected network, any two points are usually connected by more than one path meaning that some lines form loops within the system. This is typical in urban areas where there is a more density of loads. The interconnected networks usually are explored in radial configuration.

The distribution networks can also be aerial or underground. The main difference between the two is the cost. The construction of aerial lines is much cheaper than to bury those lines. So in isolated or rural areas, it is preferred the aerial option. However, for safety reasons, the lines are almost always buried in urban areas.

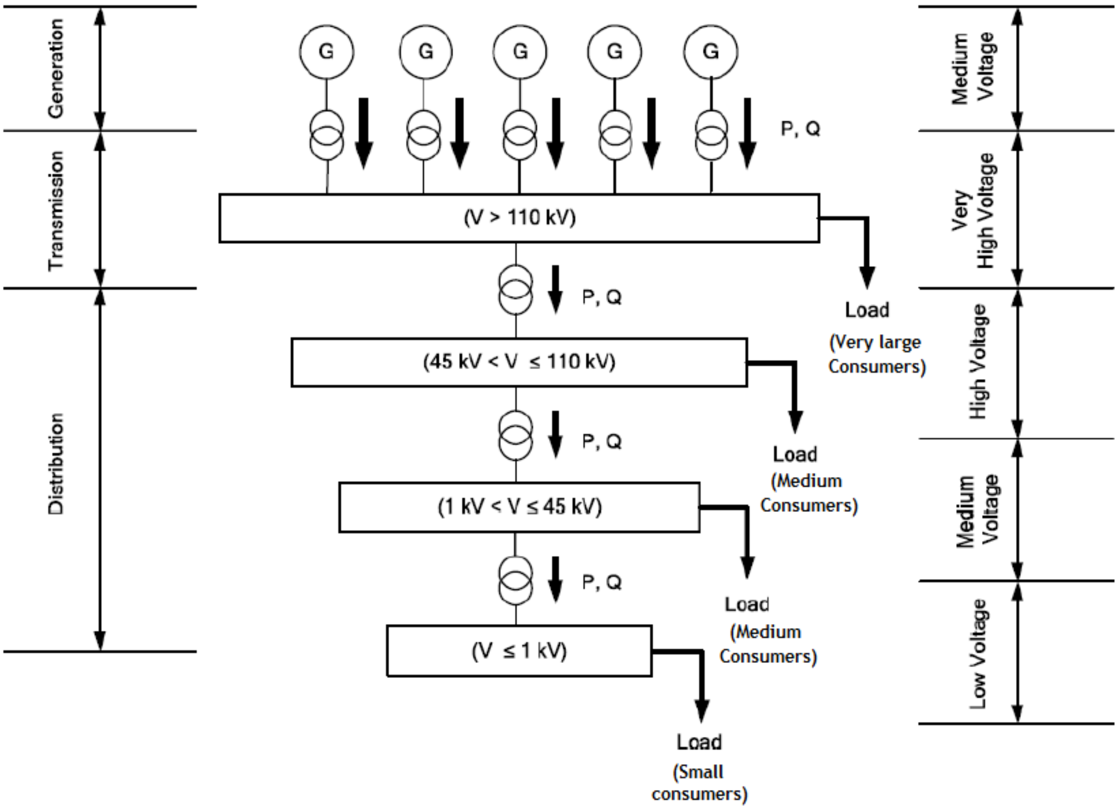

Figure 2.1 - Structure of a traditional power system [2]

2.2 - Distributed generation

This section is dedicated to the distributed generation. After a brief definition, a comparison between the DG and the traditional centralized generation system will be discussed and some types of DG will be presented. The impact of the integration of such units is the next topic followed by an explanation of the future active management of the distribution networks. To end this section, some available storage technologies are reported.

2.2.1- Definition

Distributed generation describes the application of small generators, located in the distribution network close to the point of consumption. Such generators produce electric power to the consumers on site or may sell a portion, or perhaps, all of it to the distribution network for near consumers. If there is a waste heat available, the overall efficiency can be improved with process heating, space heating and air conditioning. In some cases it can operate isolated from the grid. [2]

2.2.2- Traditional power systems versus distributed generation

Traditional distribution systems were designed to accept bulk power at the bulk supply transformers and distribute it to the consumers. Therefore the flow of both active and reactive power was always from the higher to the lower voltage levels.

With the penetration of DG units, the distribution network is no longer a passive circuit supplying loads. Power flows may become reversed, the distribution network turns into an active system with power flows and voltages determined by the generation as well as the loads. The figure 2.2 shows this change in the distribution network. As it can be seen in the example, the CHP unit can only export active power but it may absorb or export reactive depending on the setting of the excitation system of the generator. The voltage source converter of the PV system allows the export of real power with a certain power factor. [2]

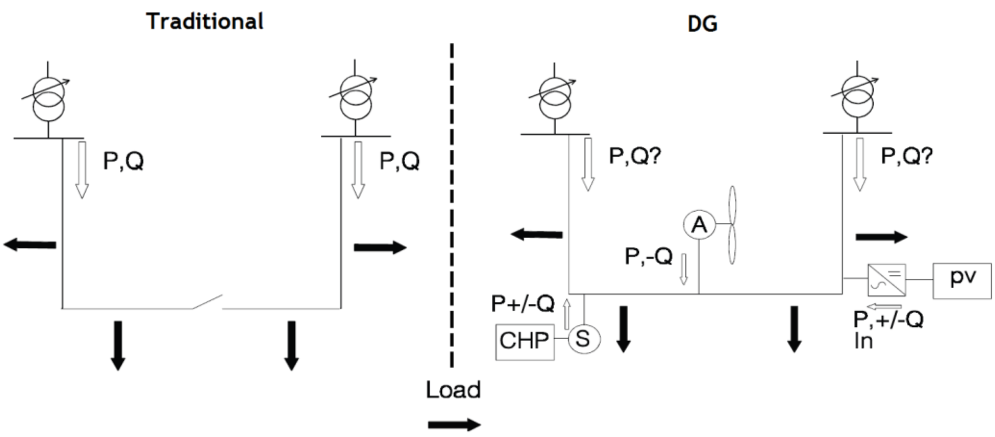

Figure 2.2 - Traditional power system and distributed generation [2]

So, a traditional centralized power system can offer a number of advantages over the DG. Large generating units can operate efficiently with only a relatively small number of personal. The interconnected high voltage transmission network allows generator reserve requirements to be minimized and the most efficient generating plant to be dispatched at each time. Also, large quantities of power can be transported through large distances with limited electrical losses because of the high voltage transport and power is more economical to produce in very large amounts. [2]

Despite all of these, DG units can overcome traditional power systems in many aspects. DG units using renewable sources have a reduction in gaseous emissions which, in an environmental society, is very important. DG units also have smaller construction times which permits a better and a quicker introduction of power in the system, lower capital costs and can reduce the transmission losses due to its proximity with the loads. The modular introduction of new DG units can also reduce the investments of new power plants to satisfy the growing demand. The diversification of energy sources improve the energy security as a failure of one DG unit would have limit impact compared to one large power plant or bulk electricity transmission facility and improves the quality service to the consumers. The mix of energy sources, especially with renewable sources also guarantees that future generation will have a better control over its energy needs. [2]

However, this change of active and reactive power introduces important technical and economic implications for the power system which will be better detailed in Section 2.2.4.

2.2.3- Types of Distributed generation

The DG includes some different forms of producing electrical energy which can be or not from renewable sources. Among them are, we can cite:

- Micro-turbine
- Fuel cell
- Reciprocating piston engine
- CHP (cogeneration)
- Biomass
- Solar photovoltaic generation
- Wind power
- geothermal
- Small-scale hydro-generation

Micro turbines

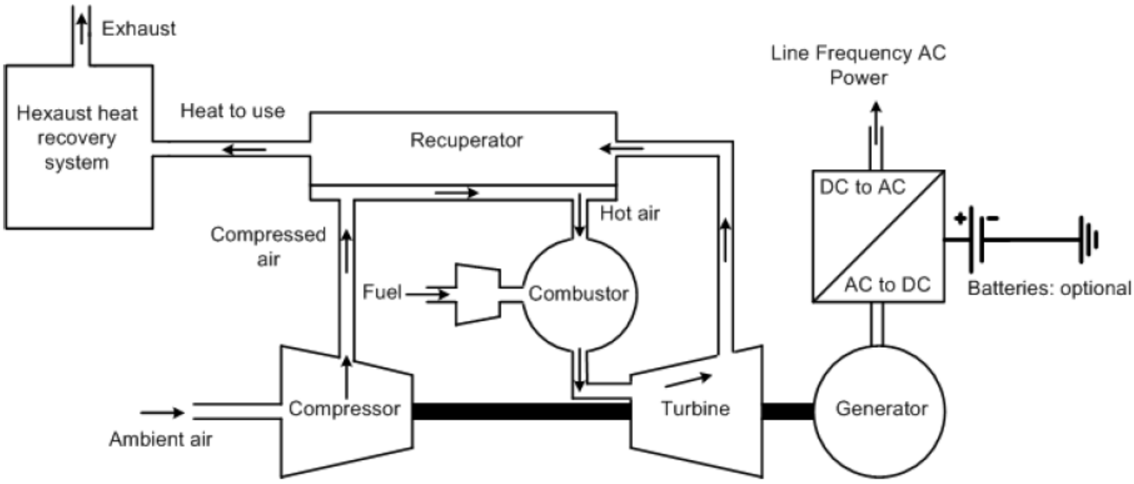

Figure 2.3 – Operation diagram of a single shaft micro turbine unit [3]

Micro-turbines are tiny combustions turbines with a range of 20kW to 250kW which works at a very high rotation velocities to optimize the efficiency. It is used for the combustion gas, biogas, diesel and kerosene. There is no use of liquid coolants as the refrigeration is made with air and it uses an air bearing which make the use of lubricant unnecessary. It has a high reliability, low maintenance needed, can operate in parallel with the grid or in isolated systems and has low gas emissions.[3]

Technologically speaking there are two constructive types of micro turbines:

- Single shaft (figure 2.3)
- Split shaft

The advantages and disadvantages of each technology are shown in table 2.1.

Table 2.1 - Advantages and disadvantages of technologies present on micro turbines [3]

Technology	Advantage	Disadvantage
Single shaft	• Less moving parts • No need for a gear box • Less noise	• Compromise between the needs of the turbine and an electric load well defined
Split shaft	• Flexibility in combining a turbine and the electric load required • Less mechanical stress • Better life time	• More moving parts • Needs a gear box • More expensive
Air bearings	• Eliminates the necessity for a refrigeration and oil lubrication system ant the maintenance associated	• Reliability issues associated to attrition during the start and stop
Oil bearings	• Mature technology	Require an oil pump and auxiliary refrigeration equipment
Without heat recovery	• More cheap • Better reliability • More heat available to co-generation	• Worse efficiency
With heat recovery	• Better efficiency	• More expensive • Less reliability an life time
Ceramic hot sections	• Bigger working temperature • Better efficiency	• More complex project • Still in development
Metallic hot sections	• Conventional project • Available on market	• Less working temperature • Worse efficiency

Fuel cell

Just like usual batteries that are used every day to power, for example, our remote controls, fuel cells can produce electricity directly with reactions of oxidation-reduction. By other words, converts the chemical energy in the cell directly into electricity.

A fuel cell is composed by four main parts [3]:

- The anode has a negative charge and it conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit.

- The cathode has a positive charge and it conducts the electrons back from the external circuit to the catalyst, where they can recombine with the hydrogen ions and oxygen to form water.
- The electrolyte is the proton exchange membrane composed by a specially treated material that only conduct positively charged ions, blocking electrons.
- The catalyst is a special material that facilitates the reaction of oxygen and hydrogen

Individually cells connected in series can produce higher voltages. The composition and the operation of a fuel cell is shown in figure 2.4

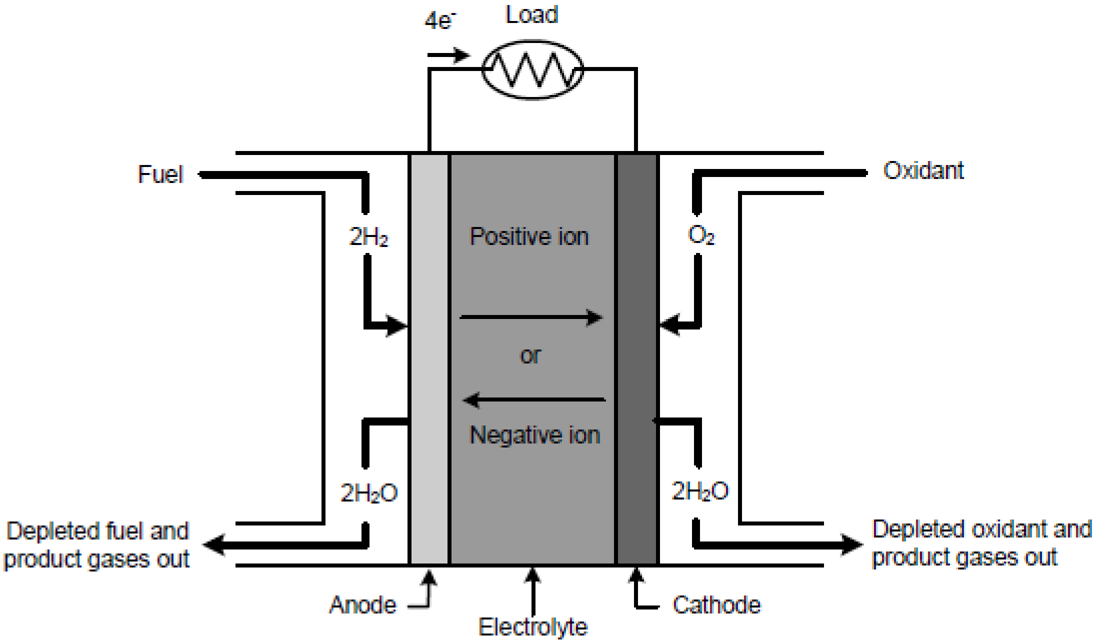

Figure 2.4 - Constitution of a fuel cell [3]

The main advantage of this type of DG is the efficiency boost obtained in the conversion process mainly because there is no need of intermediate energy conversion process as shown in figure 2.5.

Another advantage is the fact that the fuel cells do not produce gas emissions and as there are no moving parts, they are very silent. It's a very flexible technology and an excellent potential substitute to fossil fuels in mobile applications.

However it still has issues that need to be resolved before it can be commercialized at full scale. This technology lacks of maturity as its price still it's too high and the lifetime short. The lack of infrastructures to the hydrogen is still a barrier so is the technological problems such as the contamination of the membranes and the difficulty to achieve high currents.

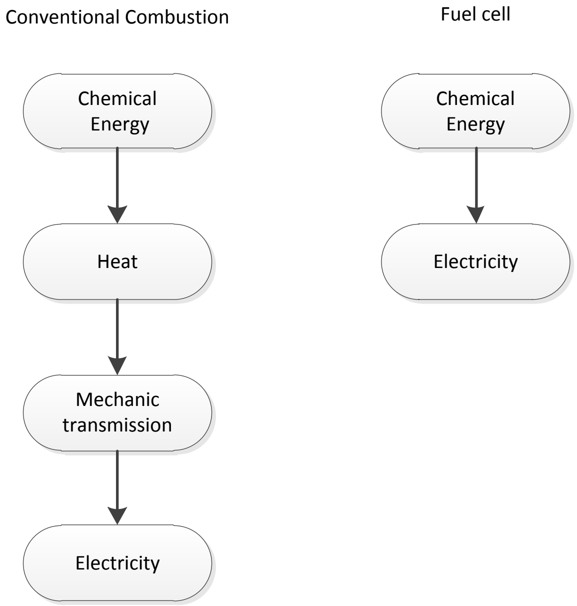

Figure 2.5 - Process comparison between conventional combustion and fuel cells [3]

Reciprocating piston engines

Reciprocating piston engines are the most widely used type of power source for distributed generators. Such generators use a gasoline, diesel, natural gas, or propane/methane powered piston engine to spin an electric generator with the engine's crankshaft and the generator's rotor usually spinning at the same rate on the same or directly coupled shafts. Although there are rare exceptions. Almost all piston engine DG units use a constant-speed alternating-current generator. Alternating current frequency is therefore controlled by controlling engine speed.[4]

The basic process for the reciprocating piston engines is the Otto cycle. A cycle consists of four strokes, each stroke the movement of the piston through a full back or forth motion, with each also corresponding to one-half revolution of the crankshaft for a total of two revolutions required for one complete cycle. Air, perhaps, already mixed with fuel at this point, is drawn into the cylinder in the intake stroke in which the engine uses its inertia to do work pulling the air into the cylinder. The cylinder contents are then compressed in the second stroke and combustion takes place producing pressure and heat to move the piston in the third power stroke, the only one of the four that produces a net energy gain. In the exhaust stroke, the engine's rotational inertia forces the products of the combustion (exhaust) out of the engine, and it is ready for another two-revolution cycle [4]. The complete Otto cycle is shown in figure 2.6.

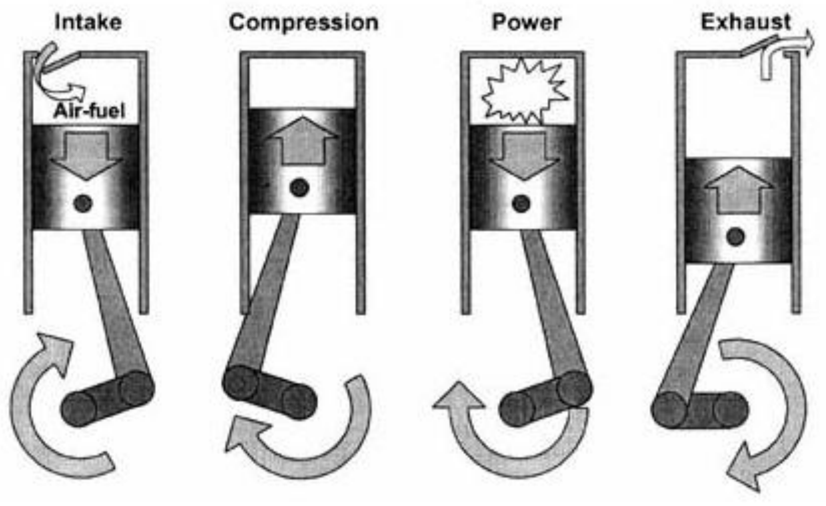

Figure 2.6 - A basic Otto cycle [4]

To achieve the conversion to electrical power, the internal combustion piston engine transfers the mechanical motion to a rotating electric generator. Four types of generator can be attached to the reciprocating engine, synchronous AC, inductive AC, DC with DC/AC conversion, or written pole synchronous AC generation. [4]

Because of its extensive use in personal automobiles, public transportation, tractors and similar machines, the basic technology has been evolved to a high level. A century of competition in both the marketplace and automobile racing as well as R&D programs of automobile manufacturers also contributed to the mature of this technology. But their greatest advantages are the low-cost manufacturing base and simple maintenance needs. As disadvantages are the lacks of good use of the heat for co-generation purposes, the exhaust emissions, noise and vibration. [4]

CHP

CHP is the combined production of heat and power and their effective utilization. Generally this type of production is used in industry as it can use great quantities of heat and electricity. When the production exceed the amount needed by the industry unit, it’s possible to inject that excess of production into the network. The same principle is applied to the heat. As enormous amounts of heat are required to produce electricity, this heat can be used to industrial processes and heating the interior facility or transport for local district heating. [5]

The main advantage of this type of DG is the fact that the combine production of heat and power can achieve an efficiency of about 90%. The time of return of the initial investment is very small and if the fuel is the natural gas, the pollution levels are low. Also, the industry where it’s located becomes less vulnerable to electrical failures. The figure 2.7 shows the efficiency advantage of CHP over systems with separate heat and power.

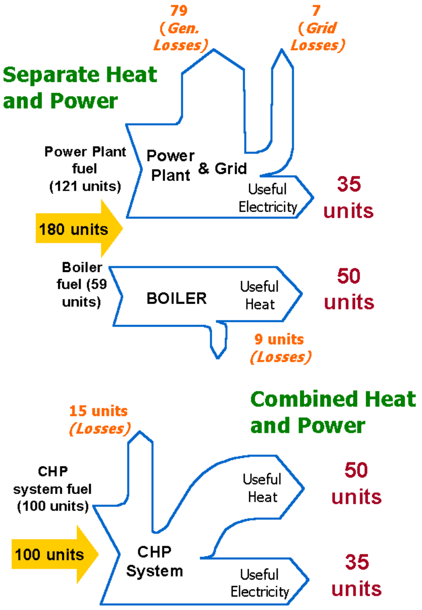

Figure 2.7 - Efficiency comparison between a unit with separate heat and power and the CHP [6]

Biomass

Biomass is the burning of biological material derived from living or recently living organisms which include:

- Fast growing trees and grasses
- Agricultural residues like used vegetable oils, wheat straw or corn
- Wood waste like paper trash, yard clippings, sawdust or wood chips
- Methane that is captured from landfills, livestock and municipal waste water treatment

There is also two other methods to convert biomass into electricity. The alcohol fermentation where biomass is converted into alcohol fuel and landfill gas which consist in decomposing the biomass harvested to generate gas that will be turned into electricity.

Solar photovoltaic

Solar photovoltaic is the conversion of sunlight into electricity. This type of DG is used for the optimization algorithm developed in this thesis so it will be fully covered in section 2.3.

Wind Power

Wind power just as the name says, take advantage of the wind to convert its energy into electricity. This conversion is achieved by extracting kinetic energy from the wind passing through its rotor as shown in figure 2.8. The passage of the wind slow it down as the difference of the after and before is the kinetic energy collected. Slowing it completely would also stop the generation as it would mean that no mass was in motion past the turbine rotor blades, and that the energy collected was zero. Thus, energy is extracted from Wind when it is slowed, but not stopped. The maximum energy is extracted when it is slowed to 1/3 of its speed when the energy collected from wind is about 59%.[4]

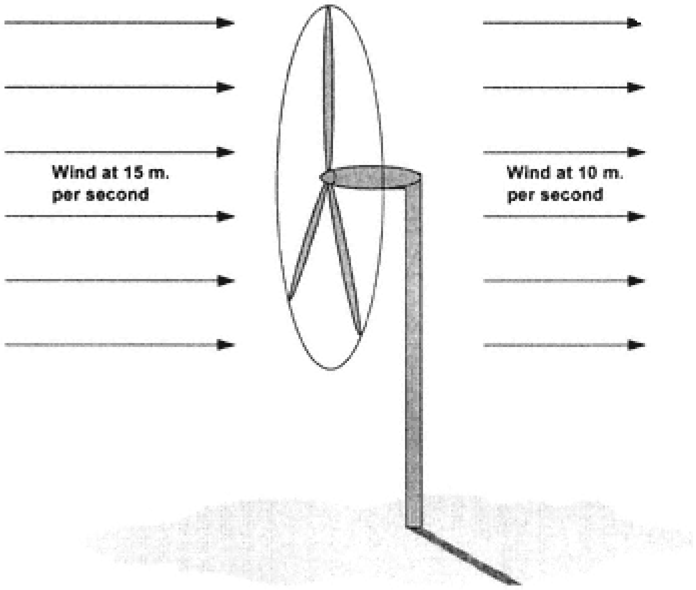

Figure 2.8 - Wind energy captured by a wind power generator [4]

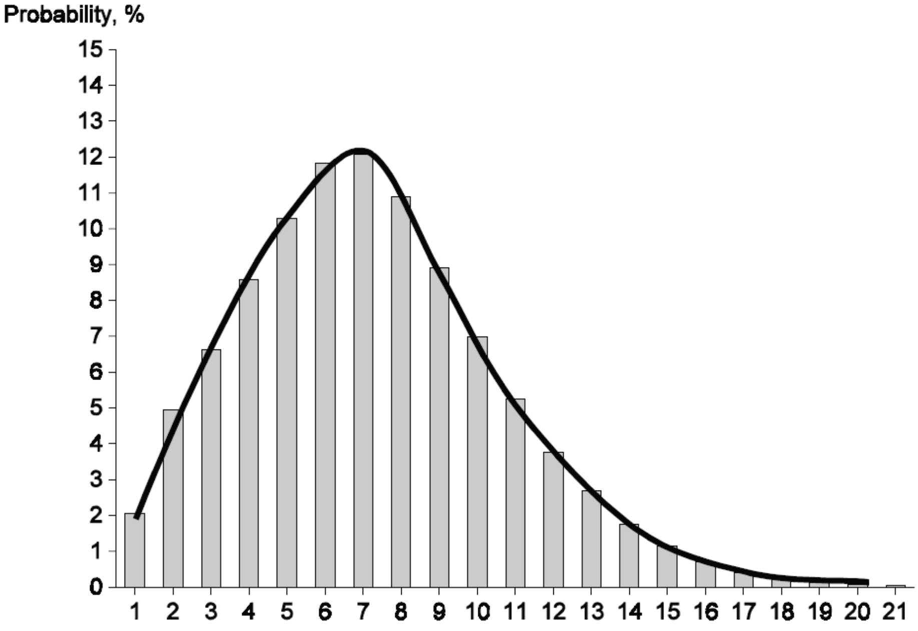

Figure 2.9 - Distribution of hourly mean wind speeds of a typical lowland site [5]

Although, managing wind energy is difficult as the wind is not completely predictable making it impossible to depend upon it entirely, or to commit to a production schedule or firm power sales contract. As a result, Wind energy is often labeled a "non-dispatchable" resource: the owner has to take whatever power is available, when available. This unpredictability can be observed with the distribution of hourly mean wind speeds that is shown in figure 2.2.7. [4]

The power developed by a wind turbine is given by [7]:

$$P = \frac{1}{2} C_P \rho V^3 A \quad , \tag{2.1}$$

where " C_P " is the power coefficient, "P" the Power (W), "V" the wind velocity (m/s), "A" the swept area of rotor disc (m^2) and "ρ" the density of air which is equal to 1.225 kg/m^3.

The equation (2.1) show that the power developed is proportional to the cube of the wind speed demonstrating how important is to locate any electricity generating turbines in areas of high mean annual wind speed. These areas are often away from habitations and located on higher ground where high wind speeds are encountered.

The power coefficient *Cp* is a measure of how much of the energy in the wind is extracted by the turbine rotor. It varies with rotor design and the relative speed of the rotor and wind (known as the tip speed ratio) to give a maximum practical value of approximately 0.59.

The power yield of wind energy converters can be determined by means of a converter-specific characteristic power curve. It reveals the dependency of the average electrical power from the respective average wind velocity and thus shows the operational characteristics of the converter.

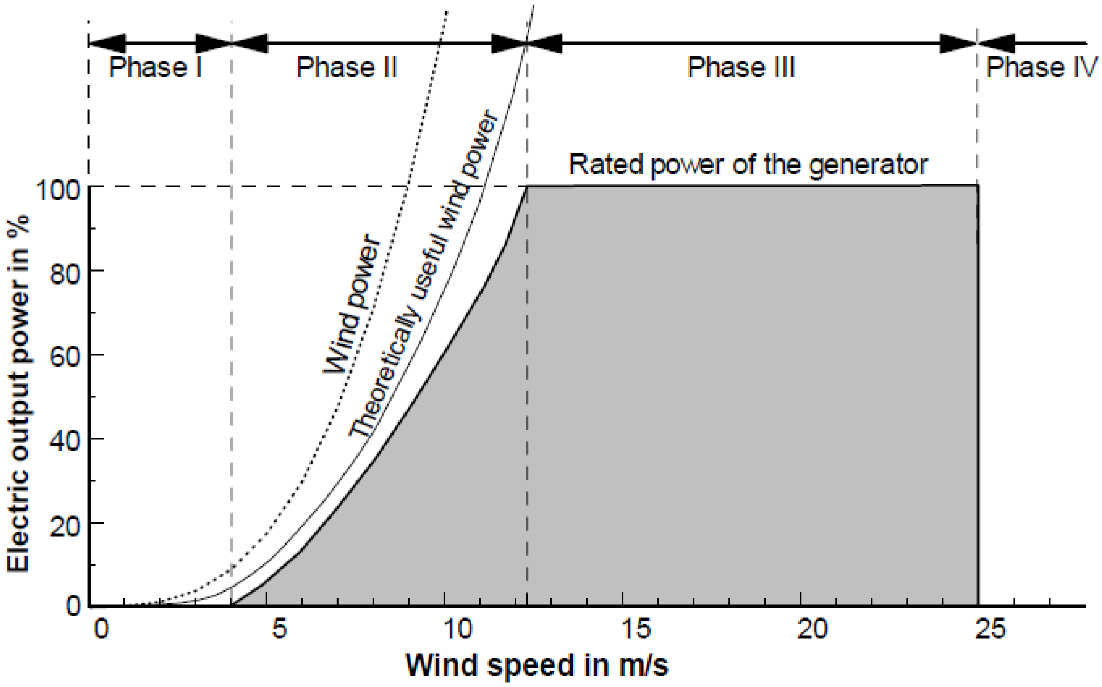

Figure 2.10 - Characteristic curve of a wind energy converter [8]

As is shown is the figure 2.10, the operational characteristics can be divided in four parts. In the first one, if the wind speed is lower than the specific converter minimum speed, the converter will not start. The power of the useful speed difference is insufficient to surmount the converter's friction and inertia forces and to enable converter operation. Thus, there is no electrical power output. In the phase 2, as the wind speed exceeds the required for the converter to start, it will begin to generate electrical energy. Yet, the useful electrical energy at the generator outlet is not exactly proportional to the theoretic useful energy as losses which are not linear to speed. In phase 3, Due to the limited generator capacity, matching the respective converter dimensions, the power absorbed by the rotor of a given wind energy converter must not exceed the installed nominal generator power over an extended period. For wind energy quantities that exceed the nominal wind speed and that are below the cut out wind speed of the converter, which theoretically enable energy absorption beyond the installed capacity, an appropriate control must ensure that the rotor axle transmits at most the installed generator capacity to the generator. Finally, at phase 4, if the wind speed exceeds a certain speed limit determined by the converter design and type the wind energy converter must be shut down to prevent mechanical deterioration. At this phase, there is no power output. [8]

The wind power can use two types of turbine generators, a synchronous Generator or an asynchronous Induction Generator. As the wind turbine is allowed to spin at whatever speed it needs to deliver the maximum power, when its connected to the generator the electrical output will have variable frequency. This means that for connection to the grid purposes, a conversion is needed to match the grid frequency. The figure 2.11 show the basic concept of this type of network connection containing an AC/DC rectifier to convert the AC frequency into DC, an DC/AC inverter to convert it back to Ac but with the frequency of the grid and finally a filter to smooth the output. [8]

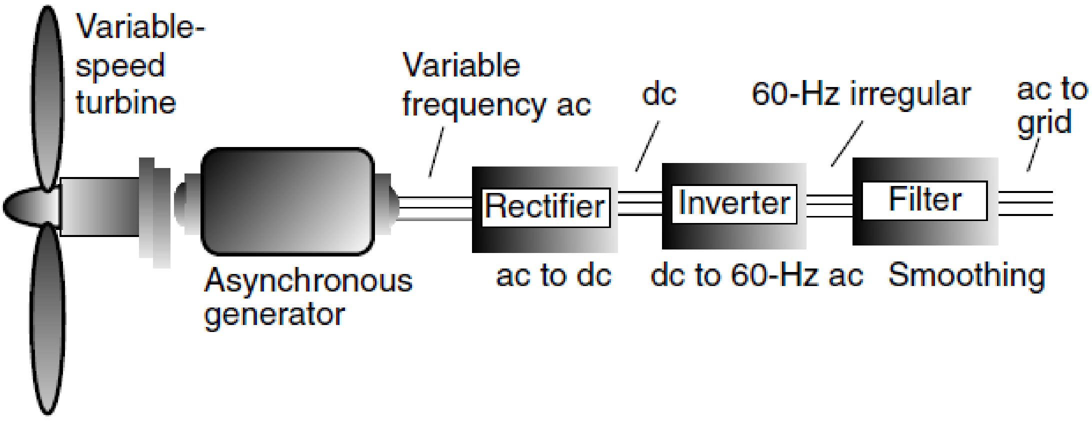

Figure 2.11 - Constitution of a basic network connection [1]

As conclusion, the main advantages of wind power are [4]:

- The wind is a free renewable resource, does not emit pollution and it can be collected efficiently
- There's a wide range of wind turbines which make it a multipurpose energy source
- Remote areas with difficult network access can now produce their own energy supply.

The mains disadvantages are:

- Wind turbines can have a undesirable appearance changing the landscape.
- Because of their tall, thin shape, they are more susceptible to lighting which can cause damages.
- Wind turbines are in general noisy
- Large wind farms (group of wind turbines) are needed to provide entire communities with enough electricity.

Geothermal

Some locations have thermal energy in near-molten rocks below the earth's surface. Water can be pumped into such locations, where the heat tums it to steam, which in turn can be used to power a steam turbine generator. Numerous sites like this exist around the world, most in volcanically active or tectonic plate activity line areas.[4]

The main advantages of this type of DG are the fuel free generation, produce no pollution, the energy is almost free, as the only energy required is for the pump and the power station does not take much space, which have limited impact on the environment. Despite of these positive aspects, there are few places all over the world that can sustain this type of generation. Also, Hazardous gases and minerals may come up from underground which can be hard to dispose of and sometimes geothermal sites can gradually draw off so much of the underground heat that it cools the rock to the point that the plant is no longer functional, in some cases for decades.[4]

Small-scale hydro-generation

Hydro-electric power is a proven and mature technology for electric power production (over than 40 years). While most hydro plaits have a substantial head (difference between high and low water levels on opposite sides of the water turbine), it is possible to generate electric power in small amounts with a small difference and a flow equal to that of many small rivers and large streams. They do not have a substantial reservoir of Water storage behind them to vary output, but instead work with whatever flow the river provides, registering only small variations from day to day. It’s a technology with high efficiency (ranges from 70% to 90%) and has a high capacity factor, which is the proportion between the production in a period of time and the maximum capacity in that period (P/P_{max}). It’s considered a renewable resource because its impact relatively to large hydric is very small.

Mini hydrics cannot be seen as reduced copy of the large hydric power plants. It has some particular characteristics:

- The introduction of new technologies that reduces the cost
- The construction of compact and simple systems are oriented to reduce local works
- It has normalized turbines with good efficiency for a wide range of operating schemes
- Uses synchronous machines as generators
- It can be implemented in a larger number of sites as it requires a low-head

- More simplicity in the operation including the full automation of the plant.

The output of a hydro-turbine is given by the equation (2.2) [5]:

$$P = QH\eta\rho g \quad , \tag{2.2}$$

where “P” is the output power, “Q” the flow rate (m^3/s), “H” the effective head (m), “η” the overall efficiency (which include the efficiency of the turbine and generator), “ρ” is the density of water (1000 kg/m^3) and “g” the acceleration due to gravity

Clearly a high effective head is desirable as this allows increased power output while limiting the required flow rate.

The types of turbine used depend on the flow rate and head. At lower heads, reaction turbines operate by changing the direction of the flow of water. Common designs of reaction turbine include Francis (medium flows) and Kaplan (big flows) types. At higher heads, impulse turbines are used which include the Pelton types. It operates by extracting the kinetic energy from one or more jets of water which are at atmospheric pressure. The head flow to different types of turbines is shown in figure 2.12.

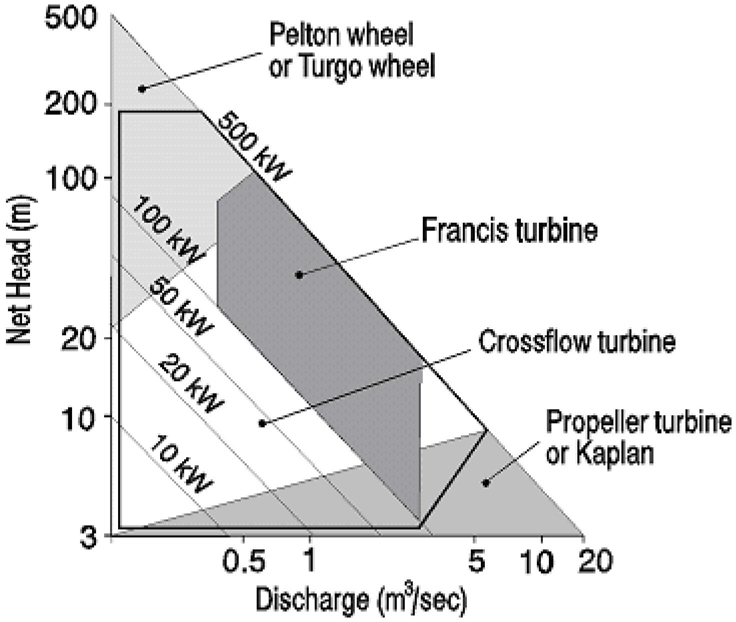

Figure 2.12 - Head-flow chart for different types of turbines [9]

Small-scale hydro-generation can use either induction or synchronous generators and because the low head turbines tend to be run more slowly, it may require the use of a gearbox or a multipole generator.

2.2.4- Integration and impacts of distributed generation on distribution networks

The introduction of DG modifies the characteristics of the distribution network. A certain number of technical constrains and factors arise which are impacted by the amount of DG that is connected. These constrains are the following:

- Network voltage changes
- Increase in network fault levels
- Power quality
- Protection
- Stability
- Network operation
- Losses

Network voltage changes

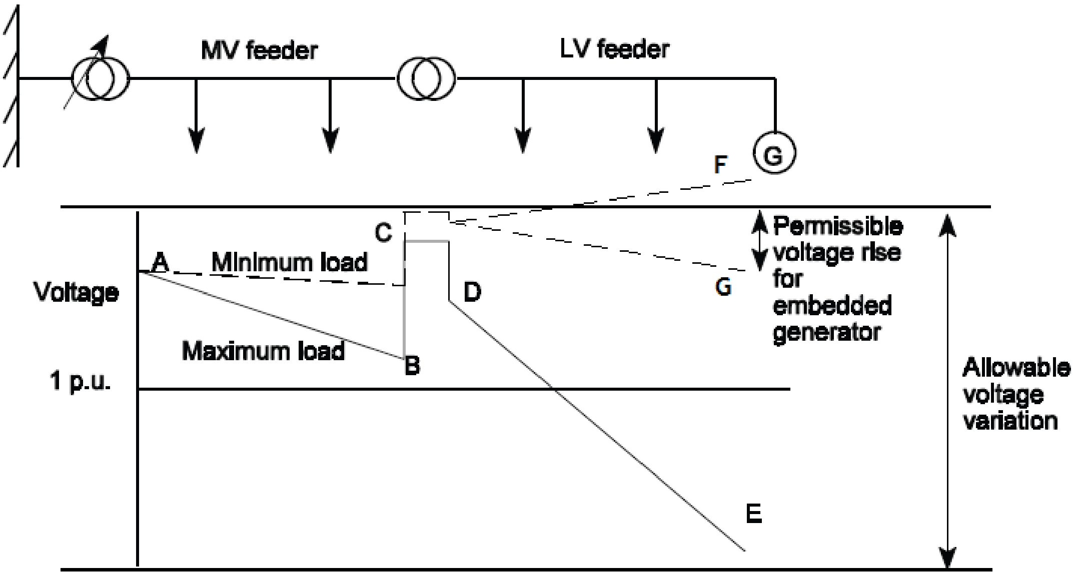

Figure 2.13 - Voltage variation down a radial feeder with DG [5]

Every company that owns a distribution network must supply its clients at a voltage within specified limits. This requirement often determines the design and expenses of the distribution circuits and that's why over the years many techniques have been developed to maximize the use of this distribution circuits within this voltage limits. [5]

Figure 2.13 shows the impact in voltage of a DG unit in a radial feeder containing MV and LV consumers, a distribution transformer, a MV/LV transformer. As the power flows from the distribution transformer through the MV feeder and reaches the consumers present there, the voltage drops until it reaches the MV/LV transformer as it rises here. Finally when it flows through the LV feeder, the voltage drops until the last consumer is powered. When the DG unit is introduced in the end of the LV feeder, the voltage rises on the LV feeder. If the integration level of the DG unit is too high, the voltage will rise and can exceed the superior limit permitted (F). [5]

Increase in network fault levels

Many DG units use rotating machines that contributes to the network fault levels although induction and synchronous generators have different behaviors under sustained fault conditions.

Power quality

In the power quality, two aspects have to be considered. One is the transient voltage variations and the other is the harmonic distortion of the network voltage.

So the DG plant can cause intransient voltage variations on the network if large currents current changes during connection and disconnection are allowed. Also some forms of prime-mover (for example fixed speed wind turbines) may cause cyclic variations on the generator output current which can lead to so-called “flicker” nuisance if no adequately controlled.

The use of power electronics interfaces to the network may inject harmonic currents if not properly designed which can lead to unacceptable network voltage distortion. [5]

Protection

The different aspects of DG protection can be divided as follow:

- Protection of the generation equipment from internal faults
- Protection of the faulted distribution network from fault currents supplied by the DG
- Anti-islanding or loss-of-mains protection
- Impact of DG on existing distribution system protection

Protection of the DG generator from internal faults is usually simple as a fault current flowing from the distribution network is used to detect the fault, and techniques used to protect any large motor are generally adequate.

Protection of the faulted distribution network from fault currents supplied by the DG is often more difficult as induction generators cannot supply sustained fault current to a three-phase close-up fault and their sustained contribution to asymmetrical faults is limited.

Loss-of-mains protection is a particular issue particularly where autoreclose is used on the distribution circuits. For a variety of reasons, both technical and administrative, the prolonged operation of a power island fed from the embedded generator but not connected to the main distribution network is generally considered to be unacceptable. The neutral grounding of the generator is a related issue because it can be considered unacceptable to operate an ungrounded system and so care is required as to where a neutral connection is obtained and grounded.

Finally, DG may affect the operation of existing distribution networks by providing flows of fault current which were not expected when the protection was originally designed. The fault contribution from an embedded generator can support the network voltage and lead to relays under-reaching.[5]

Stability

Traditionally distribution network design did not need to consider issues of stability as the network was passive and remained stable under most circumstances provided the transmission network was itself stable. So if a fault occurs somewhere on the distribution network to depress the network voltage and the distributed generator trips, then all that is lost is a short period of generation. The embedded generator will tend to over speed and trip on its internal protection. The control scheme of the embedded generator will then wait for the network conditions to be restored and restart automatically. However, this is likely to change as the penetration of these schemes increases and their contribution to network security becomes greater. The stability issues include transient (first swing stability) as well as long term dynamic stability and voltage collapse.[5]

Network operation

DG has important consequences for the operation of the distribution network as some circuits can now be energized from a number of points. This has implications for policies of isolation and earthing for safety before work is undertaken. There may also be more difficulties in obtaining outages for planned maintenance and so reduced flexibility for work on the network.

Losses

As previously referred, the integration of DG units into the distribution network alters the power flow in it and will also alter the power losses. With the DG units feeding their local loads, the power flowing through certain lines decreases, as it no longer has to power that loads. The level of losses is closely linked to power flows as losses are a function of the square of the current. So for example, a current drop to half results in a drop of ¼ of the power loss. So even small changes in power flow can make a significant impact on the losses.

Losses may even be more important in economic terms for the network owner if they receive encouragements from regulator entities. This encouragement can consist in the difference between the real losses registered in the network and the reference losses decided by the regulator entity. If the real losses are inferior to the reference ones, the distribution company is financially compensated. If not, they are charged for lack of efficiency in its network. Because the consumers pay their quota of the total losses to the distribution company, if the losses drop, so drops the bill of these consumers.

The losses verified in the network depend on the mix of DG technologies in the grid, the level of penetration and dispersion of the DG, the correlation level between the network load and the power injected by the DG and the contribution it as to the control of voltage/reactive power.

2.2.5- Active distribution network management

In contrast with the actual integration of the DG units in an "fit and forget" approach where the only service they offer is the uncontrolled production of electricity, an active management of the distribution network is being developed to be the future core management system of this type of network. Active management will allow the minimization of the losses, control of the voltage values within the limits and guarantee that the technical limitations of the various elements of the network are not violated. In result, it will improve the operation of the distribution network and will allow the integration of more DG units without any massive investment on actual infrastructures.

To achieve these goals, it is necessary to create control infrastructures and communication that will allow the control of the various elements of the distribution network, specially the DG units. So, the DMS (distribution management system) must control and monitor the loads, the on-load tap-changer on transformers and the storage systems. Also, it must control the voltage, reactive and active power of DG units and finally, control the switching devices to optimize the operational performance of the grid [10]. Figure 2.14 show this operation of the DMS on the different elements of the network.

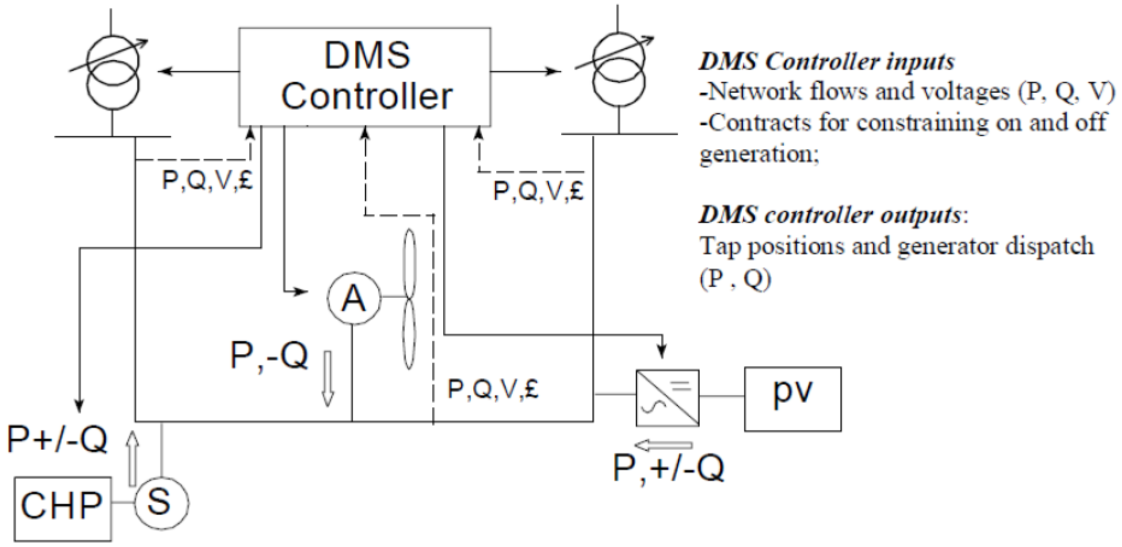

Figure 2.14 - Scheme of an Active management system [2]

2.2.6 - Energy storage for use with distributed generation

Due to the intermittent and unpredictable nature of the DG's, especially in the renewable generation, energy storage is needed to ensure that the loads are supplied when required and with quality. So, energy storage can often be applied for 3 different purposes [4] that are resumed in table 2.2.

- First, energy storage can be used for stabilization purposes, permitting the DG to run at a constant, stable output level, even if the load fluctuates greatly and rapidly

- Second, proper amounts of storage can provide energy to ride through periods when the DG unit is unavailable. For example during night time on a PV system or when a DG unit is in maintenance.
- Third, energy storage can permit a non-dispatchable DG unit to operate as a dispatchable unit by permitting its output at any moment to differ from the power being released to the demand or into the grid

Table 2.2 - The three major purposes of energy storage and their key characteristics [4]

Aspect	Energy Stabilization	Ride-Through	Dispatchability
Reason	Shave needle peaks in the non-coincident load curve, due to large appliances, etc.	Provide energy to serve load during periods when DG output is unavailable.	Provide energy stored to stabilize DG availability to meet various schedules.
Benefit	-Lowers peak DG capacity needed. -Improves voltage regulation.	Service from PV, etc, can now be maintained during night time, etc	DG owner can now bid and sell power contracts for arbitrary schedules.
Storage	Must be enough to "shave" appliance peaks and meet their short-term needs.	Dictated by load during "DG unavailable" times Usually 1/2 day's energy.	Must be enough to transform the DG schedule into the desired sales schedule.
Peak	Relatively great: all the energy stored must be released in just a few minutes.	Relatively small, only one eighth to tenth of stored energy.	Requires more than for ride-though but much less, relatively, than for energy sta
Method	Based on detailed assessment of daily load curve, on a minute-to minute basis.	Based on hourly analysis of load needs over a year and DG availability stats.	Based on hourly analysis of desired schedules, DG availability stats, business cases.
Design	Typically high-energy, low-storage design with enough capacity to avoid deep cycle.	Must achieve size balance between storage size and DG	Must achieve an overall balance among DG unit size, storage size, and total cost.

Currently there are many options in terms of storage for each of these three purposes. For large scale applications the following technologies can be used:

- Compressed air energy storage (CAES)
- Pumped hydro storage (PHS)

Hydrogen Fuel cell storage is effective for long and short term storage.

For high power efficiency applications:

- Flywheels

- Super-capacitors
- Superconducting magnetic energy storage (SMES)

Finally, the most popular and frequently used method for energy storage is the batteries storage.

A CAES uses excess power generated by the power station to compress air during off peak periods into a tank at very high pressure. During peak periods this air is then decompressed in a compression chamber before being fed to pistons or turbines, increasing energy production during peak periods.

The main advantages of CAES are the high capacity and high output depending on the size of reservoir, the quick startup time and the easy geological requirements.

As main disadvantages are the needs of high energy input during the power production process and the emission of greenhouse gases as a result of using natural gas in energy production.[11] [12] [13]

A PHS uses two storage reservoirs. One is located at the base level and the other is located at a higher level. In the off-peak hours, the power is used to pump water from the lower reservoir to the highest where the water is stored as potential energy. During peak load hours the stored water is released back into the lower reservoir upon demand. This flow of water rotates a hydraulic turbine to generate electrical power. It is possible to do both the pumping and the generation with a single unit or with separate pumps.

The main advantages of PHS are the huge energy and large power capacity which result in a store of energy for a very long time (up to more than 6 months).

As mains disadvantages are the high construction cost and the location is restricted at a geographic, geologic and environmental level.[11] [12] [13]

Hydrogen fuel cell storage is considered one of the fast growing and recent energy storage technologies. Its operation involves three different stages: electrolyzing, hydrogen storage and fuel cell stage. In the electrolyzing stage, the off-peak energy is used to electrolyze water to create hydrogen ions (H2). At hydrogen storage stage, like the name says, the hydrogen is stored. At the peak hours, the hydrogen in combined with oxygen at fuel cells resulting in a chemical reaction forming of water. The energy from this reaction is converted in electrical energy.

As main advantages of the Hydrogen fuel cell storage are the absence of CO2 emissions, cheaper storage for longer time, the high energy density, can be easily implemented in different capacity size ranges and the excess of hydrogen off-gas can be transported.

As main disadvantages is the high construction cost, the low round trip efficiency and the fact that hydrogen is highly flammable.[11] [12] [13]

Flywheels use the off-peak energy and store it as kinetic energy in a rotating wheel or in a cylinder. The stored energy is proportional to the mass and to the square of rotational velocity of the flywheel. This relation is better understood with the equations of energy (2.3) and moment of inertia (2.4).

$$E = 1/2\, I\omega^2 \tag{2.3}$$

$$I = (r^2 m\ h)/2 \quad , \tag{2.4}$$

where “r” is the radius of the rotor, “m” is the rotor mass and “h” is the height of the rotor

When power is needed, the kinetic energy is then converted into electricity. It can be necessary the use of power electronics to control de output voltage and frequency within acceptable ranges. The round trip efficiency of flywheels depends on bearing losses, winding losses and on cycled time. To reduce its size, cost and weight, the rotor should be of high strength composite material

The main advantages of flywheel are the low maintenance frequency, long life cycle, the quick recharge time and high power density.

As main disadvantages are the difficult in storage expansion, the lower energy density and the large standby losses.[11] [12] [4]

Super-capacitors are conventional capacitors with increased surface area and a double layer of charge which enables a higher energy density than conventional to be stored. The storage capacity is directly proportional to the plate area and the square of its voltage, while inversely proportional to the distance separating capacitor plates as shown on the equations of the capacitance (2.5) and energy (2.6).

$$C = \varepsilon_{\circ} A/d \tag{2.5}$$

$$E = 1/2 CV^2 = (\varepsilon_{\circ} A/2d)V^2 \quad , \tag{2.6}$$

where “ $\varepsilon_{\circ}$ ” is the Vacuum permittivity, “A” the plate area and “d” the distance that separates the plates.

High energy storage can be achieved by increasing the capacitance value which can be done by maximizing surface area and minimizing the separation between the plates. Different combinations of electrode and electrolyte material have been used in Super-Capacitors. This results in obtaining various capacitance, energy density, life-cycle and cost characteristic values

The main advantages of Super-capacitors are the high power density, long life cycle, quick recharge time, easy to implement and effective operation in most adverse environmental conditions.

As main disadvantages are the high cost, low energy density and the requirement of power electronics.[11] [12] [13]

SMES uses off peak energy to pass DC current a superconductive coil. This energy is stored in the magnetic field created around the coil. During discharge time, the conducting wire is cooled to -269ºC, which causes the resistance of the material to electrical current to disappear making the conduction of very high current with almost no losses.

The main advantages of SMES are the very quick energy transfer and the change between charge and discharge that takes about 17 milliseconds, the very high efficiency and the unlimited number of charges and discharges.

As main disadvantages are the expensive cost of energy storage, the refrigeration losses and the low energy density.[11] [12] [13]

The Batteries storage are composed by one or more electromechanical cells. Each cell contains a liquid or solid electrolyte having a positive and a negative electrode. During the off-peak hours, the battery is charged which causes reactions in the electromechanical cells to store the energy in a chemical form. When power is needed, the battery discharges which causes the reverse chemical reactions in the electromechanical cells and energy is produced [11] [12] [13]. The process of charging and discharging is shown in figure 2.15.

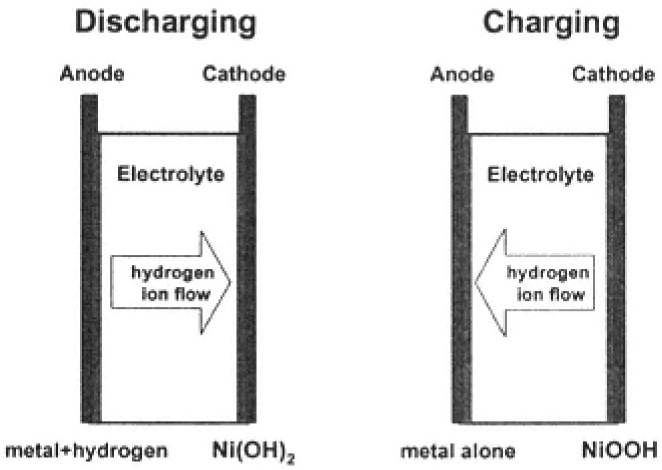

Figure 2.15 - Composition and operation of a battery [4]

There are different types of batteries technologies. The most important are:

- Lead acid batteries
- Nickel Cadmium batteries
- Sodium sulphu
- Lithium Ion batteries
- Sodium Nickel Chloride

Each of this batteries differs in possible depth of discharge of the battery, cost, number of charge/discharge cycles the battery can tolerate, efficiency, self-discharge, maturity of the technology and energy density.

The main advantages of the batteries are the fact that there is no need to be connected to an electrical system, can be used in areas where electricity is not provided and its ready factory-built modules reduce construction lead times and make it easily expandable

As main disadvantages are their expensive cost, the limited lifetime and the need for periodic maintenance. [4]

2.3 – Solar energy

Because this work focuses on the use of PV, this section will detail the constitution, operation and configuration of this type of DG.

2.3.1- Introduction

Solar energy is the radiant energy produced by the sun. It arrives at Earth in the form of light and heat which can be used in many ways, as example for heating and for electricity. This is one of the most important and abundant renewable resource.

2.3.2- Earth's energy budget

Of the 174 petawatts (PW) of solar radiation that reach the atmosphere, 31% are reflected back to the space (8% reflected by the atmosphere, 17% reflected by clouds, 6% reflected by the surface). From the remaining 69%, 23% are absorbed by the atmosphere and clouds and the rest 46% are absorbed by the surface. This energy balance can be observed in the figure 2.16 [14].

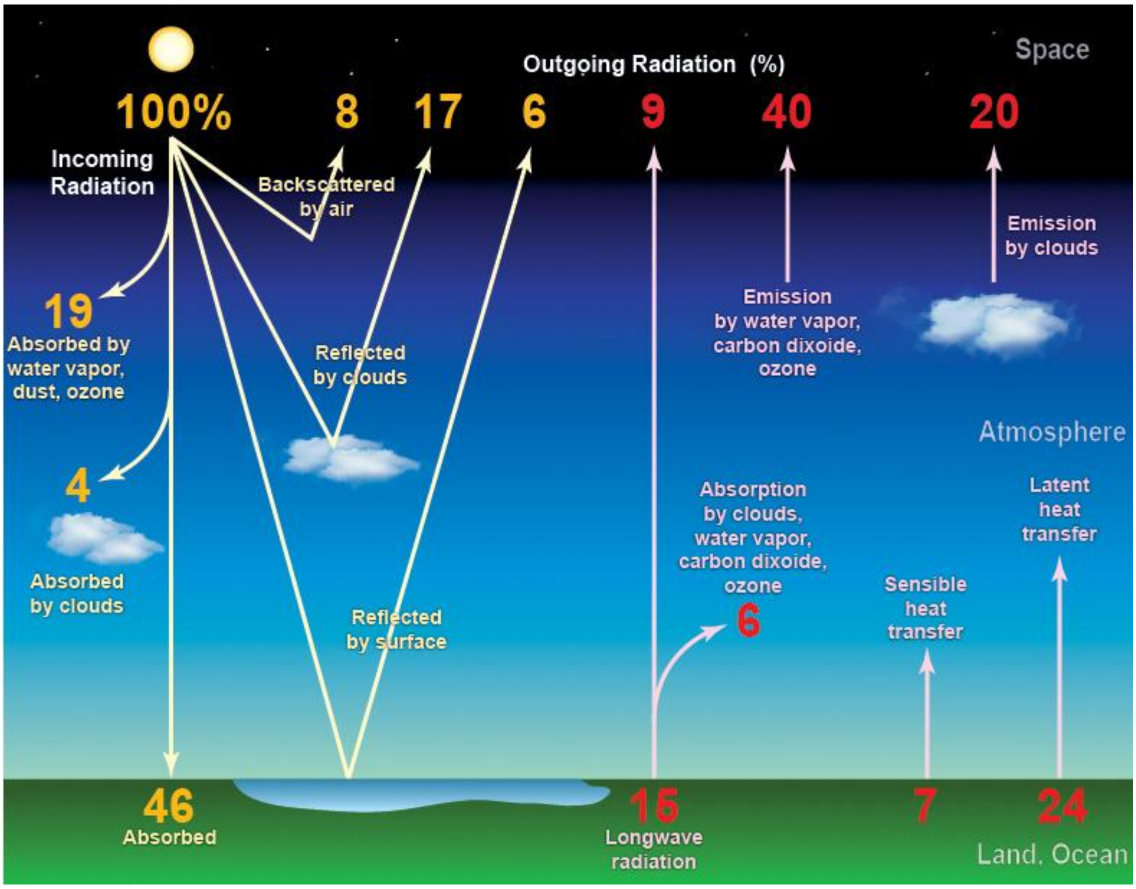

Figure 2.16 - Earth's energy balance [14]

2.3.3- Irradiance

To determinate the PV production in a specific point, the global irradiance is used and consist in the total radiation that focuses in the surface. This irradiance is divided in two: the direct radiation and the diffuse radiation. The direct radiation is composed by the solar rays received in a direct line with the sun and the diffuse radiation is all the radiation coming from all the visible sky, excluding the solar disk, which is caused by the non-direct rays dispersed in the atmosphere.

In each month of the year, the irradiance changes as the same happens during the day. By observing the figure 2.17, for example in December at 12h the irradiance is smaller than the one on June. Also the irradiance at 6h is smaller than at 12h.

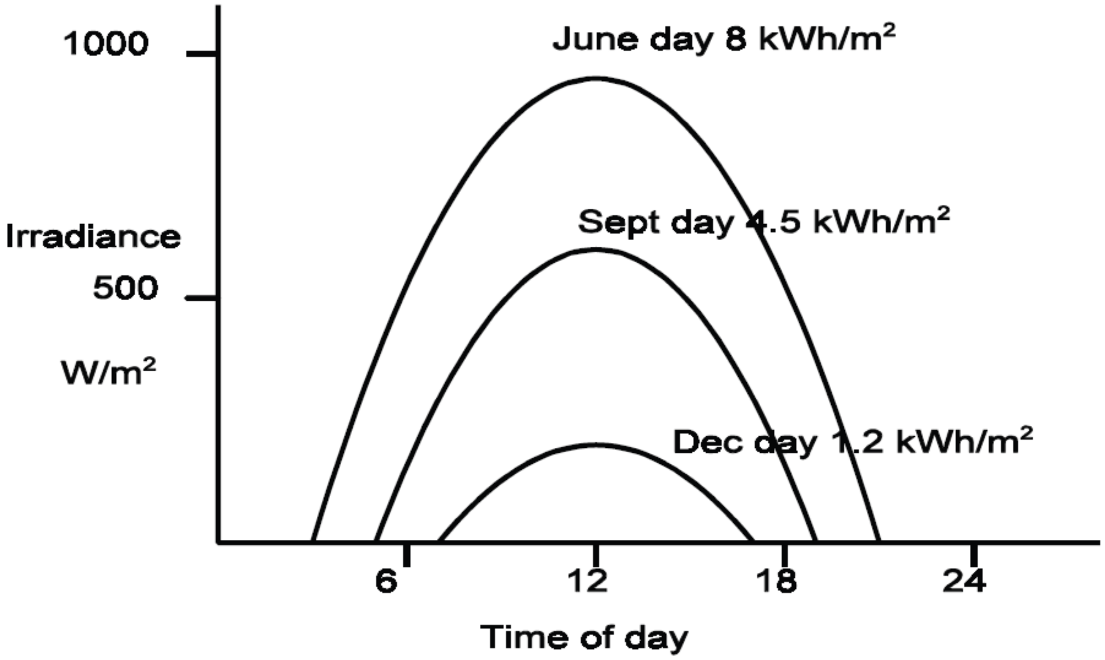

Figure 2.17 - Solar irradiance in a flat terrain at 48° [5]

Another factor that affects the irradiance is the weather. The figure 2.18 shows that in a cloudy or rainy day the irradiance drops as wells as the generation output.

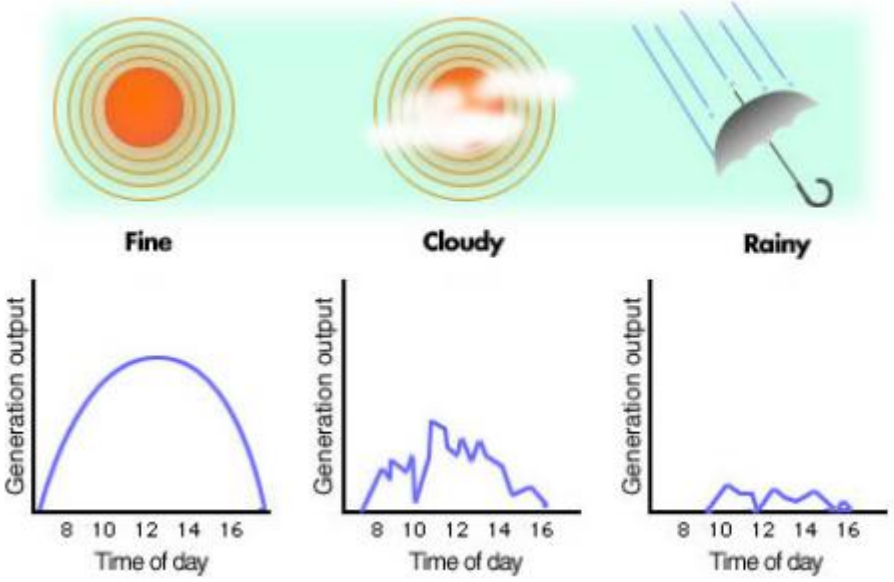

Figure 2.18 - Impact of the weather on the PV generation [15]

2.3.4- PV cell

PV energy is the conversion of direct sun light into electricity in an atomic level through PV cells. These are composed by two types of semiconductors, type P and type N, whose electrical characteristics are different (The Type P has positive charge and type N has negative charge). The thickness of the type P is bigger than the type N. The union of these two semiconductors is called the P-N junction and it generates an electric field due to the electrons in the type N semiconductor that occupy the empty spaces in the structure of the type P. [4][8]

The incidence of light on the PV cell causes the shock between the photons and the electrons of the semiconductor structure providing energy and turning them into conductors. Due to the electrical field generated by the P-N junction, the electrons flow from the type P to the type N layer. This flow is possible using cables that closes the circuit and will occur as long as sun light hit the cell. The flow of electrons and the sun light are proportional so if the sun light increases, the flow will also increase.[8]

This function of the PV cell can be modeled in an equivalent circuit which contains a generator, a diode and two resistances and is demonstrated in the figure 2.19.

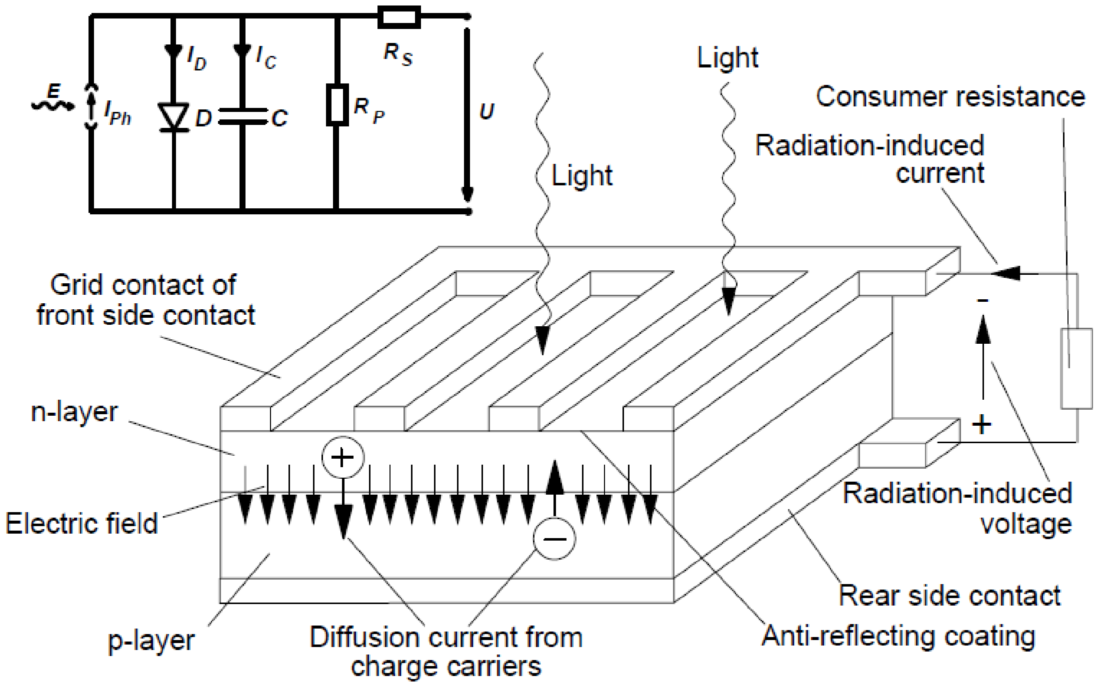

Figure 2.19 - Structure of a typical solar cell and the equivalent circuit diagram [8]

In figure 2.19, “R_P” modeled the current losses, “R_S” the voltage losses, “I_L” the photocurrent of the cell and the diode “D” the junction P-N.

As a single cell produce voltage and currents with low values, the cells are assembled in photovoltaic modules (panels) and connected generally in series or in parallel according to the desired output characteristics. This means that the nominal voltage of each module it is equal to the number of cells in series multiplied by the nominal voltage of each one. As for the current it is equal to the number of cells in parallel multiplied by the current of each cell. The connection of these modules in parallel or in series can increase even more the voltage and current output of the PV system, forming a PV generator.

Cell Types

Despite the fact that all photovoltaic cells operate on the same general principles, there are a number of different materials used and different types of PV cells. The mono-crystalline is the most used worldwide and its production is already well known. To produce this type of cell, Silica sand (SiO2) serves as base material for high-purity silicon. Silica sand is then transformed into "metallurgical grade silicon" characterized by a maximum purity of 99 %. However, this purity is still insufficient for solar cell production. A further purification process must be applied in order to achieve a greater purity level in the order of 99,9999%. The most common process used is the Czochralski. This process involves melting the silicon with a small amount of dopant type "p", usually boron. A crystal is used as "seed" with the appropriate crystallographic orientation and during the process with full temperature control, cylindrical block of monocrystalline silicon lightly doped is formed properly oriented in the crystallographic point of view, and with the desired characteristics mainly on the purity desired degree. To assemble the cell, this cylinder is cut perpendicularly to the main crystallographic axis in thin sheets with a thickness of about 300µm. These sheets, after cutting and cleaning to remove any surface impurity, are not yet ready for use in the cell. Finally, the introduction of impurities or dopant type "n" to form the joint "pn". This will be achieved through a diffusion process controlled by the exposure of silicon wafers to the vapor of phosphorus in an oven maintained at a temperature range between 800 ° and 1000 ° C. The cells produced with this process can achieve an efficiency with a wide range of 15% to 18%.[8] [16]

Polycrystalline silicon cells are often the most interesting option at the economical point of view because they are much cheaper than those of mono-crystalline silicon. By contrast, the efficiency is a little lower compared to the mono-crystalinne as it can achieve a range from 13% to 15,5%. The purification process of the silicon used in the production of polycrystalline silicon cells is similar to the process of monocrystalline silicon, but with lower levels of control, which translates, at the end of the process a slightly lower efficiency. The sheets or tablets can be obtained from cutting a silicon ingot prepared in advance, or by deposition a purified silicon film on a substrate which can be a sheet of quartz crystal, for example. In the latter two cases only the polycrystalline silicon can be obtained. Each technique produces crystals with specific characteristics, including size, morphology and impurities concentration. The mono-crystalline and poly-crystalline cells are also called the first generation technologies.[8] [16]

The thin-layer amorphous silicon cell is relatively different from the other crystal structures because the mineral has no crystalline structure defined and ordered as in the case of cells mono or polycrystalline silicon, amorphous silicon predominates in the high degree of disorder in the structure of atoms. Still, the use of amorphous silicon for use in solar cells has shown great advantages both in electrical properties as in the manufacturing process. Amorphous silicon is characterized by absorbing solar radiation in the visible range and thus can be fabricated by deposition of various types of substrates. This way, the amorphous silicon has proven to be a good option for low cost photovoltaics. But despite the advantages represented by the reduced cost in production, the use of amorphous silicon has its shortcomings. The first one is the low conversion efficiency compared to single cells and polycrystalline silicon, second, a natural process of decay damage to cells at the beginning of its operation and this helps to reduce its efficiency over the lifetime. On the other hand, the amorphous silicon has some advantages that compensate for the deficiencies mentioned above, such as a manufacturing process relatively simple and inexpensive and the possibility of manufacturing cells with large areas and low energy consumption in production. The thin-layer amorphous silicon is integrated in the so called second generation technologies which includes other technologies. For example, CIS- Copper Indium (Galium) diSelenide, the Cadmium telluride and the Gallium arsenide (GaAs). Currently, the third generation technologies are being developed.[8] [16]

2.3.5- Characteristic curve of PV cells

The typical representation of the characteristic output of PV device (cell, module, and array) is denominated I-V curve which is shown in figure 2.20. Also represented in the figure, is the active power for each value of the current-voltage allowing the determination of the operation point with maximum power.

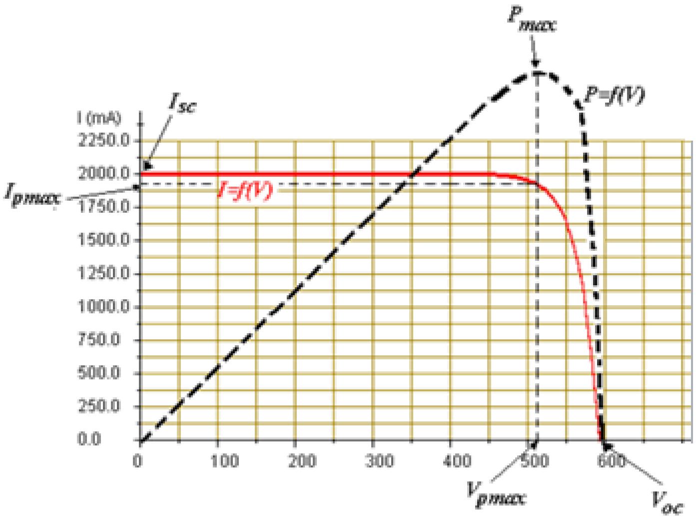

Figure 2.20 - Current-voltage and active power curves [17]

The current output is practically the same within the range of operating voltage and so the PV device can be considered a constant current source in these conditions. The operation current and voltages are affected by the values of the internal resistances, the incident solar radiation, the temperature and the characteristics of the connected load.

2.3.6- Configuration of PV production systems

Depending on the purposes of the PV system, it can be configured in three different ways. It can operate connected to the grid and isolated from the grid. The mains purposes of each configuration are shown in figure 2.21.

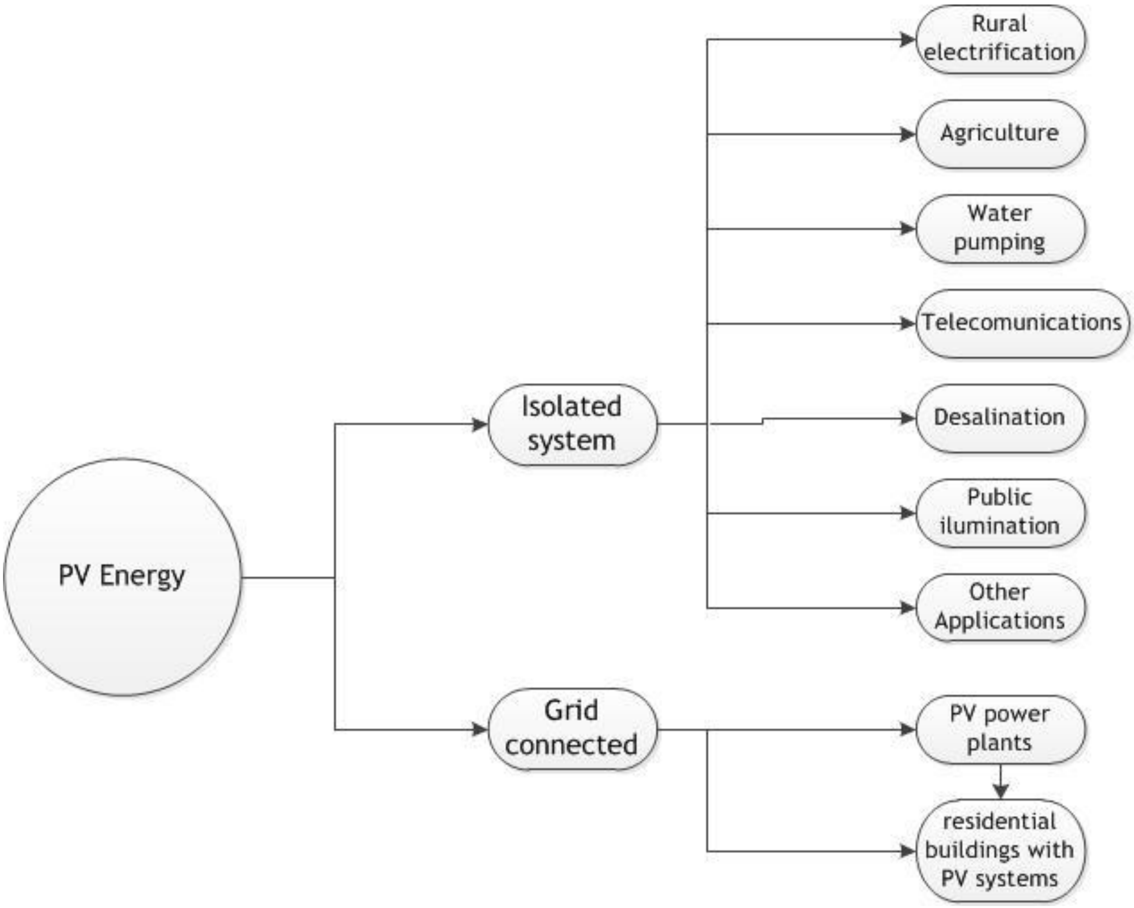

Figure 2.21 - The different application of each PV configuration [18]

In PV systems connected to the grid, energy is injected through the use of inverters to adapt the direct current from the photovoltaic system to the characteristic of the grid. It has three basic schemes available shown in figure 2.22.

The decentralized systems have the PV modules installed in the load (for example roofs) for small generation. The modules are connected to the grid using an inverter adapted to the small PV generator capacity. The difference between the PV generation and the load consumption is supported by the grid. This coordination is shown in figure 2.23. During the day, as the solar production overcomes the consumption of the local load, the excess is injected into the grid. During the night, as there is no PV production, the load is powered by the grid.[8]

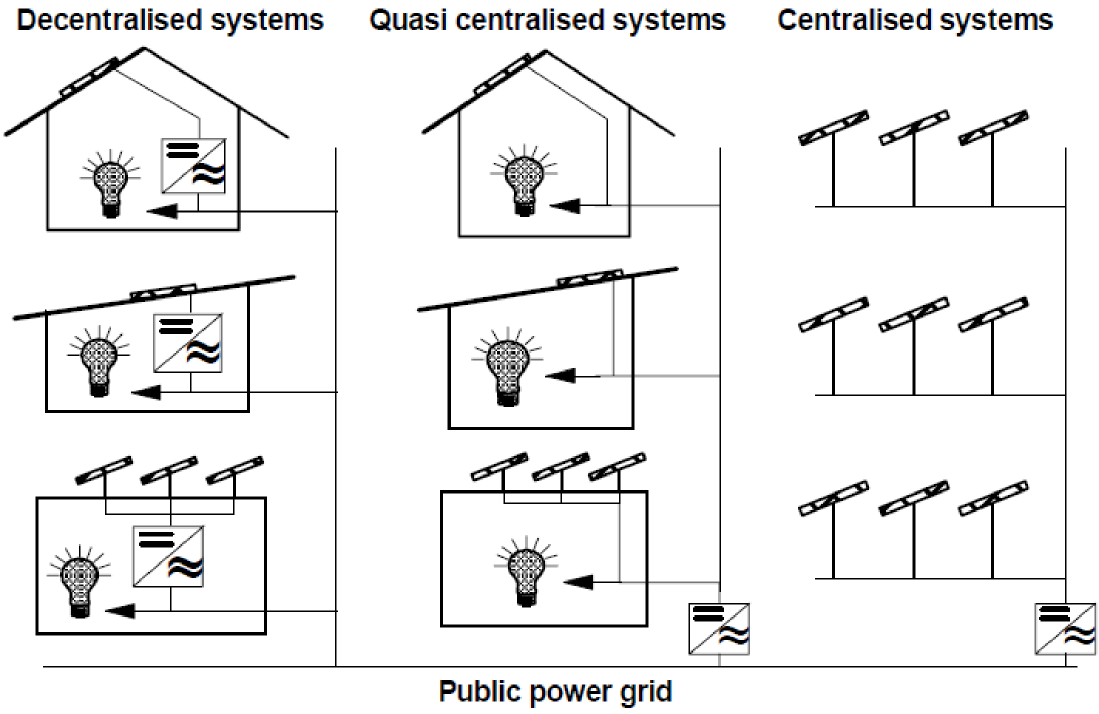

Figure 2.22 - Types of schemes used to connect PV systems to the grid [8]

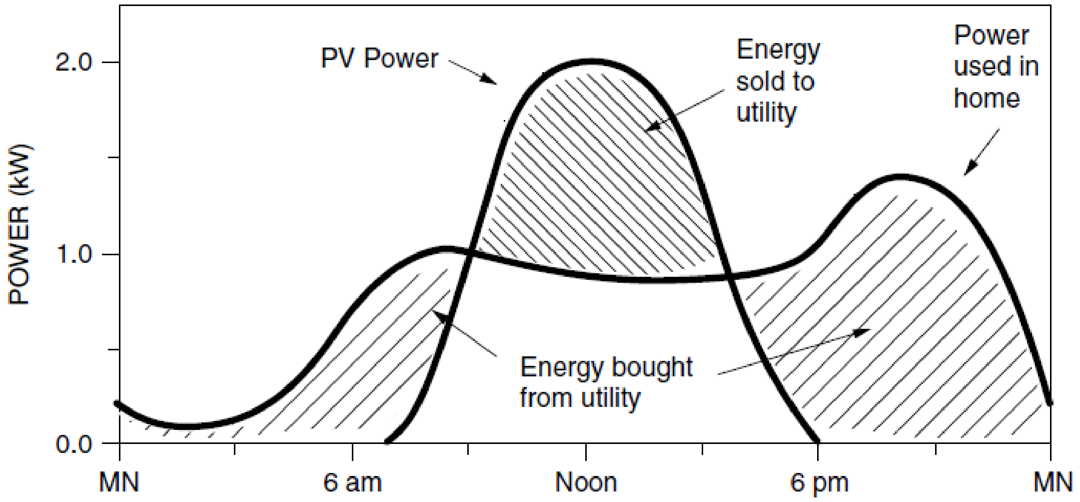

Figure 2.23 - Load and PV production curves of PV decentralized system [1]

The “quasi centralized” systems are a very rare mixture of small scale systems and large scale photovoltaic power plants. It can be also installed on roofs but unlike the decentralized systems, the individual PV generators are combined to larger units on the DC side. This system is then connected to the medium voltage network through large inverters and a transformer. For the implantation of this PV a technical-economic optimum between the distance to be covered and the related transportation losses and the lower inverter losses associated with higher installed capacities needs to be found.[8]

The centralized systems are usually mounted on the ground or on very large roofs. They have a large generation capacity typically from a range of 100 kW to 5 MW. It is connected to the lower or medium voltage networks through the use of several inverters and a transformer.[8]

The isolated systems are further distinguished into stand-alone and off-grid applications. In stand-alone applications, photovoltaic energy supply is applied alternatively to power supply by the grid for reasons of cost-efficiency, handling, safety or environmental protection, despite the fact that the power from the grid is available. Classic example is the PV powered calculator or PV garden lamps. In off-grid applications, power grid is inaccessible for technical or economic reasons. [8]

Isolated photovoltaic systems, applied, for instance, for household or small consumer supply, generally consist of a solar generator, a charge controller and an energy storage which are interconnected by a direct current bus-bar. The connection to the load is made directly or with inverters, depending on the characteristics needed. The scheme of an isolated system is shown in figure 2.24.[8]

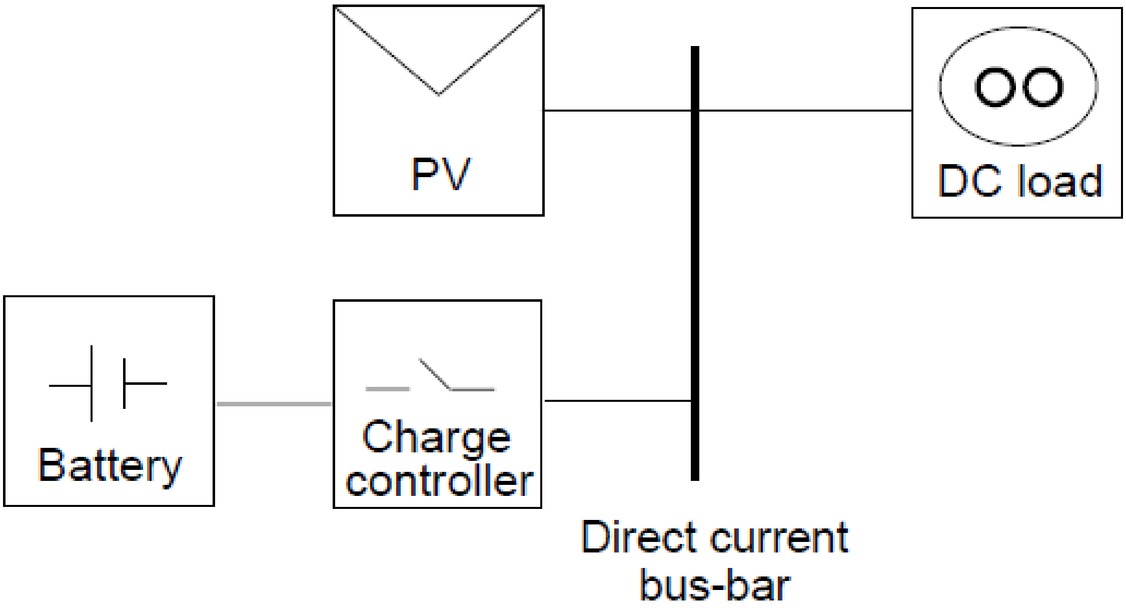

Figure 2.24 - PV system isolated from the grid [8]

System components

Inverters

PV generators as well the storage units provide (DC). Although, most of the appliance require AC to operate as well the power grid. So inverters can convert DC into AC making possible the feed of AC loads.[8]

Charge controllers

Charge controllers are needed to optimize the battery charge increasing the batteries life time. They must protect the battery against deep discharges and overcharges. In addition, charge controllers are responsible for the charging strategy.[8]

MPPT

Maximum Power Point Tracking also referred as MPPT, is an electronic system that can operate the PV modules at their maximum generation capacity at each instant. An example is shown in figure 2.25. In the PV system without MPPT, the charge controller connects the modules directly to the batteries, forcing it to operate at the batteries voltage level. With the MPPT, The voltage level of the modules is changed to maximize their power output. A high efficiency DC/DC power converter converts the voltage level of the modules to the one on the batteries [19].

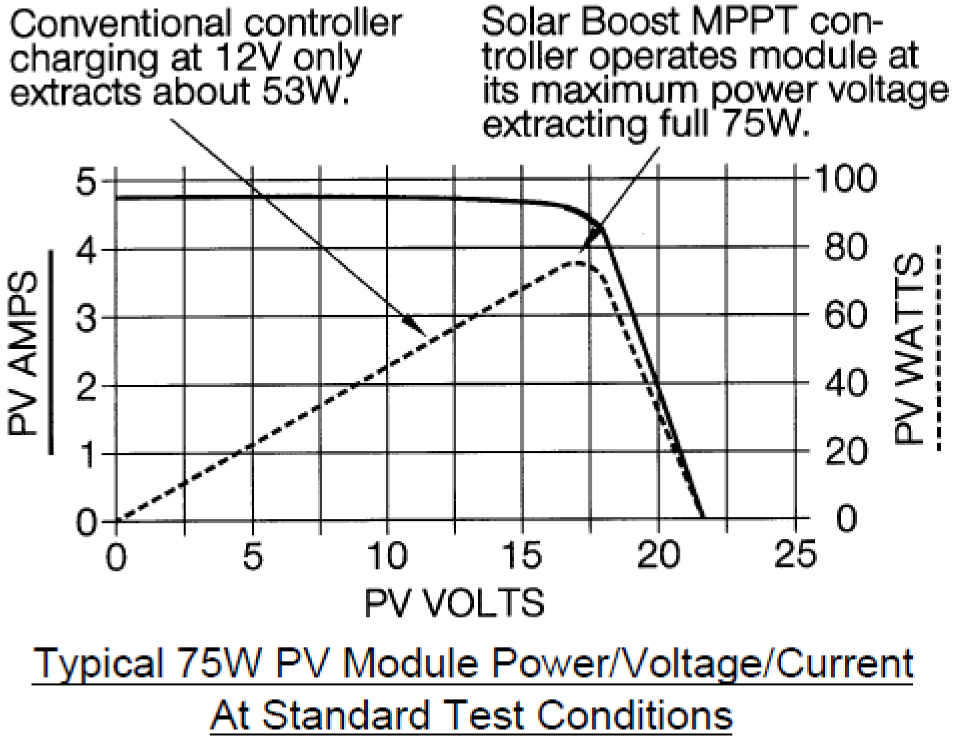

Figure 2.25 - Comparison of a PV system with MPPT and without MPPT [19]

Other system components

Other systems components that have an impact on the total cost are the connecting cables, fuses, grounding, lightning protection, energy meters as well as low voltage or overvoltage monitoring Protection. Photovoltaic power plants also require a transformer to feed the electric energy into the grid with the required power characteristics. [8]

2.3.7- Advantages and disadvantages

A PV system has plenty of advantages. Perhaps the most important of them is the absence of fuel. So, after the installation of a PV module, it will continue to operate without any additional fuel costs as long it has a good maintenance. The only maintenance required is the panel which needs to be clean and the tracking system, if it exists. It's the most modular technology and of smaller scale that exist, with the possibility to be assemble in calculators to generate 3V or it can be assemble in a series or parallel system to generate kilowatts. Also, it is extremely clean without any pollution produced or environmental contamination, does not have moving parts (except the tracking system, if it exists) which makes it very silent. Does not have odor, does not spills liquids and it is resistance to extreme weather conditions (hail, wind, rain, temperature, humidity). Therefore, they are extremely secure systems with a good life time.

Although, the prices for this type of DG are still high, despite the drop on cell construction prices in the last decade. For commercial projects, it requires large extensions of land and also, there are a lot of places on earth that does not have enough and constant solar light to make PV generation viable at a commercial level.[4] [8]

2.4 - Load curves

The load curves reflect the variations of the consumption over 24 hours per day, each day of the year. Through this curves, it is possible to study which periods of the day, the network has to provide more energy or which periods of the day the consumption is low, and provide measures to distribute this loads more efficiency. To reduce the peaks of the curves the consumption on off-peak hours is stimulated as the consumption on peak hours is discouraged. As result, more loads can be connected to the grid without the need to expand the capacity of the transmission and production systems [20].

Despite that, there are conditions that affect the load curves. The season of the year, the day of week, the hour of the day, the weather, special events (like holidays) and the current legislation.

The loads can be classified by their activity and may be divided into the following groups:

- Residential
- Commercial
- Industrial
- Others (public illumination, public services, government installations, etc.)

The typical load profiles for each one of this groups is shown in figure 2.26.

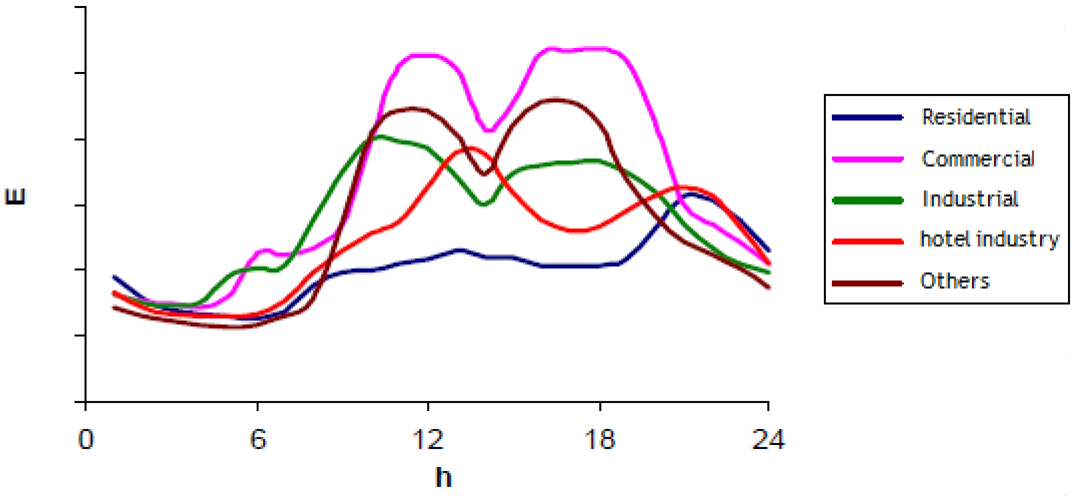

Figure 2.26 - Load curves for different types of loads in Portugal 2004 [21]

2.4.1- Residential

A typical residential load curve is shown in figure 2.27.

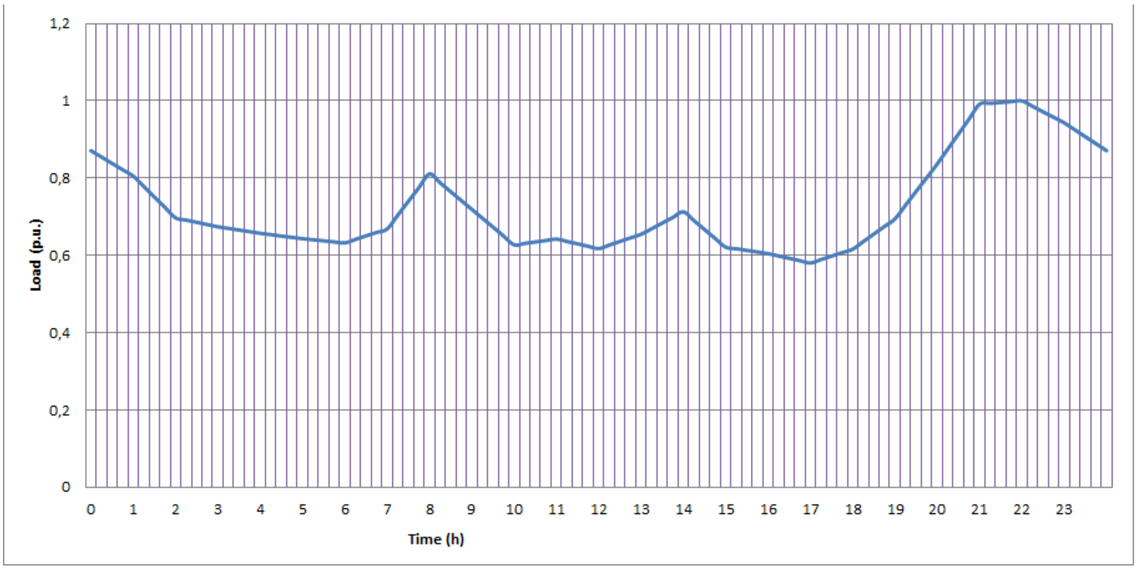

Figure 2.27 - Typical residential load curve (week day)

During the night, the residential consumption reaches its minimum value as only minimal devices are operating (like fridges). As the day begins, the consumption rises as consumers begin to wake up and tend to stabilize until night comes as the illumination and the operation of multiple devices at homes makes the consumption reach its maximum day value. This load curve is affected mainly by weekends and holidays.

2.4.2- Commercial

A typical commercial load curve is shown in figure 2.28.

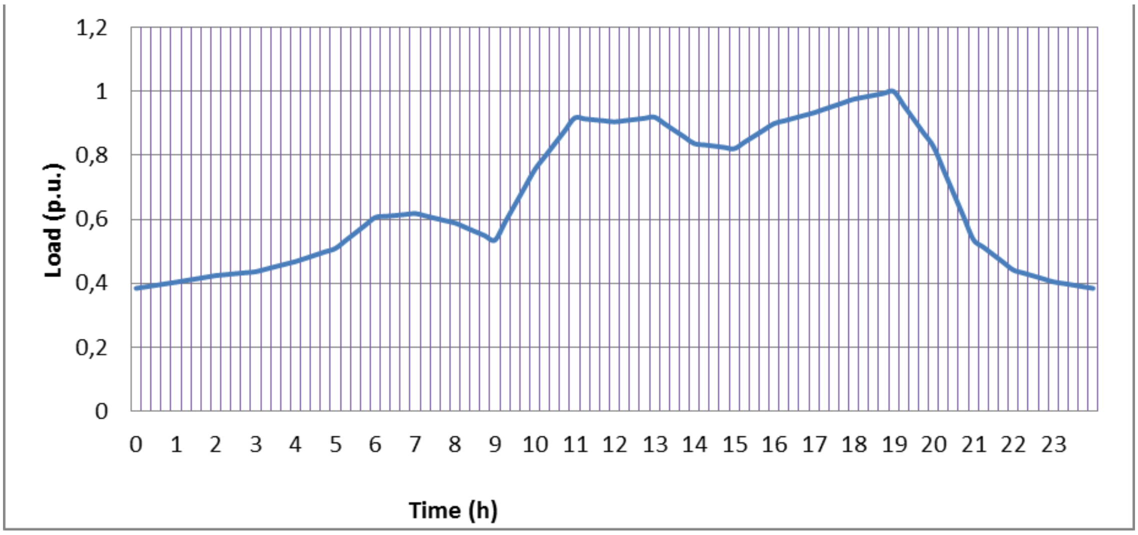

Figure 2.28 - Typical commercial load curve

A typical commercial load curve has its peak at the beginning of the night due to the illumination that is turn off as soon as the commerce is closed. During the day the load is almost constant.

2.4.3- Industrial

A typical commercial load curve is shown in figure 2.29.

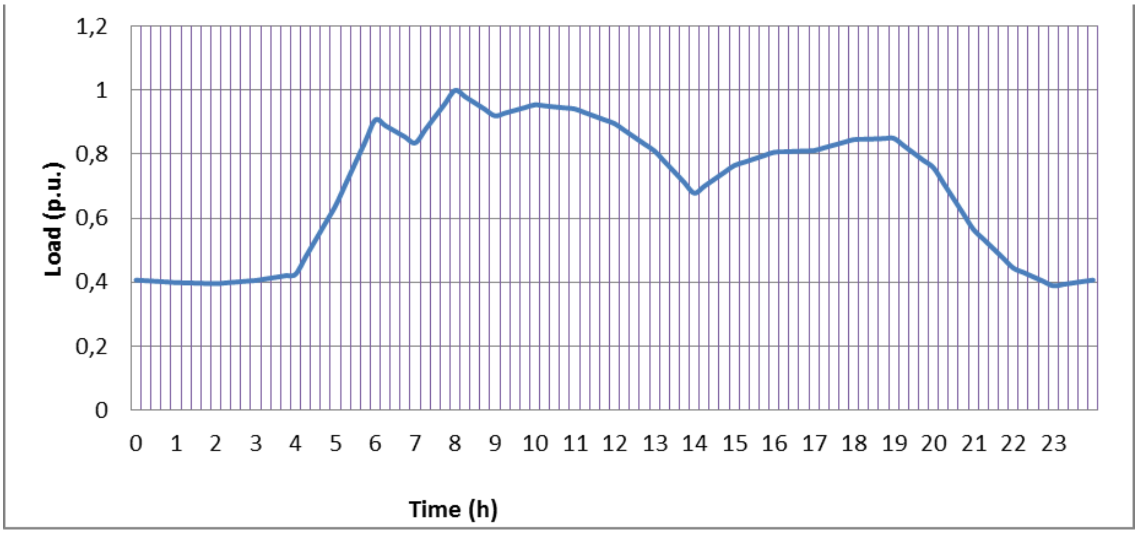

Figure 2.29 - Typical industrial load curve

A typical industrial load curve has its consumption distributed along the day as most of the industry units only work during the day. There are industries that work day and night, without stopping. The load curve for this type of industrial units is constant all day.

2.5 – Power Flow analysis

The objective of a power flow is to determine the voltage magnitude and angle of each bus in an instant of a power system with specific conditions (load, generation, voltage). With the results of a power flow, it is possible to determine the active and reactive power flow on the branches and transformers and respective losses, reactive power injected in PV nodes, active and reactive power injected in the slack bus, total losses and currents in the branches.

The study of a power flow is required in the planning and exploration of the power network. In the planning area, it allows studying the expansion of the production system, the expansion and reinforcement of the transmission and distribution networks and it allows the study of interconnections. In the exploration point of view, it allows the monitoring of variables subject to limits, comparison exploitation strategies, analysis of the consequences of scheduled and forced out of service components, simulation of the online and offline system state and the necessity to be incorporated in other studies.

The methods covered by this work are the Newton-Raphson method and the backward forward sweep method.

2.5.1- Newton-Raphson Method

The Newton-Raphson method is a popular approach for power flow solutions primarily because of its quadratic convergence characteristics. Its generalized form is used to determine the roots of polynomial, trigonometric equations, exponential functions or logarithmic.

2.5.1.1 – Generalized Newton-Rahpson Method

If a solution x_r is known as approximately a nonlinear equation (2.7):

$$f(x) = 0 \quad , \tag{2.7}$$

then a better approach for the solution can be obtained by (2.8):

$$x_{r+1} = x_r + \Delta x \tag{2.8}$$

Developing in Taylor series of $f(x_r + \Delta x)$ (2.9):

$$f(x_r + \Delta x) = f(x_r) + \Delta x f'(x_r) + \Delta x^2 / 2! f''(x_r) + \dots \tag{2.9}$$

If Δx is small, by other words, if the first approach is correct enough, then the terms of higher order than the first, can be skipped and the solution for $f(x) = f(x_r + \Delta x_r) \approx 0$ is approximately given by (2.11) (2.12) [22]:

$$f(x' + \Delta x') = f(x') + \Delta x' f'(x_r) \approx 0 \tag{2.10}$$

$$\Delta x' = -f(x_r) / f'(x_r) \tag{2.11}$$

$$x_{r+1} = x_r + \Delta x_r = x_r - f(x_r) / f'(x_r) \tag{2.12}$$

We have obtained an iterative process to find a solution to the non-linear equation (2.12). This geometric is shown in figure 2.30

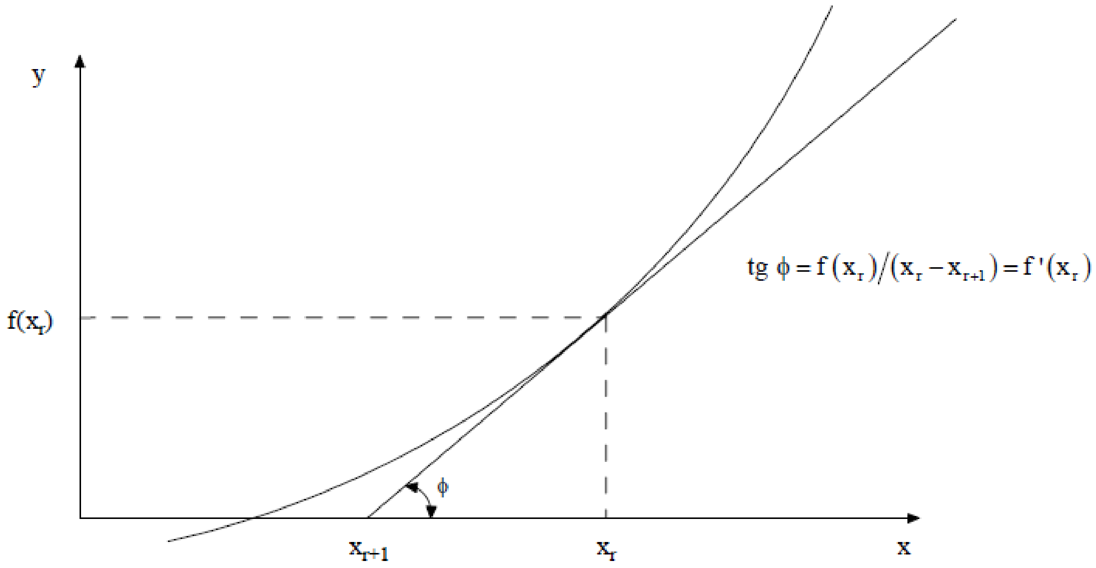

Figure 2.30 - Geometric interpretation of the Newton Raphson method [22]

For multiple variables, consider a system containing n equations with n variables (2.13):

$$\begin{aligned} f_1 &= (x_1, x_2, \dots x_n) = 0 \\ f_2 &= (x_1, x_2, \dots x_n) = 0 \\ &\vdots \\ f_n &= (x_1, x_2, \dots x_n) = 0 \end{aligned} \tag{2.13}$$

Which can be rewritten in a more compact form (2.14) (2.15):

$$\begin{aligned} f_1(X) &= 0 \\ f_2(X) &= 0 \\ &\vdots \\ f_n(X) &= 0 \end{aligned} \tag{2.14}$$

$$\left[x\right] = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \tag{2.15}$$

If an approximately root of the system $|X_0|$ is known, a better approach for the solution of the system can be obtained as follow (2.16) [22]:

$$\left[X_1\right] = \left[X_0\right] + \left[\Delta X\right]$$

That

$$\Delta X = \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \vdots \\ \Delta x_n \end{bmatrix} \tag{2.16}$$

Developing the Taylor series $f(X_0 + \Delta X_0)$ (2.17):

$$\begin{aligned} f_1(x_0 + \Delta x_0) &= f_1(x_0) + \Delta x_1 \delta f_1(x_0) / \delta x_1 = 0 \\ f_2(x_0 + \Delta x_0) &= f_2(x_0) + \Delta x_2 \delta f_2(x_0) / \delta x_2 = 0 \\ &\vdots \\ f_n(x_0 + \Delta x_0) &= f_n(x_0) + \Delta x_n \delta f_n(x_0) / \delta x_n = 0 \end{aligned} \tag{2.17}$$

Therefore, to calculate the solution:

$$\left[x_{r+1}\right] = \left[x_r\right] - \left[J\right]_r^{-1} \left[F\left(x_r\right)\right] \tag{2.18}$$

That $\left[J\right]_r$ is the Jacobian matrix calculated in the iteration r (2.19).

$$\left[J\right] = \begin{bmatrix} \delta F_1(x) / \delta x_1 & \delta F_1(x) / \delta x_2 & \cdots & \delta F_1(x) / \delta x_n \\ \delta F_2(x) / \delta x_1 & \delta F_2(x) / \delta x_2 & \cdots & \delta F_2(x) / \delta x_n \\ \vdots & \vdots & & \vdots \\ \delta F_3(x) / \delta x_1 & \delta F_3(x) / \delta x_2 & \cdots & \delta F_3(x) / \delta x_n \end{bmatrix} \tag{2.19}$$

2.5.1.2-Newton-Raphson method applied to a power flow

To apply this method for the resolution of a power flow, we need to write the equations that define the problem in the form of $\left[F(x)\right]=0$.

The best way and the most used form is the formulation of the power flow through the power deviations, which can be done by polar or cartesian coordenates. For polar coordenates we have[22]:

PQ buses (2.20) (2.21) [23]:

$$\Delta P_i^{SP}=P_i^{SP}-V_i\sum_{k\in i}(G_{ik}\cos\theta_{ik}+B_{ik}\sin\theta_{ik})V_k=0 \tag{2.20}$$

$$\Delta Q_i^{SP}=Q_i^{SP}-V_i\sum_{k\in i}(G_{ik}\sin\theta_{ik}-B_{ik}\cos\theta_{ik})V_k=0 \tag{2.21}$$

PV buses (2.22) [23]:

$$\Delta P_i^{SP}=P_i^{SP}-V_i\sum_{k\in i}(G_{ik}\cos\theta_{ik}+B_{ik}\sin\theta_{ik})V_k=0 \tag{2.22}$$

For the slack bus is not necessary any equation

In PQ buses, the active and reactive powers injected are known. Normally in these types of buses the consumption is known or the production is fixed. [24]

In PV buses the active power injected in known and the voltage module can be controlled by the excitation of the generator producing or consuming reactive power. [24]

In the slack bus, only the voltage magnitude and angle are known as this bus is the one that balances the active and reactive power. [24]

So the system will have to resolve two equation for each PQ bus and one for each PV bus. Q_i^{SP} is not applied for the PV bus because in this type of buses, the reactive power injected is not known. The unknown variables for the PQ buses are V and θ and for the Pv buses, θ and Q.

In term of the variables of the power flow problem, the Newton-Raphson method can be written as (2.23) [23]:

$$\begin{bmatrix}\left[\Delta\theta\right]\\ \left[\Delta V\right]\end{bmatrix}=-\left[\left[J\right]^{-1}\right]\begin{bmatrix}\left[\Delta P\right]\\ \left[\Delta Q\right]\end{bmatrix} \tag{2.23}$$

Or simply as (2.24)

$$\left[\Delta x\right]=-\left[J^{-1}\right]\left[F\right] \tag{2.24}$$

Jacobian matrix

The Jacobian matrix gives the linearized relationship between small changes in voltage angle and magnitude, Δθ and ΔV and small changes in active and reactive power, ΔP and ΔQ. It can be written as (2.25) [23]:

$$\left[J\right]=\begin{bmatrix}\left[\delta P/\delta\theta\right] & \left[\delta P/\delta V\right]\\ \left[\delta Q/\delta\theta\right] & \left[\delta Q/\delta V\right]\end{bmatrix} \tag{2.25}$$

We can subdivide the Jacobian matrix in 4 parts each one containing a relationship (2.26):

$$\left[J\right]=\begin{bmatrix}-\left[H\right] & -\left[N\right]\\ -\left[M\right] & -\left[L\right]\end{bmatrix} \tag{2.26}$$

The equation of each submatrix are(equations (2.27) to (2.34)) [23]:

$$H_{ik}=-\delta P_i/\delta\theta_k=V_iV_k(G_{ik}\sin\theta_{ik}-B_{ik}\cos\theta_{ik}) \tag{2.27}$$

$$H_{ii}=-\delta P_i/\delta\theta_i=-V_i^2B_{ii} \tag{2.28}$$

$$M_{ik}=-\delta Q_i/\delta\theta_k=-V_iV_k(G_{ik}\cos\theta_{ik}+B_{ik}\sin\theta_{ik}) \tag{2.29}$$

$$M_{ii}=-\delta Q_i/\delta\theta_i=-V_i^2G_{ii} \tag{2.30}$$

$$N_{ik}=-\delta P_i/\delta V_k=V_i(G_{ik}\cos\theta_{ik}+B_{ik}\sin\theta_{ik}) \tag{2.31}$$

$$N_{ii}=-\delta P_i/\delta V_i=V_iG_{ii} \tag{2.32}$$

$$L_{ik}=-\delta Q_i/\delta V_k=V_i(G_{ik}\sin\theta_{ik}-B_{ik}\cos\theta_{ik}) \tag{2.33}$$

$$L_{ii}=-\delta Q_i/\delta V_i=-V_iB_{ii} \tag{2.34}$$

Note that the i and k indices of the matrices H, M, N, and L are not the indices of the elements of the matrices.

With the Δx found, we can now calculate the solution as (2.35):

$$\left[x^{r+1}\right]=\left[x^{r}\right]+\left[\Delta x\right] \tag{2.35}$$

The process is repeated until ΔP and ΔQ are small enough. Then we can say that the method has converged to its solution. The flowchart of the algorithm is shown in figure 2.31.

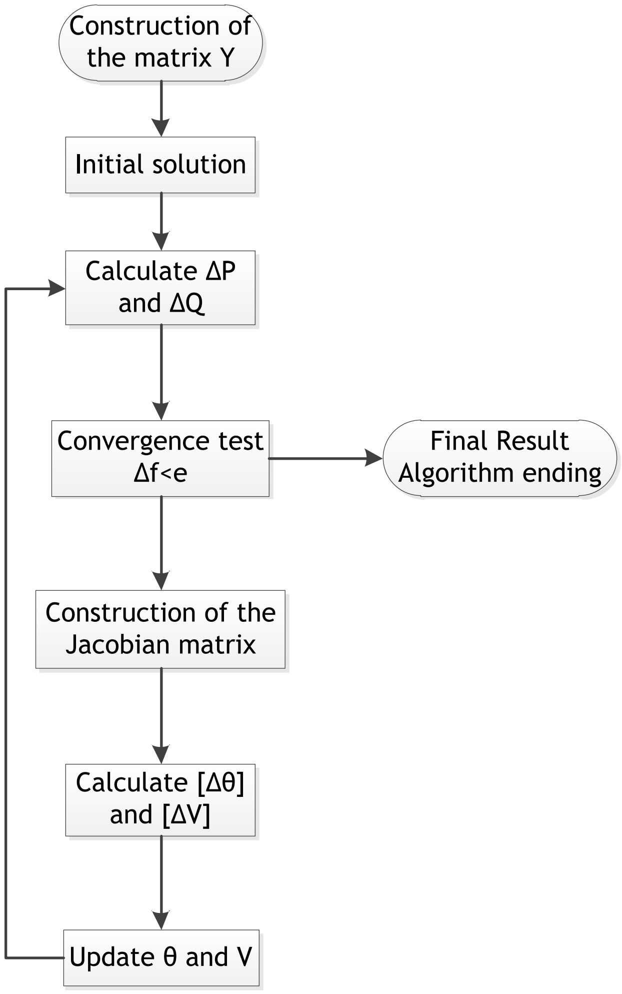

Figure 2.31 - Flowchart of the Newton-Raphson power flow method

2.5.2- Backward forward sweep method

Another good power flow method for radial distribution network is the backward forward sweep method. It consists in two basic steps. In the backward sweep the currents with the actual voltages are determined. In the Forward sweep, the voltage drop is determined and the voltages updated. This method is very simple to implement. The steps of this method are the following:

1 – **Element ordering** – An element ordering scheme is needed to represent a radial network topology by using references from an element to its supplying element in order to efficiently perform the BFS power flow calculation. Several element ordering schemes are available. An alternative to the element ordering is the use of layers. This consists in identifying in which layer of the network is each node. The method of element ordering by layer is shown in figure 2.32 [25].

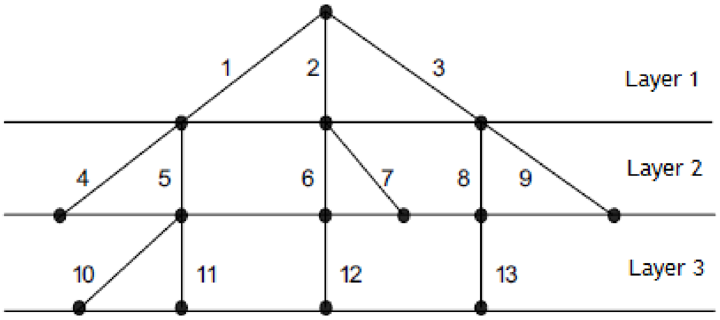

Figure 2.32 - Layer identification [25]

2 – **Nodal currents [25]** - Calculate the nodal current injection assuming a flat voltage profile (2.36).

$$I_k^s = \left(\frac{S_k^s}{V_k^s}\right)^* \tag{2.36}$$

3 – **Backward sweep** – The so called backward sweep is performed in this step and consists in calculating the summation of the branch currents starting from the line segments connected to the far ends and moving towards a certain swing bus or reference bus. With the use of layers start from the last layer and work its way up towards the upper layers. The calculation can be expressed as in (2.37) [25]:

$$J_k^s = -I_k^s + \sum_{m \in \Omega_M} J_m^s \tag{2.37}$$

Where J_k^s is the total phase s current at branch k and Ω_M the set of branches directly connected to branch k, in the lower layer.

4 – **Forward Sweep** – The nodal voltages are corrected starting from the line segments connected to the source bus or swing bus and moving toward the line segments connected to the far ends. With the use of layers, start from the first layer towards the bottom layers. The calculation can be expressed as in (2.38) [25]:

$$V_m^s = V_k^s - Z_{km}^{st} J_k^s \tag{2.38}$$

5 - **Calculate Voltage Mismatches** – The voltage mismatches at each bus are calculated by (2.39) [25]:

$$\Delta V_i^k = \left|V_i^k\right| - V_i^{(k-1)} \tag{2.39}$$

where k is the Iteration number and i the Bus number.

This steps are repeated until the converge criteria is reached. This convergence criteria is defined by the user as it can be, for example, the number of iteration, the mismatches of voltage or active losses. As a note, to start the method, the initial voltages of each node are usually considered the same as the slack bus. The flowchart of the algorithm is shown in figure (2.33).

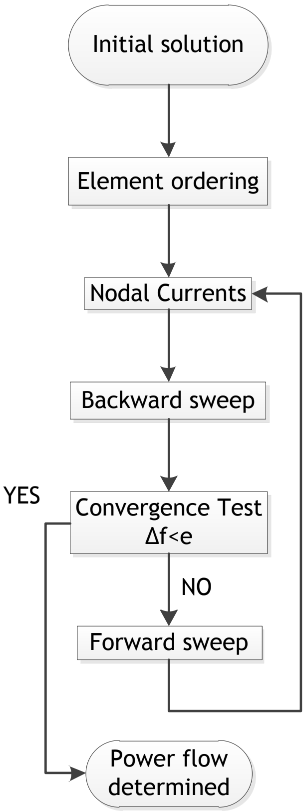

Figure 2.33 - Flowchart of the backward forward sweep algorithm

2.5.3 – Newton-Raphson versus Backward forward sweep method

Newton-Raphson method is a great power algorithm reaching higher precision and better convergence in the transmission network. Because of the topology structure of the distribution network (generally in radial configuration), the Newton-Raphson is not always convergent in this type of network and its stability is challenged. So, for the distribution network, the running time of the BFS is shorter as the programming it's more simple. However, this method is not perfect. Its element ordering can by complicated especially in large scale distribution networks, and its precision is inferior to the one verified in the Newton-Raphson. Also, the BFS works very well with a network with PQ buses, but when PV buses are introduced, the complexity of the algorithm increases and the precision becomes very different from the one verified with the Newton-Raphson. As consumers demand more electrical energy with quality, the integration of PV buses increases which emphasizes this problem. Finally, dealing with large scale distribution networks, the speed advantage of the

BFS quickly disappear as the iterations required for the Newton-Raphson does not increase considerably. [26]

2.6 – Loss allocation on distribution networks

A significant portion of the network operating costs is the power losses. This means that an appropriate, effective and fair allocation of this losses are required in order to provide correct signals to the technical and economical operators of the electric market for an efficient network operation. It also offers important information for the future sitting of generators, loads and network development.

As already covered in section 2.2.4, the integration of DG units alters the power flow on the distribution network from unidirectional to bidirectional and so the power losses. The main difficulty to perform an efficient loss allocation is the non-linear relationship between losses and power flows. Thus there are some requirements for an ideal loss allocation method. It must be economic efficient to reflect the true cost that each user imposes on the network with respect to cost of losses, accurate and equitable, must avoid or minimize cross subsidies between users and between different times of use and must be consistent. Also it must use metered data and must be simple and easy to implement. [27]

There are some methods developed that meet this requirements but for the purpose of this work, the ones studied are the marginal loss coefficients and branch current decomposition for loss allocation method due to the fact that they allow incentives for generators which are contributing to loss reduction and to the fact that their implementation is easy.

2.6.1– Marginal loss coeficients

By definition, this method measure the change in total active power losses L due to a marginal change in the generation/consumption of active power Pi and reactive power Qi at each node “i” in the network. The active and reactive power related to MLCs can be expressed by (2.40) (2.41) [27]:

$$\rho_{Pi} = \frac{\partial L}{\partial P_i} \tag{2.40}$$

$$\rho_{Qi} = \frac{\partial L}{\partial Q_i} \tag{2.41}$$

If a user takes part in voltage control by injecting required reactive power (PV node), there are no loss-related charges for the reactive power to be allocated. This is reflected by (2.42) [27]:

$$\frac{\partial L}{\partial Q_i} \overset{\text{def}}{=} 0 \qquad \text{if i is a PV node} \tag{2.42}$$

Since in power flows, the slack bus compensates the losses in the network, the loss-related charges for this node is 0 (2.43).[27]

$$\frac{\partial L}{\partial P_s} = \frac{\partial L}{\partial Q_s} = 0 \qquad \text{if s is the slack bus} \tag{2.43}$$

Because the transmission network can be taken as the slack bus, this assumption has no impact on both magnitude and polarity.

Next, the following general system of linear equation can be established for calculating MLCs (2.44) [27]:

$$\left[\begin{array}{cccc:cccc}
\frac{\partial P_1}{\partial \theta_1} & \frac{\partial P_2}{\partial \theta_1} & \cdots & \frac{\partial P_N}{\partial \theta_1} & \frac{\partial Q_1}{\partial \theta_1} & \frac{\partial Q_2}{\partial \theta_1} & \cdots & \frac{\partial Q_N}{\partial \theta_1} \\
\vdots & \vdots & & \vdots & \vdots & \vdots & & \vdots \\
\frac{\partial P_1}{\partial \theta_N} & \frac{\partial P_2}{\partial \theta_N} & \cdots & \frac{\partial P_N}{\partial \theta_N} & \frac{\partial Q_1}{\partial \theta_N} & \frac{\partial Q_2}{\partial \theta_N} & \cdots & \frac{\partial Q_N}{\partial \theta_N} \\
\hdashline
\frac{\partial P_1}{\partial V_1} & \frac{\partial P_2}{\partial V_1} & \cdots & \frac{\partial P_N}{\partial V_1} & \frac{\partial Q_1}{\partial V_1} & \frac{\partial Q_2}{\partial V_1} & & \frac{\partial Q_N}{\partial V_1} \\
\vdots & \vdots & & \vdots & & & & \\
\frac{\partial P_1}{\partial V_N} & \frac{\partial P_2}{\partial V_N} & \cdots & \frac{\partial P_N}{\partial V_N} & \frac{\partial Q_1}{\partial V_N} & \frac{\partial Q_2}{\partial V_N} & & \frac{\partial Q_N}{\partial V_N}
\end{array}\right]
\left[\begin{array}{c}
\frac{\partial L}{\partial P_1} \\ \vdots \\ \frac{\partial L}{\partial P_N} \\ \hdashline \frac{\partial L}{\partial Q_1} \\ \vdots \\ \frac{\partial L}{\partial Q_N}
\end{array}\right]
=
\left[\begin{array}{c}
\frac{\partial L}{\partial \theta_1} \\ \vdots \\ \frac{\partial L}{\partial \theta_N} \\ \hdashline \frac{\partial L}{\partial V_1} \\ \vdots \\ \frac{\partial L}{\partial V_N}
\end{array}\right] \tag{2.44}$$

In a more compact form (2.45):

$$A.\rho = b \tag{2.45}$$

Where the matrix A is the transpose of the Jacobian in the Newton Raphson power flow and can be calculated on the basis of power flow results for a particular system operating point. The vector ρ represents MLCs whereas the vector b represents sensitivies of total losses with respect to voltage angle and magnitude. So, total system active loss L is given by (2.46) [27]:

$$L = \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N} G_{ij}\left[V_i^2 + V_j^2 - 2V_iV_j\cos(\theta_i - \theta_j)\right] \tag{2.46}$$

Therefore, the entries of vector b are (2.47) (2.48) [27]:

$$\frac{\partial L}{\partial \theta_i} = 2\sum_{j}^{N} G_{ij} V_i V_j \sin(\theta_i - \theta_j) \qquad \text{with } i=1,\dots,N \qquad (2.47)$$

$$\frac{\partial L}{\partial V_i} = 2\sum_{j}^{N} G_{ij} \left[V_i - V_j \cos(\theta_i - \theta_j) \right] \qquad \text{with } i=1,\dots,N \qquad (2.48)$$

As previously defined, there are no equations for the slack bus and PV buses will not have (2.49) [27]

$$\frac{\partial L}{\partial V_i}. \qquad (2.49)$$

Reconciliation: The result of applying MLCs calculated in accordance with the procedure outlined is approximately twice the amount of losses (2.50).[27]

$$\sum_{i=1}^{N-1} \left[\rho_{Pi}.P_i + \rho_{Qi}.Q_i \right] \cong 2L \qquad (2.50)$$

To obtain the vector of reconciled MLCs ρ, a constant multiplier reconciliation factor k_0 is applied. This factor in calculated as follows (2.51) [27]:

$$k_0 = \frac{L}{\sum_{i=1}^{N-1} \left(\rho_{Pi}.P_i + \rho_{Qi}.Q_i \right)} \qquad (2.51)$$

The reconciled MLCs ρ can now be calculated as follows (2.52) [27]:

$$\rho = k_o.\rho \qquad (2.52)$$

The allocation of the total active power losses to individual users can be calculated using the reconciled MLCs as follows (2.53) [27]:

$$\sum_{i=1}^{N-1} \rho_{Pi} P_i + \sum_{i=1}^{N-1} \rho_{Qi} Q_i = L \qquad (2.53)$$

2.6.2- Branch current decomposition method for loss allocation

Despite the fact that MLC method is effective in dealing with distribution systems with distributed generation (DG) and can provide correct sensitivity information, it require the calculation of the Jacobian matrix for the power flow which makes this method computationally intensive.

The branch current decomposition for loss allocation method takes benefit from the radial structure of the distribution network and needs only the solution of the power flow equations which can come from a backward/forward sweep algorithm without the necessity of calculating ant other additional parameters. With respect to the MLC method, this method is very fast as it does not have to calculate and to invert the Jacobian matrix.

In this way, considering a radial distribution system in which the root node is assumed as slack and its voltage angle as the angle reference, the branches losses can be defined as (2.54) [29][30]:

$$L^{(b)} = R^{(b)} \bar{I}^{(b)} \sum_{k \in K^{(b)}} \bar{I}_k^* \quad , \tag{2.54}$$

where $K^{(b)}$ is the set of downward nodes supplied from branch b.

The losses associated to branch b are assigned to the nodes located in the path from branch b to the root as follows (2.55) [29] [30]:

$$L_k^{(b)} = \begin{cases} \mathrm{Re}(\bar{I}_k^* R^{(b)} \bar{I}^{(b)}) & \text{if } k \in K^{(b)} \\ 0 & \text{if } k \notin K^{(b)} \end{cases} \tag{2.55}$$

So, the total losses allocated to node k is the sum of the components related to each branch (2.56) [29] [30]:

$$L_k = \sum_{b=1}^{B} L_k^{(b)} = \mathrm{Re}(\bar{I}_k^* \sum_{b \in B_k} R^{(b)} \bar{I}^{(b)}) \tag{2.56}$$

Chapter 3

Problem formulation

3.1 – Problematic

As the actual integration of DG units is based in a “fit and forget” approach, their full potential contribution to the network is not being exploited as the power generated by them are not controlled.

In PV systems, the use of storage system is mainly in isolated systems to supply energy to small loads when the solar energy is unavailable. For this type of consumers, this configuration can be good for their purposes. But when dealing with PV generation plants connected to the grid, the use of storage units is ignored and all the solar production in each period of the day is directly injected in the grid. The example 3.1 shown the operation of a PV unit connected to a distribution network with the load curves represented without a storage unit. As it can be seen, all the power generated in each period is supplied to the network. But the periods of the day when the PV in operating, is not the best in term of loss reduction as the peak-load occurs between 21 and 24h. Also if the load of the network is small on the periods of the day that the PV is injecting power, the problems mentioned in section 2.2.4 can arise.

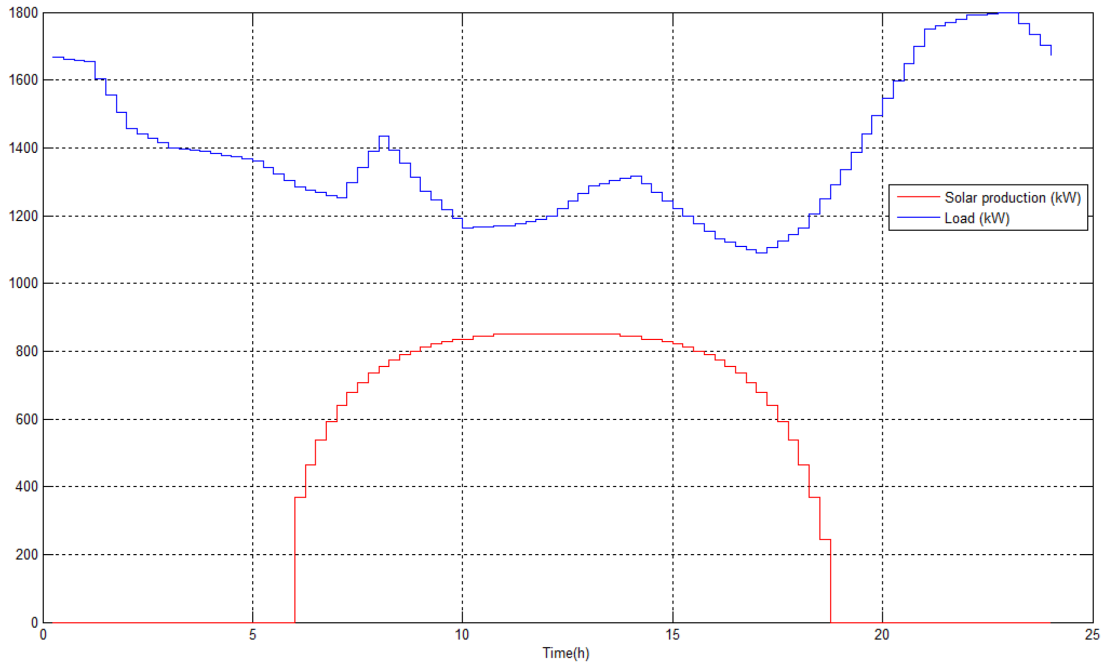

Figure 3.1 - Operation of a PV unit connected to a distribution network without storage

From the point of view of losses, the integration of a PV system in the distribution network can improve the efficiency of the system, but not in their full potential as the periods of the day that they inject power in the grid can have less impact if it was injected in another period of the day.

So, if the power generated by a PV system could be stored and made available in the periods when the impact on losses is greater its contribution to reduce losses can be maximized. This optimization could bring benefits in different ways. In the point of view of the consumer, their impact on the losses will be lesser with the integration of the PV, so the money paid to support their quota of the losses is lowered. In the point of view of the distribution company, the power brought from the transmission network is smaller which means less costs, the encouragements received from regulator entities are increased due to the better efficiency of the network and it can integrate more DG units in the network without making any investment in the network structures. Finally, in the point of view of the PV system owner, it ensures that the power will be injected in the periods of time that the energy is more expensive (typically on peak-loads), so its profit is maximized either.

By the reasons mentioned above, the algorithm developed in this work is focused in the coordination between a PV and its storage unit to optimize their contribution in reducing the losses on the distribution network that they are imbedded.

3.2 - Problem formulation

The problem defined is a minimization of an objective function with a number of variables. So it can define as (3.1):

$$\text{Min } F(x) \tag{3.1}$$

Restricted to:

$$\text{Xmin} \leq x \leq \text{xmax} \tag{3.2}$$

Variables

In an optimization problem, it is necessary identify and use variables to model its operation and characterize its state during the time of his function. They can be divided in 3 categories. The decision variables are the ones that have influence in the system behavior. The only decision variable present in this problem is the power supplied to the grid by the PV/storage system in each period of the day. The constrains are the variables that restrict the problem and the solutions obtained. They are the line capacity that connects the PV to the grid and the storage capacity. The parameters are the problem data that are not affected in the resolution. So the parameters are the loads of the network at each node in each period and the solar production in each period. The table 3.1 shows the variables present in the problem discussed in this thesis. "t" is the period of the day and "k" is the node of the network.

Table 3.1 - Types of variables and their description

Variable type	Variable	Description
Decision variable	Ss_t	Power supplied to the grid by the PV/storage system in the period t
Constraints	Lb_z	Line limit at the branch z that connects the PV to the network
	Bl	Storage capacity
Parameters	Ld_{kt}	Load at node k in the period t
	Sp_t	Solar production in the period t

Restrictions

The usage of the PV system in coordination with the storage units have some restriction that will be now detailed.

The storage units, for a perfect minimization of the losses, are considered with an infinity capacity. But in reality, the implementation required to limit this capacity to a value that has the better economic/technical impacts. Also, the energy in the battery cannot drop below 0 as it cannot supply energy when it is depleted.

Also, the production of a PV system during the day in not constant. As the day passes, the production changes and can be affected by factors as for example the weather or shadows. More important of all, is the fact that during the night the PV system dos not generate energy. The PV/storage system cannot supply to the network more or less energy than the daily generation from solar. In result, the Energy supplied to the network must be equal to the PV daily production.

Another restriction is the capacity of the transmission lines that connect the PV with the storage system to the grid. This line has a limit and if there is a peak load, the PV/storage system cannot supply endless power as the line limit this power injected.

These restrictions can be described mathematically by the following expressions (3.3) (3.4) (3.5).

$$0 \leq Bl \leq Blmax \tag{3.3}$$

$$\sum_{t=1}^{N}(Sp_t) = \sum_{t=1}^{N}(Ss_t) \tag{3.4}$$

$$0 \leq Lbz \leq Lbmax \tag{3.5}$$

where "Bl" is the battery capacity, "Sp" is the Solar production in each period, the "Ps" is the production supplied to the grid by the PV/storage system in each period, "Lb" is the power flow on each branch, and "z" the line that connects the PV/storage system to the grid.

Complete formulation of the problem (3.6) (3.7) (3.8) (3.9):

$$Min\sum_{t=1}^{N} L_{PVt} \tag{3.6}$$

Subject to:

$$0 \leq Bl \leq Blmax \tag{3.7}$$

$$\sum_{t=1}^{N}(Sp_t) = \sum_{t=1}^{N}(Ss_t) \tag{3.8}$$

$$0 \leq Lbz \leq Lbmax \tag{3.9}$$

Where "L_{PVt}" are the losses in the PV bus in each period of the day and "N" the number of periods in each day.

3.3 – Methodology (optimization algorithm)

To resolve the problem previously explained, a specific methodology was applied as well the development of an algorithm to make the optimization. This algorithm was developed to integrate only one PV system.

To start, a forecast of the loads of the network and solar production in each period of the day is needed. Next, for each period of the day, the optimal PV production for loss reduction purposes is determined increasing step by step the power injected in the grid. The procedure stops when the increase of DG power causes a decrease the contribution to the loss reduction.

For example, if the increment has the value of 5kW per iteration, in the first iteration is with 0 kW and the second iteration is with 5kW. At the end of each power flow, the losses allocated to the PV node are calculated. When the loss allocated to the PV plant in the current iteration, are higher than the one registered in the previous iteration, the iteration process stops and the ideal PV generation that minimize the losses of the network for that period is the one on the previous iteration. This is explained by the fact that the PV contributes to the network losses until a certain point, when the contribution starts to drop. This is the PV generation value that has a maximum contribution to reduce the losses on the PV node. Then, the process is repeated to the next period of the day until all the ideal PV generation (in the point of view of loss reduction) for all periods are found. This step of the algorithm is in the figure 3.2 that shows the losses on a PV node as it generation increases. As it can be seen, the PV generation increases and its contribution to the network also increases until a certain point when its contribution starts to drop.

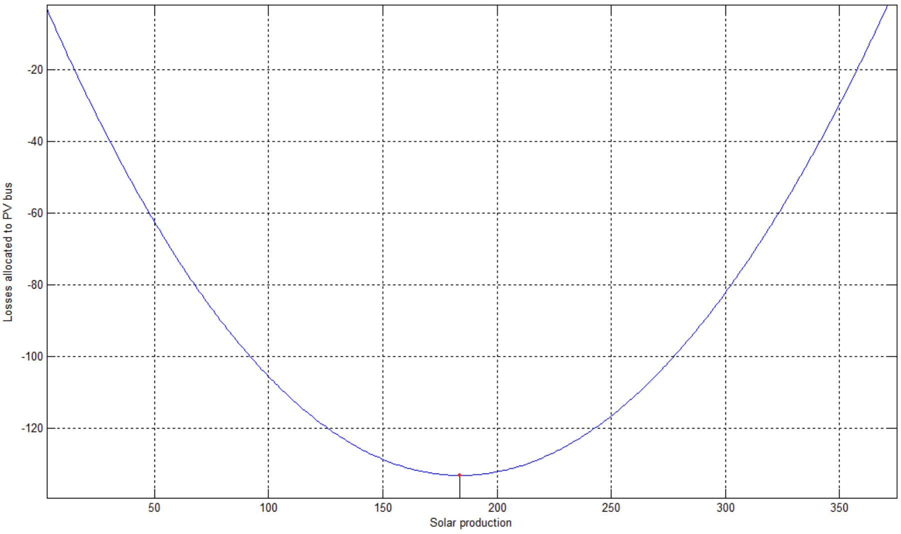

Figure 3.2- Contribution of the PV/storage system to reduce losses for different values generation at a random period of the day and the optimal generation value

With the optimal PV/storage generation at each period of the day, is possible to plot the absolute optimal contribution for the whole day as shown in figure 3.3

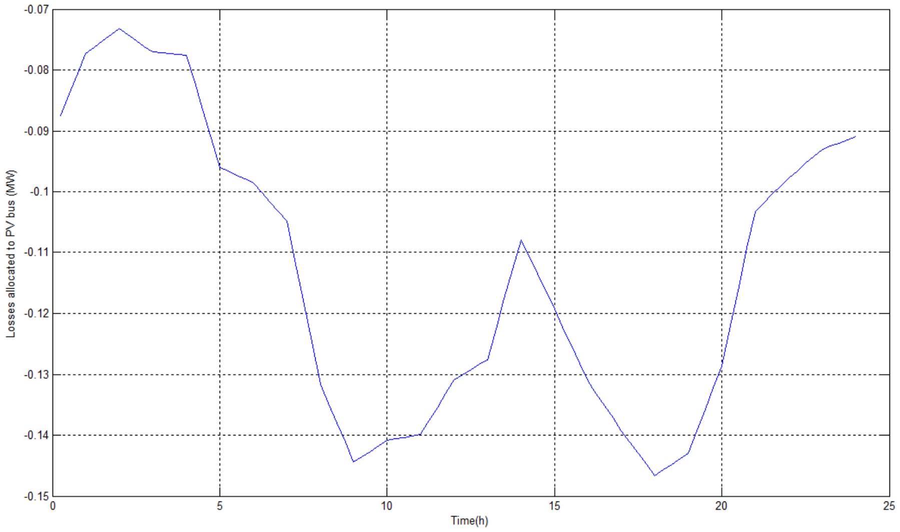

Figure 3.3 – Optimal losses on the PV bus each period of the day

At this time, it is created a vector that contains the optimal generation values of the PV sorted in descending order of their respective losses. Next, the values of this vector that exceeds the limit of the line capacity that connect the PV/storage system to the grid are readjusted to the value of such limit. For example, if the line capacity limit is 500 kW and the optimal generation is 600 kW, then it is readjusted to 500 kW. After this, a variable will read the sum of the elements of the vector beginning from the first one. When the value of the sum reaches the daily solar production forecasted to that day, the remaining values of the vector are changed to 0. In result, it is obtained the vector with the optimal generation of the PV/storage system required of each period of the day, that summed equals the daily solar production and can minimize the losses on the network. So the power produced equals to the power consumed.

With the vector that contains the optimal production for each period of the day, the power flow on the battery is calculated where the injection on the battery is equal to the solar production minus the Optimal generation of the PV/storage and the energy stored in the battery is equal to the integral of the storage device injection.

The next step is to check if the lower battery limit (that is 0) is violated. If so, a reallocation of injection is needed in order to prevent this situation. The first step of this reallocation is to determine the periods of the day in which the limit is being violated and when the battery is discharging. In these periods, the injection on the battery is increase until it reaches 0 and a variable will count the amount of injection changed. For the balance of the system, if an injection is increase, it must be decreased on another period(s). So, a search is made to find the periods that are after the last allocation of injection and where the battery is charging. Having this periods determined, the one where the contribution of the generator is higher is choose to remove injection from the battery to increase the amount injected to the grid. The remove of injection cannot make the production to the grid higher than the absolute optimal production or the limit of the line that connects it to the grid. If this restriction does not arise, then the minimum value between all the injection and the remaining amount is removed. With this process, it is assured that the battery cannot deliver more energy that it has.

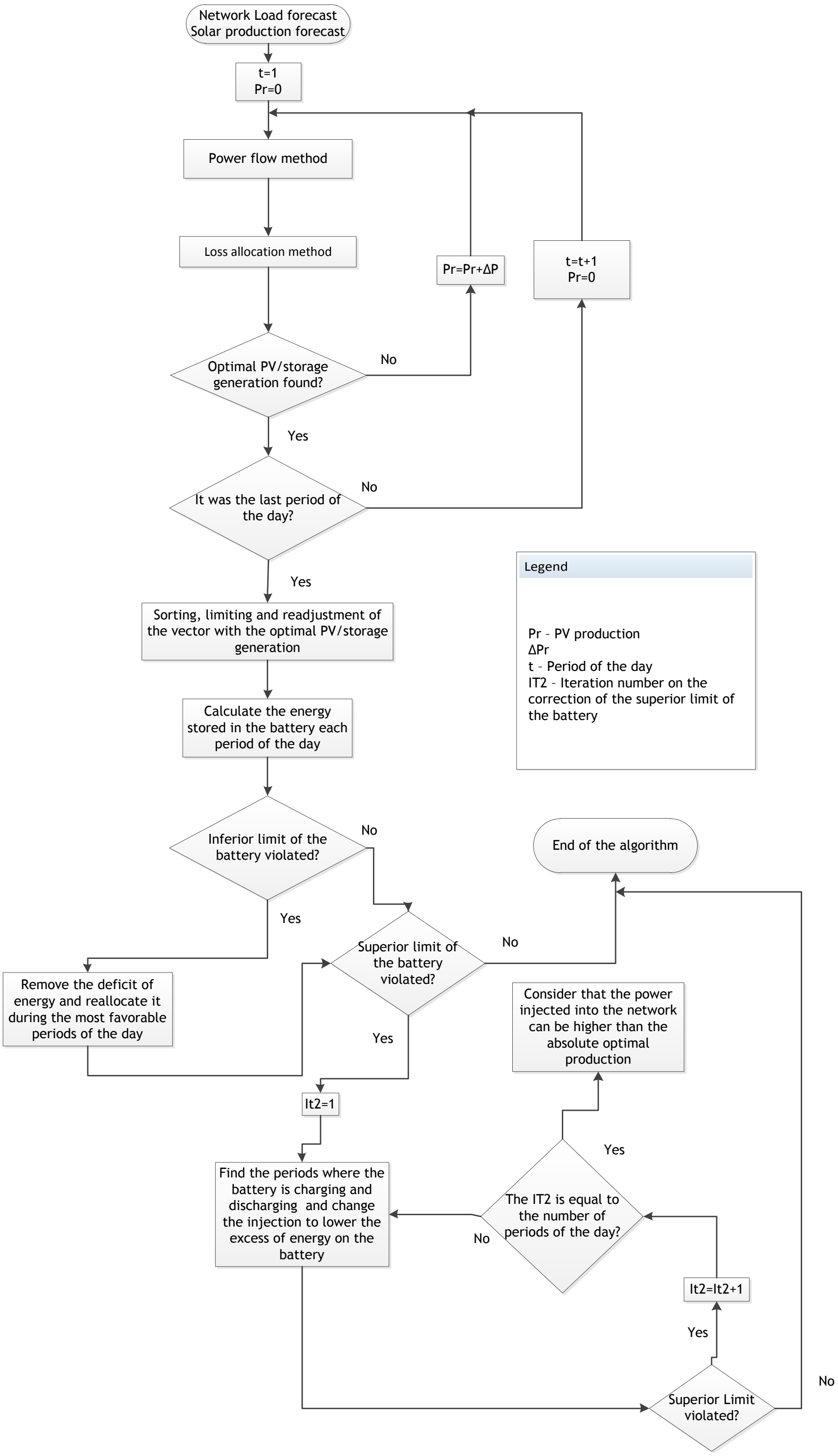

Figure 3.4 - Flowchart of the algorithm developed

The next step is to determine the energy on the battery for each period of the day with the new profile of injections. As the minimum limit is assured to be fulfill, the superior must be check. If it is exceeded, another reallocation of injections must be done. First, a sweep along the day is made to find the periods where the battery is charging and where it is discharging. The charging period that has a better contribution to loss reduction is chosen and the injection on the battery in this period is decreased at the same time that the injection to the grid increases. Once more, the remove of injection cannot make the production to the grid exceed the absolute optimal production or the limit of the line that connects it to the grid. So the amount of injection removed is the minimal between these two, and the excess of power being injected in the battery. This amount of injection removed must be added in another period of the day. So the discharging period that has a lower contribution to the reduction of the losses is chosen and the injection is increased. With this solution, the energy on the battery is determined again for each period of the day and the limits are checked. If one of the limits is violated, the reallocation process is run once again from the last solution obtained until the solution is feasible.

If the absolute optimal production determined is lower than the solar production for a relevant part of the day, this reallocation can be insufficient to drop the maximum value of the energy stored in the battery. In this case, the maximum injection to the grid is set to the maximum capacity of the line in order to permit the use of the total solar energy available during the day.

To better comprehend this “modus operandi” of the algorithm, the figure 3.4 contains the flowchart of the algorithm developed:

Chapter 4

Case study - Results

This chapter is dedicated to the application of the proposed methodology to a distribution system considering different load profiles and different solar energy curves. The obtained results will be presented and discussed.

4.1 - Network, irradiance and load profiles

To implement and study the performance of the developed algorithm, the distribution network presented in [28] without the redundant lines with the addition of a bus with the PV/storage unit was used. The resistance and reactance values of the branches used are the same presented in the document. As it can be seen in figure 4.1, the network tested is composed by 34 buses (1 slack bus and 33 PQ buses), 33 branches, a PV generator with a storage unit connected to the original network by the means of a transformer and an inverter. The new bus is modeled as a PQ bus with Q = 0 (without voltage control).

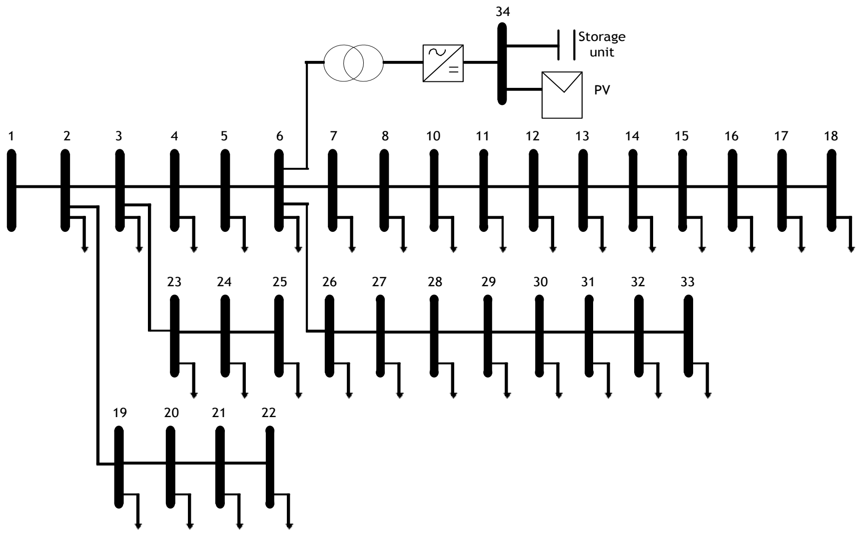

Figure 4.1 - Topology of the network tested

The load profiles used during the simulation are similar to the ones registered in typical working day at the beginning of the last decade in Portugal. These curves used are divided in 3 types, residential, commercial and industrial, which are shown in figures 4.3, 4.4 and 4.5 respectively. The total load in the network for each month is shown in figure 4.6. The nominal power output of the PV generator is 800 kW and the PV power forecasted refers to "clear sky" irradiance for a plant located in Porto area [31]. With this, the solar production forecast for each typical day of each month was considered and is shown in figure 4.2. The capacity of the branch that connects the bus 34 to bus 6 is set at 900kW and the storage capacity considered is 1500 kWh.

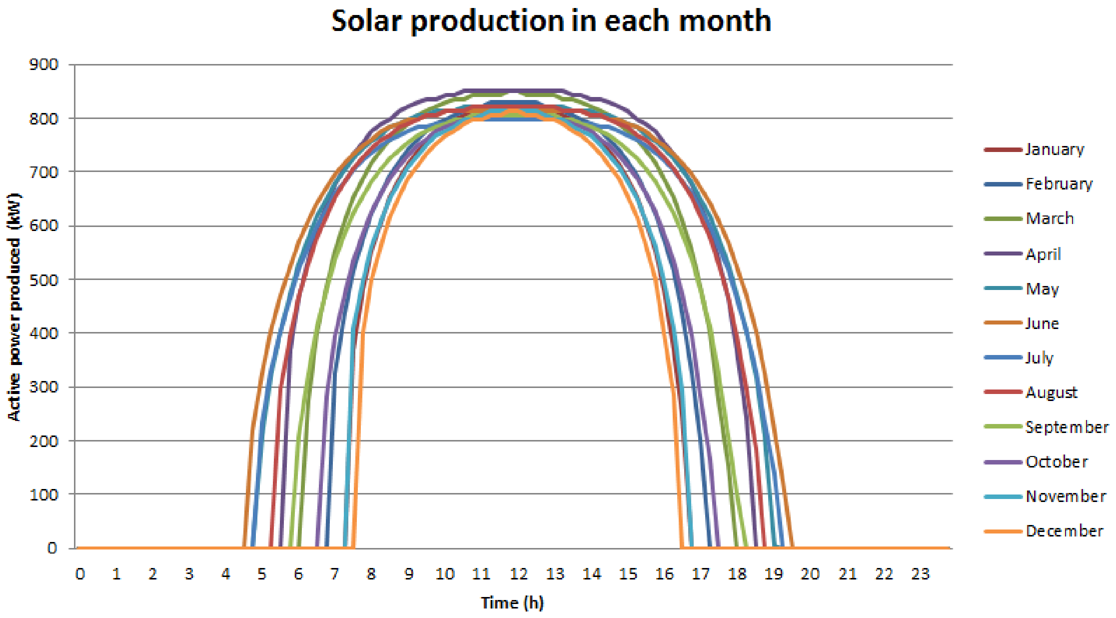

Figure 4.2 - Solar production for each month of the year

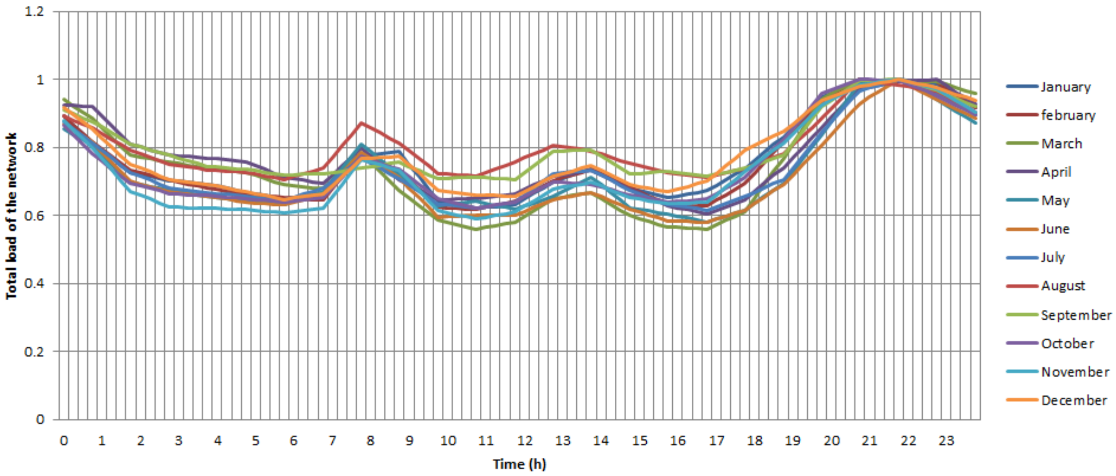

Figure 4.3 - Load curves of residential consumers in the network for each month

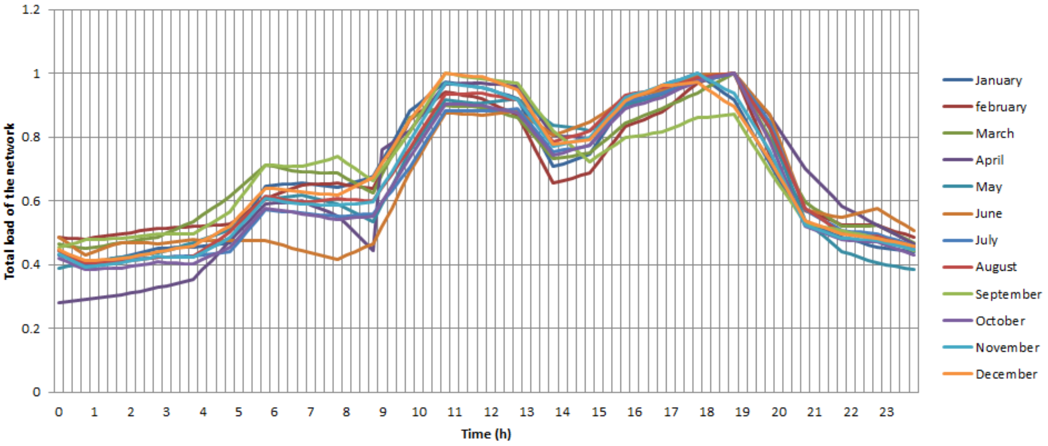

Figure 4.4 – Load curves of commercial consumers in the network for each month

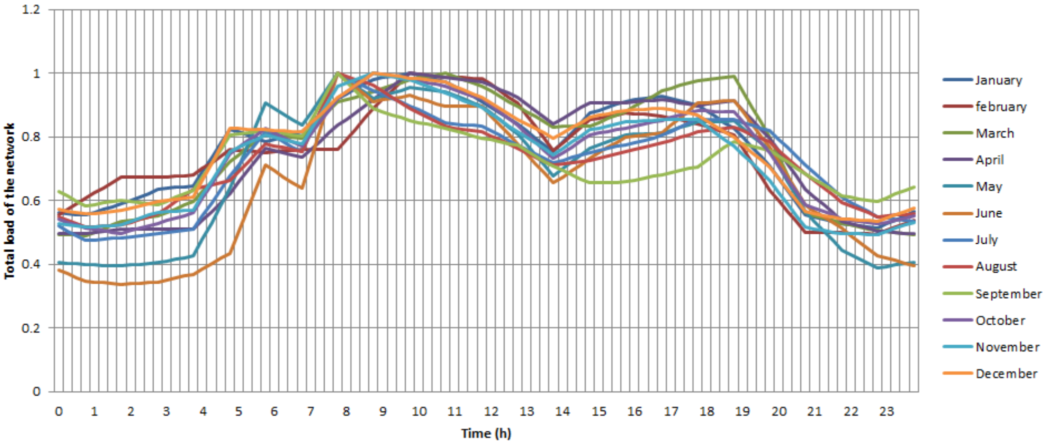

Figure 4.5 – Load curves of commercial industrial in the network for each month

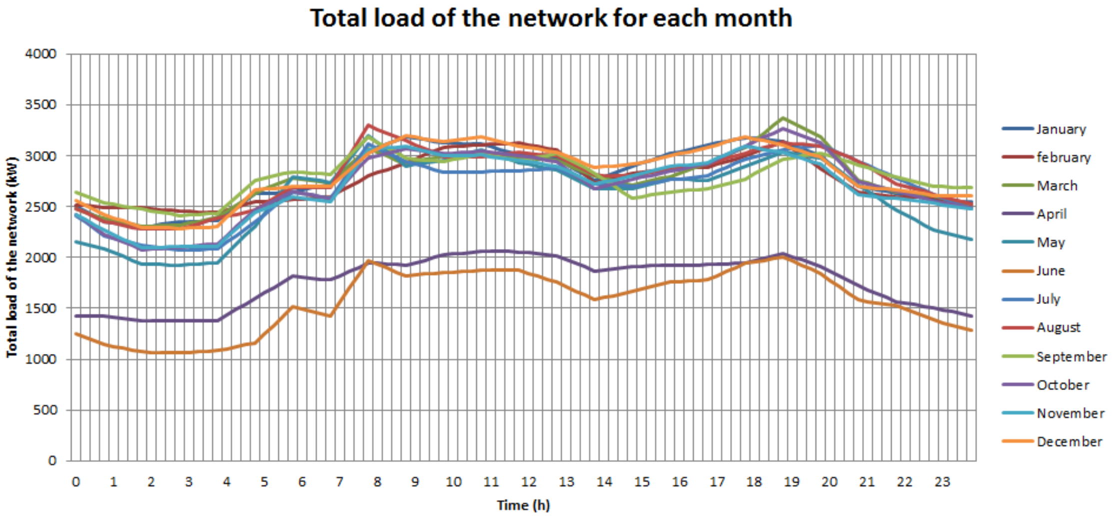
Total load of the network for each month

Figure 4.6 – Total load of the network for each month of the year

4.2 - Results

A typical working day for each month of the year as been simulated in three different conditions:

- without the presence of PV plant,
- with the presence of a classical PV plant without storage,
- with the optimal coordination of PV plant and storage.

Table 4.1 resumes the total daily loss energy and the contribution of the PV plant for loss reduction calculated using the loss allocation algorithms. MLC and BCDLA provide the same results. These values are highlighted in Figure 4.7 and figure 4.8.

Table 4.1- Total losses on the network and the contribution of the generator to reduce losses

	Total losses (MWh/day)			PV contribution (MWh/day)	
	Without PV	PV without storage	PV with storage	PV without storage	PV with storage
January	108.9	96.1	95.6	-4.44	-4.69
February	105.0	91.4	91.0	-4.70	-4.82
March	107.8	92.3	91.8	-5.26	-5.50
April	111.7	99.3	98.6	-3.28	-3.94
May	95.9	78.1	77.8	-6.09	-6.09
June	93.5	82.0	81.2	-2.90	-3.61
July	99.2	81.9	81.6	-5.95	-6.00
August	106.1	88.4	88.1	-6.14	-6.15
September	105.0	89.9	89.5	-5.26	-5.43
October	102.8	89.1	88.5	-4.76	-5.05
November	100.7	89.1	88.0	-4.25	-4.47
December	110.0	97.8	97.4	-4.32	-4.49

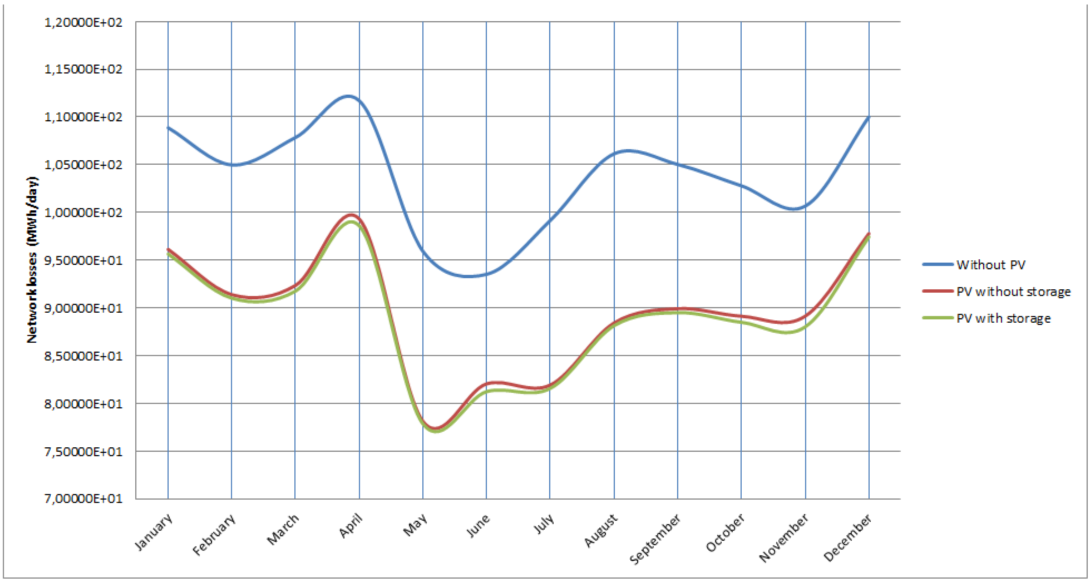

Figure 4.7 - Total losses on the network in each month

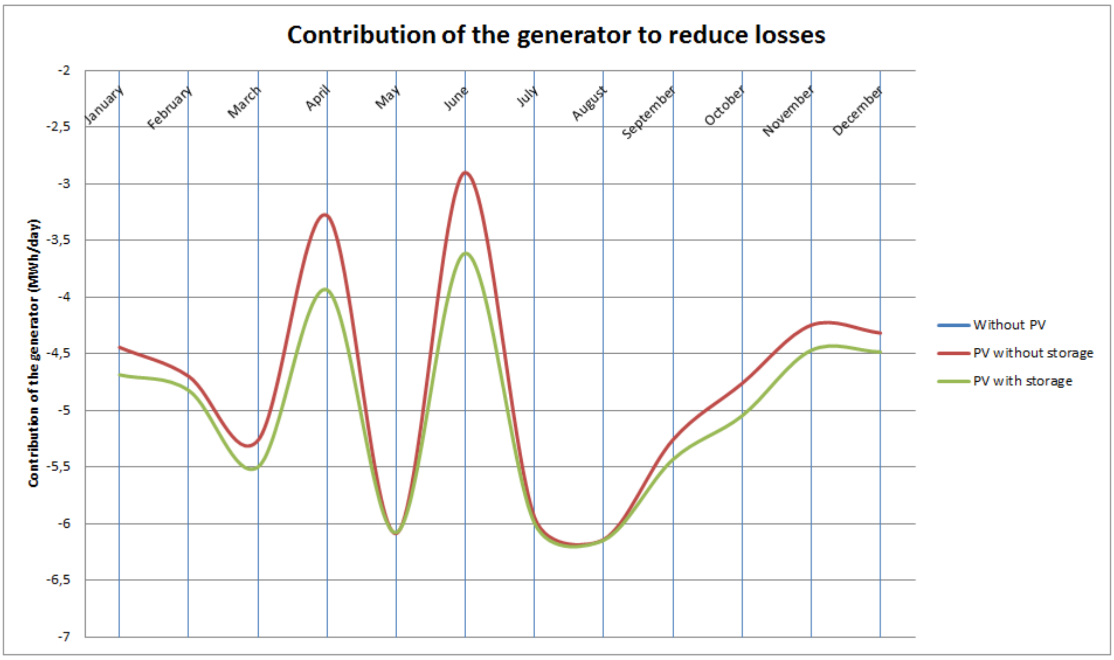

Figure 4.8 - Contribution of the PV to reduce losses in each month

The results show that that the coordination between the PV and the storage unit can achieve in general better results than the other configurations tested. Although, in three months (May, July and August) the contribution of the PV with storage is somewhat small compared to the other months. This can be explained by the fact that the solar production and the load curve in those particular months are not favorable to improve much more the contribution of the PV because the solar energy available is lower than the optimal injection according to the load.

For more details, two months will be analyzed: January in the winter and June during the summer. The figures 4.9 to 4.14 show the allocated losses in the distribution network for the month of January and June, respectively. With these results, it is possible to identify the contribution of each node (load) to the total loss and how it changes during the day. For example, in June, the bus that has the most impact on the losses of the network is the bus 29. Comparing the results obtained in each of the three cases, the network without a PV generator has higher losses as expected because all the power comes from the slack bus (connection to the higher level voltage). The presence of the PV unit decreases also the responsibility of all the loads to the loss.

The addition of a controlled storage unit decreases even more the losses and the portion of them allocated to the load. Because the algorithm developed change the injections on the battery, compared to the case without storage, the losses are in general worst in the periods with less loads and better when they are bigger. This is the first result that proves the efficiency of the algorithm.

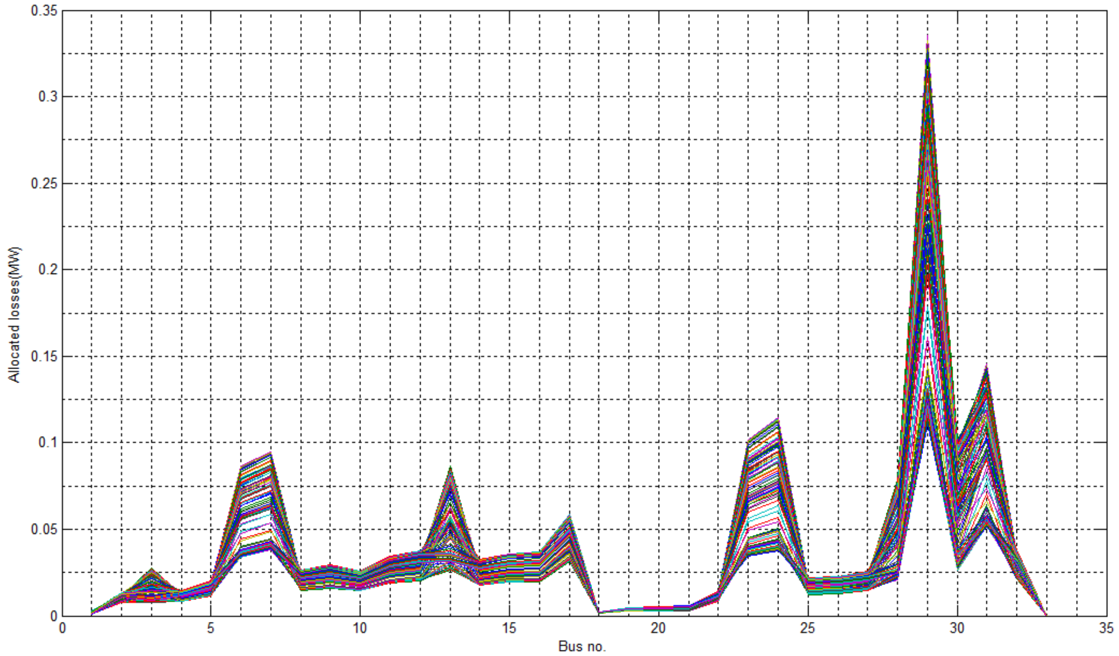

Figure 4.9 - Allocated losses in the network for each period of time without the PV in January

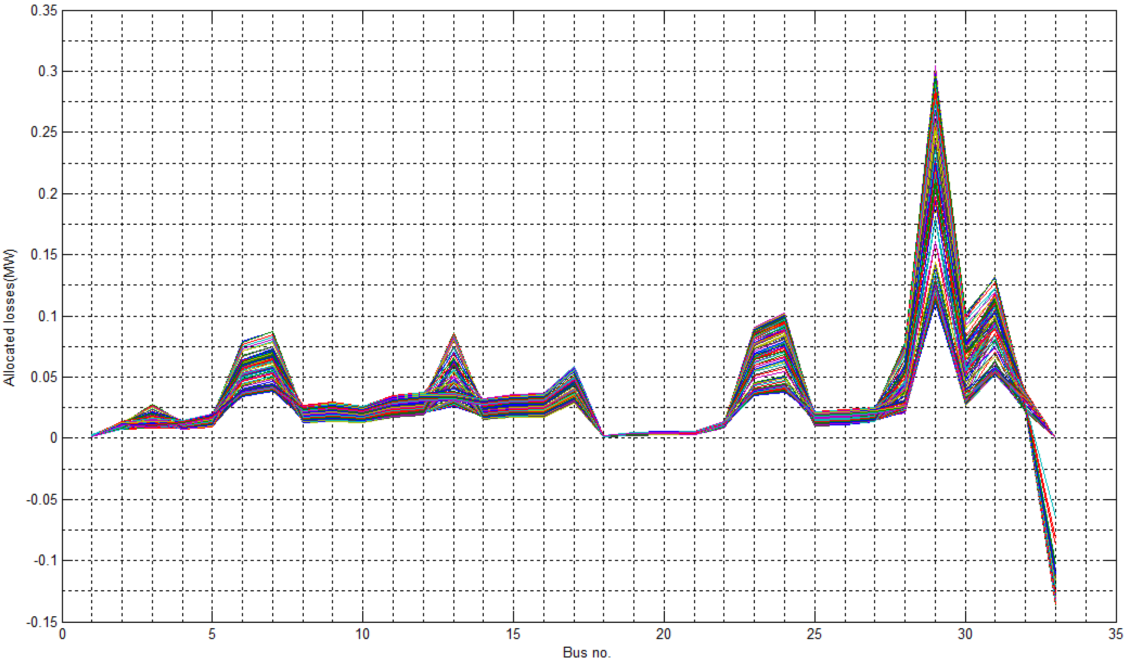

Figure 4.10 - Allocated losses in the network for each period of time to a PV without storage in January

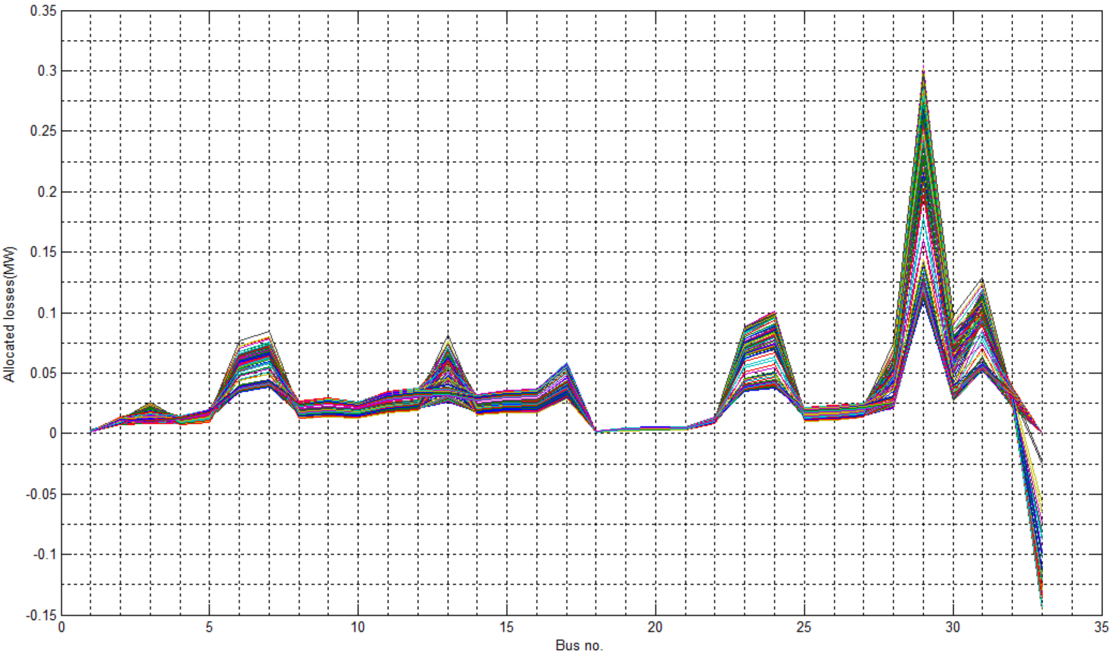

Figure 4.11 - Allocated losses in the network for each period of time to a PV with storage in January

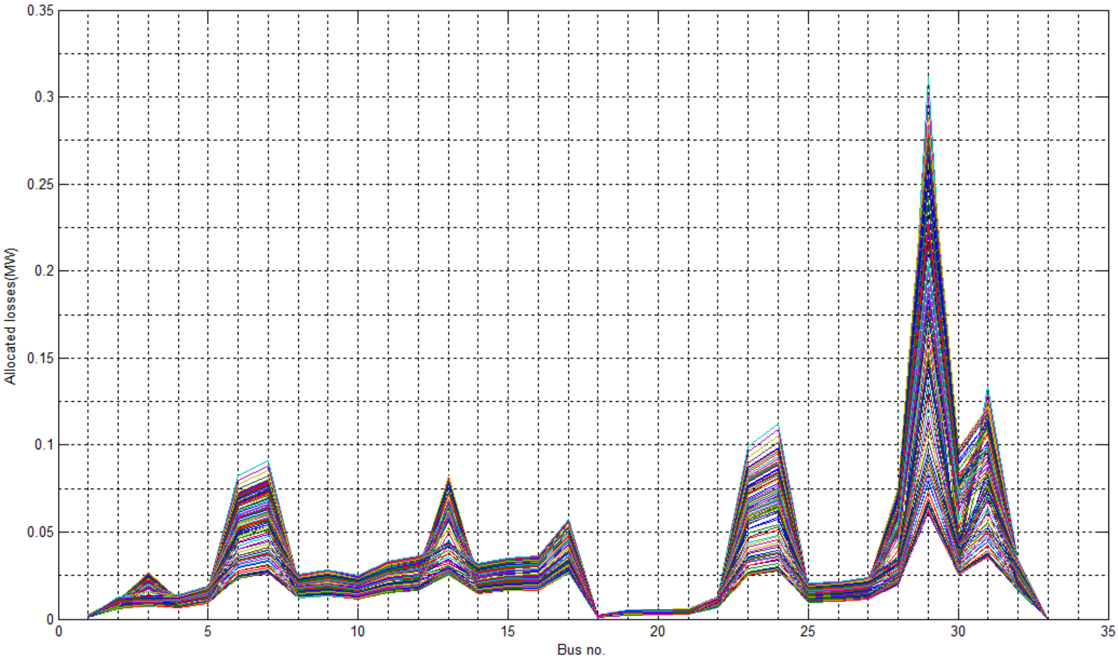

Figure 4.12 - Allocated losses in the network for each period of time without the PV in June

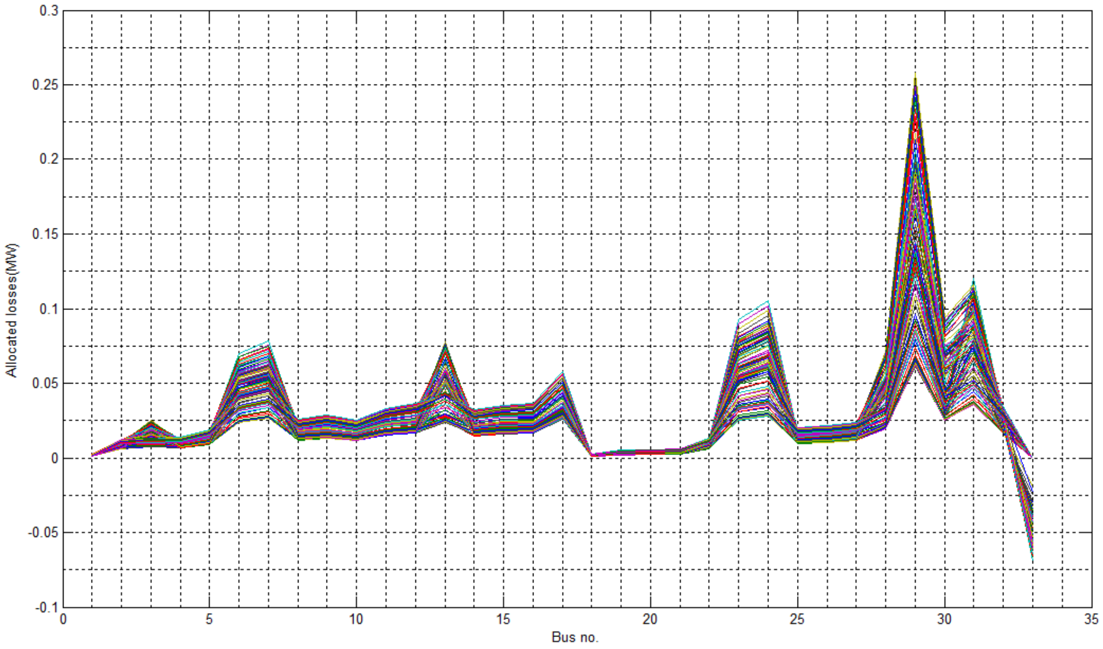

Figure 4.13 - Allocated losses in the network for each period of time to a PV without storage in June

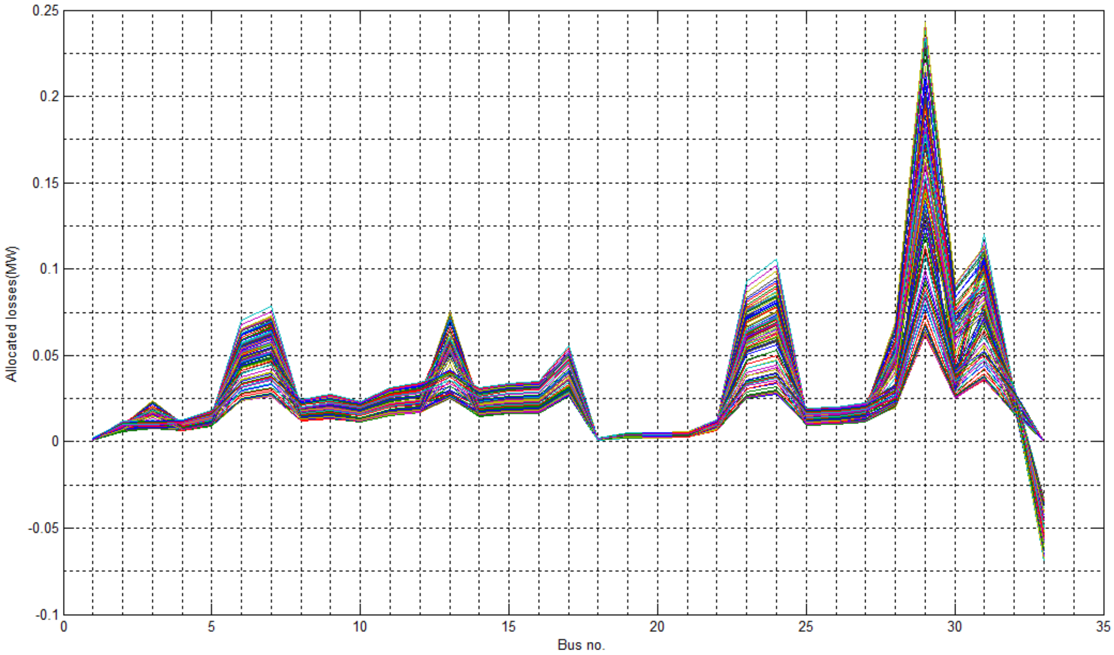

Figure 4.14 - Allocated losses in the network for each period of time to a PV with storage in June

The figures 4.15 to 4.20 show the allocated losses during the day at each node. Through this figures it is possible to see which periods of the day each node has a higher contribution to the losses or less at the same time it is possible to see the contribution of the PV to the decrease of losses (the negative curve). So comparing the three cases, the results are the same obtained in figures 4.9 to 4.14 as the losses are bigger without the PV and smaller with the PV with storage.

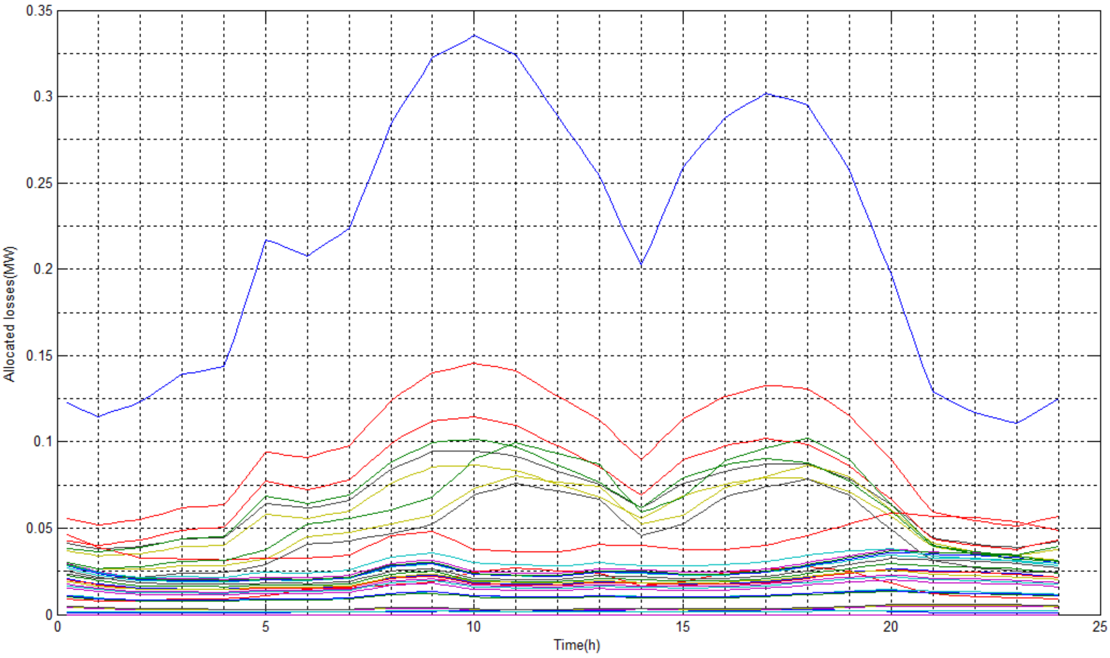

Figure 4.15 - Allocated losses in the network in each bus without a PV in January

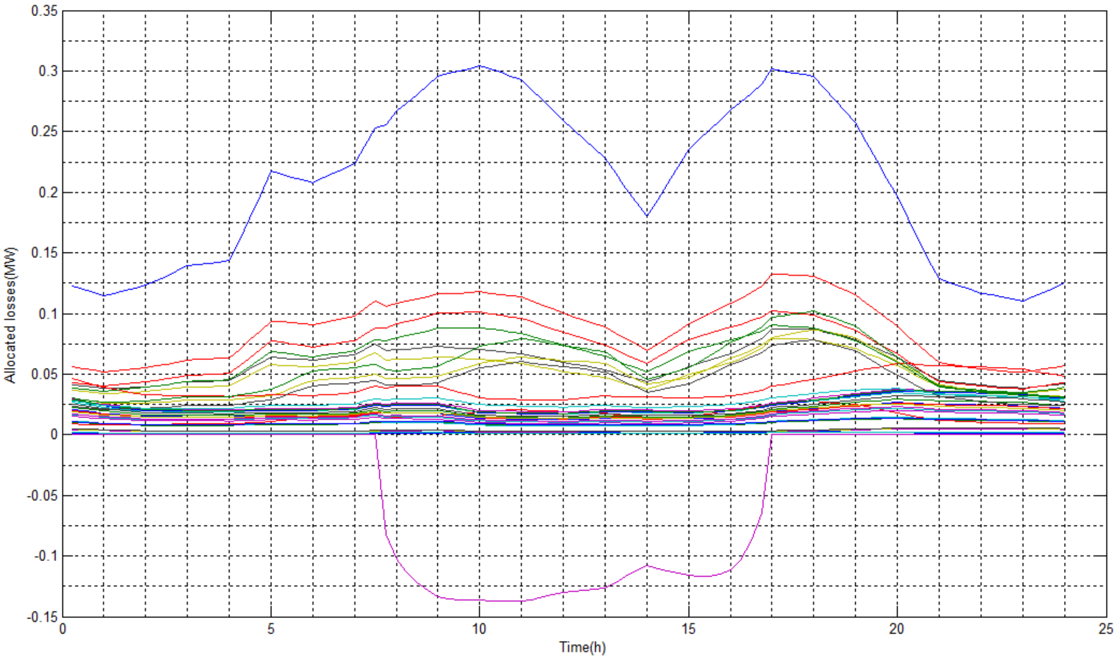

Figure 4.16 - Allocated losses in the network in each bus to a PV without storage in January

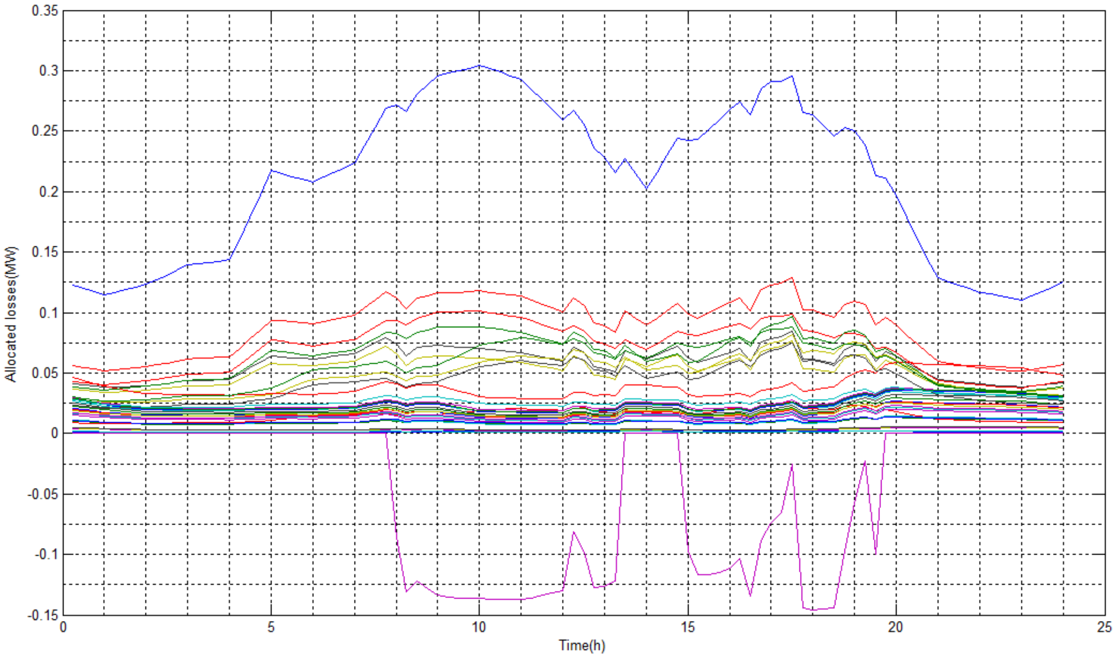

Figure 4.17 - Allocated losses in the network in each bus to a PV with storage for the month of January

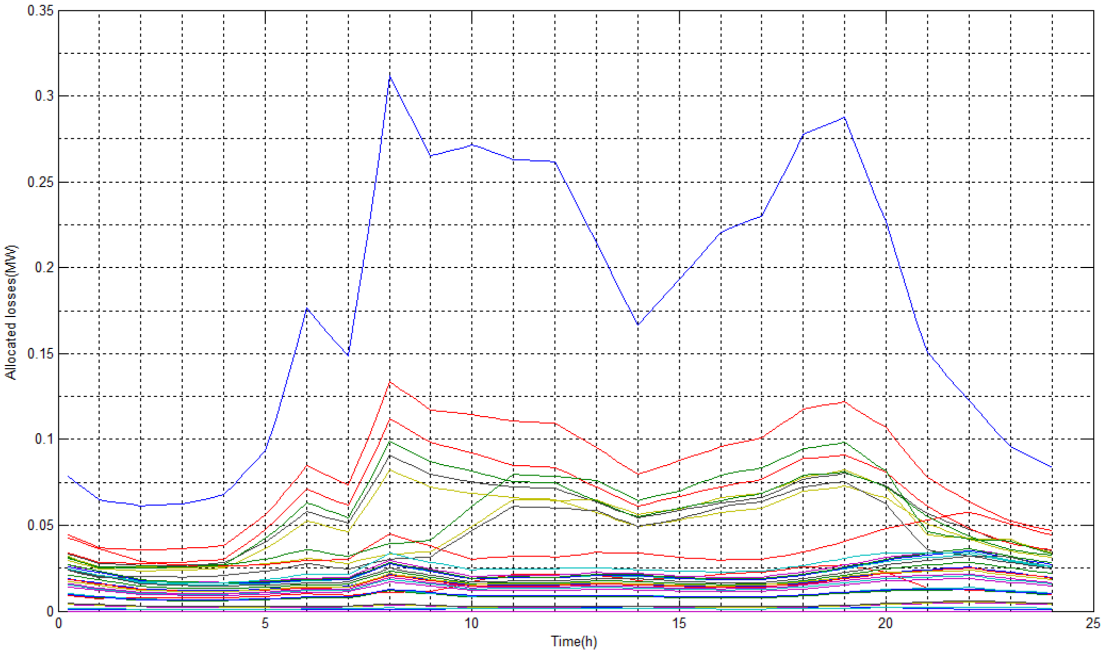

Figure 4.18 - Allocated losses in the network in each bus to a PV for the month of June

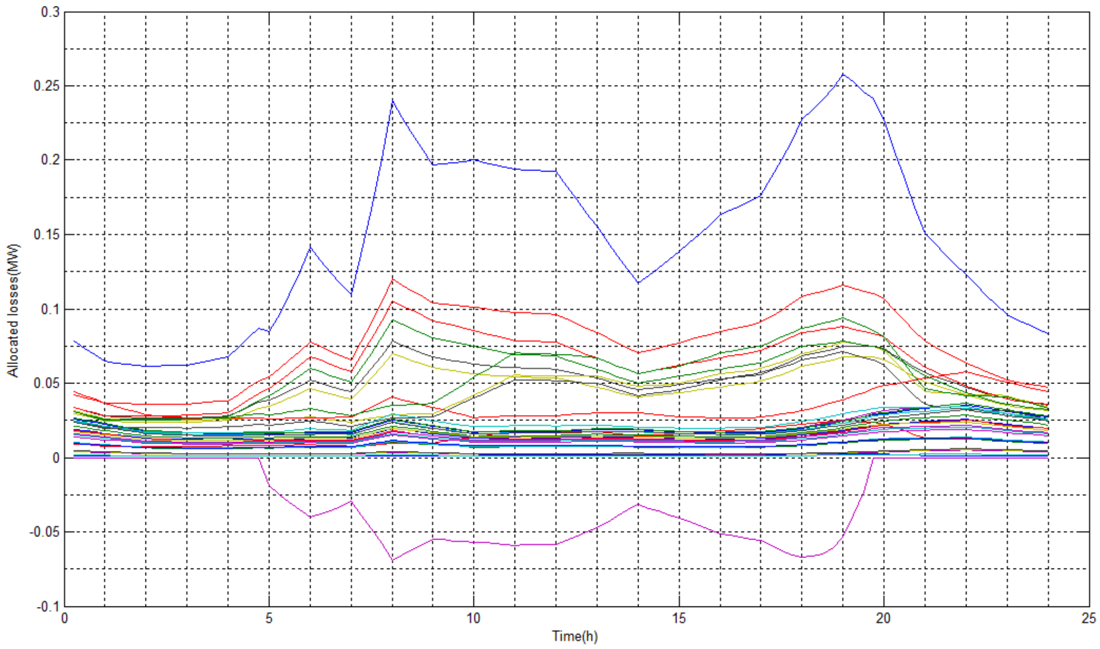

Figure 4.19 - Allocated losses in the network in each bus to a PV without storage for the month of June

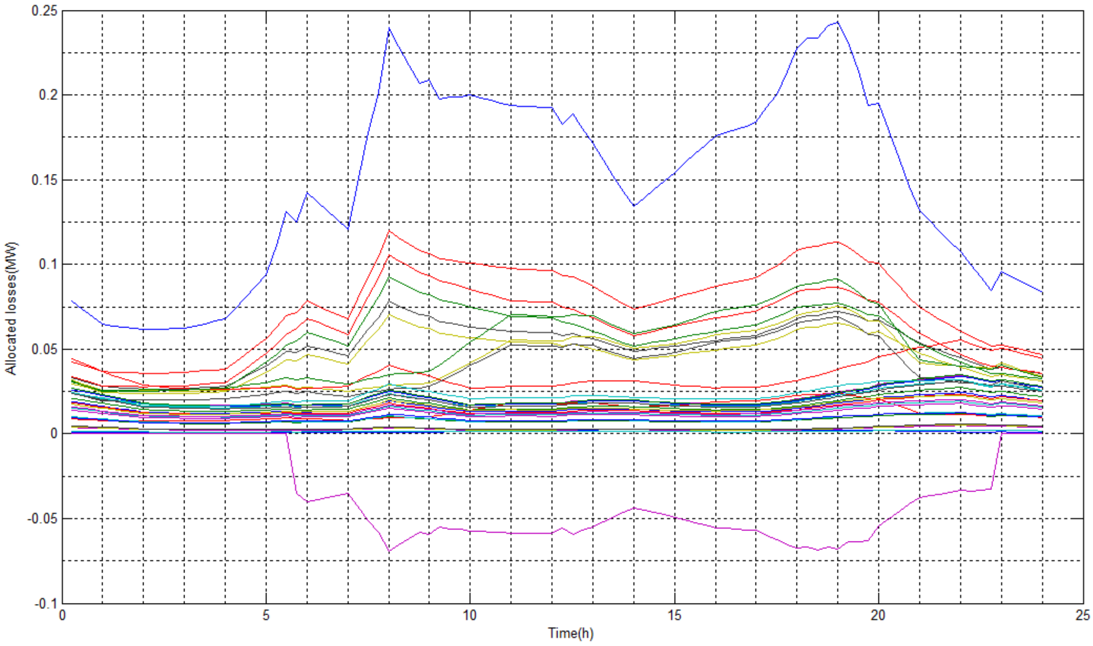

Figure 4.20 - Allocated losses in the network in each bus to a PV with storage for the month of June

Figure 4.21 and Figure 4.22 exhibit the power flow on the battery. The limits of the battery capacity limits are respected as the energy stored always range from 0 to 1500 kWh like predicted. Secondly, the power supplied to the network is concentrated in the periods where the optimal losses are higher, as in these periods the PV can have higher impact on the diminution of the losses. Considering the other restrictions, the two months have different results. In January, all the limits imposed are respected. So the power injected to the grid cannot be higher than the absolute optimal power production neither higher than the line limit. In June, the absolute optimal power injection is lower and in different periods, the injection is equal to absolute optimal power injection. In order to use all the energy available in some period, the PV plant with storage is injecting more than the optimal value in order to avoid the violation of the capacity limit of the storage.

Without ignoring the second limit (injection lower than the absolute optimal vale), the storage capacity would be violated or, in other words, part of the solar energy available would not be used.

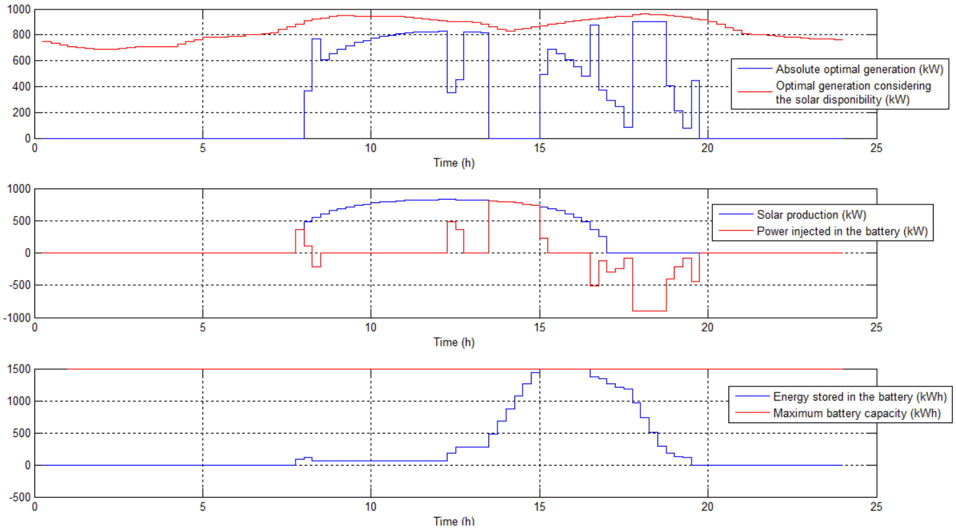

Figure 4.21 - Power flow on the PV/storage system for the month of January

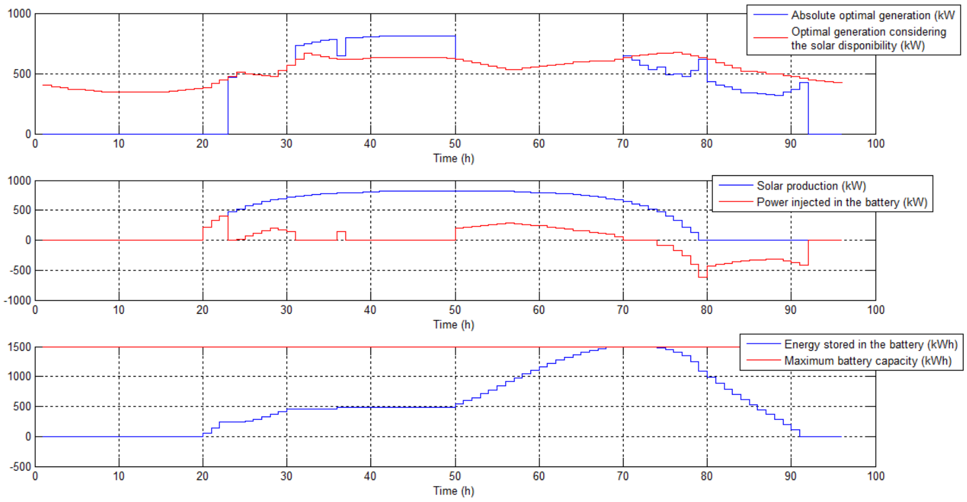

Figure 4.22 - Power flow on the PV/storage system for the month of June

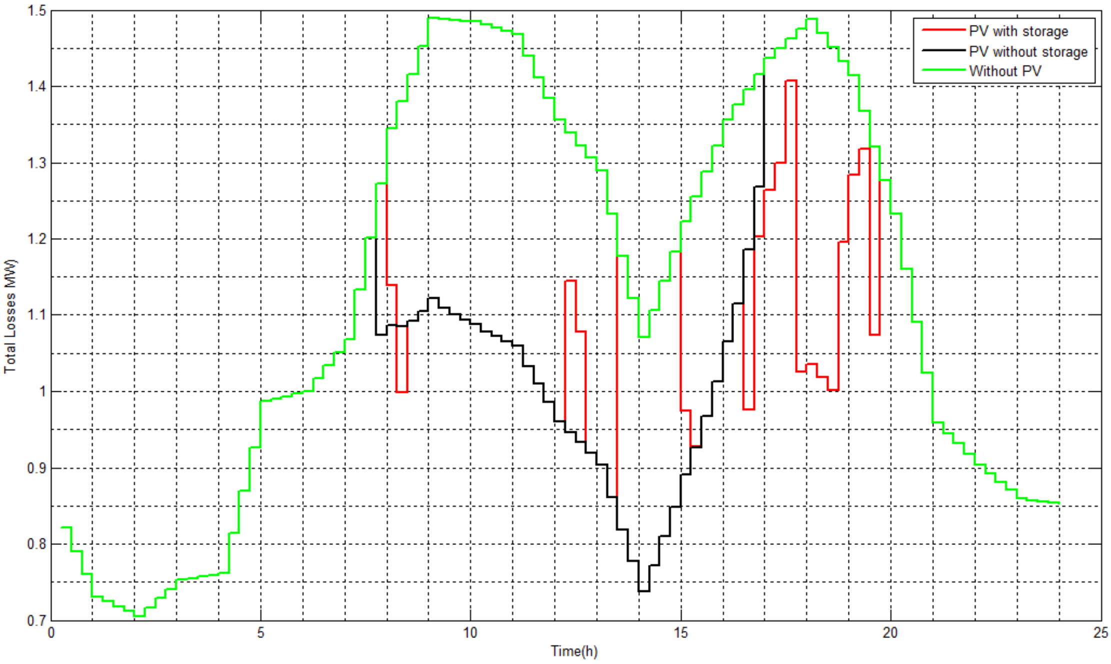

Figure 4.23 - Total losses on the distribution network in the three cases studied for January

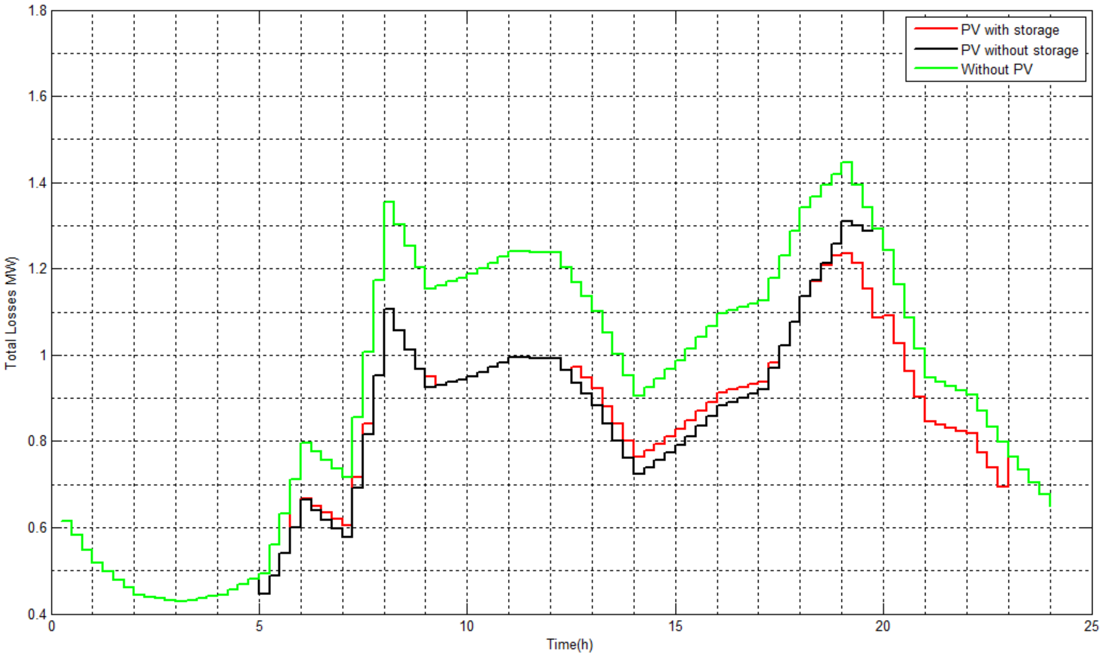

Figure 4.24 - Total losses on the distribution network in the three cases studied for June

The figure 4.25 and 4.26 show the contribution of the PV with storage and without. The results obtained show that there are periods in which the optimization algorithm achieves minor loss reduction concentrating more impact where the load is higher archiving a better global result. This also mean that the total losses increase where the loads are lower but decreases even more when they are higher as demonstrated in figure 4.23 and 4.24.

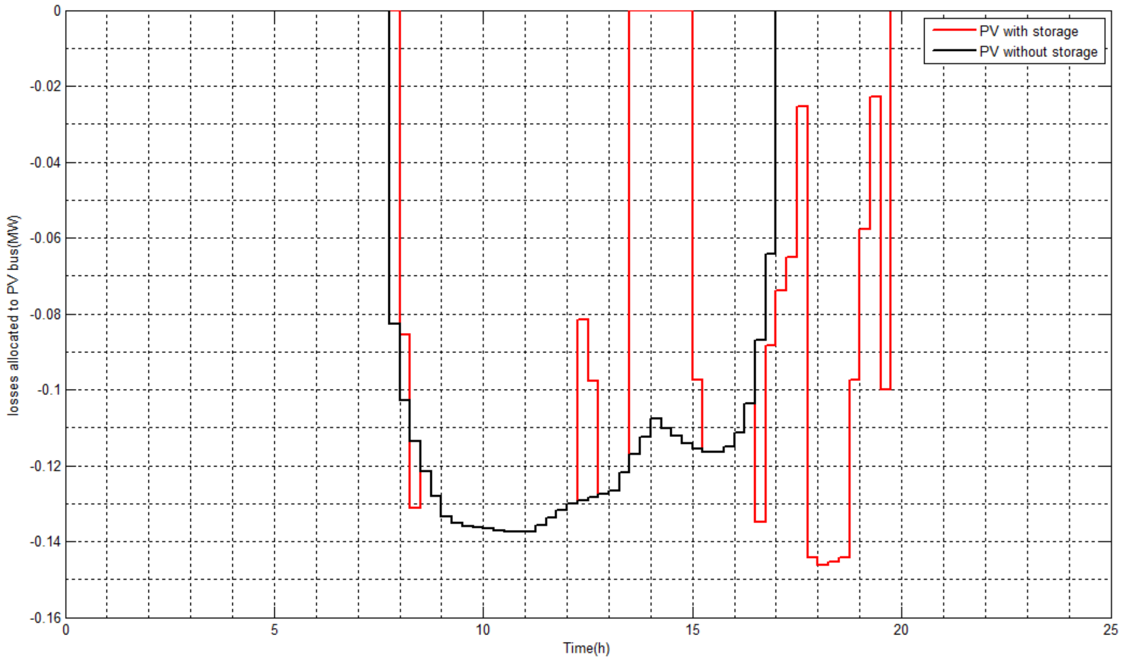

Figure 4.25 - Contribution of the PV generator to reduce losses in each period in the three cases studied for January

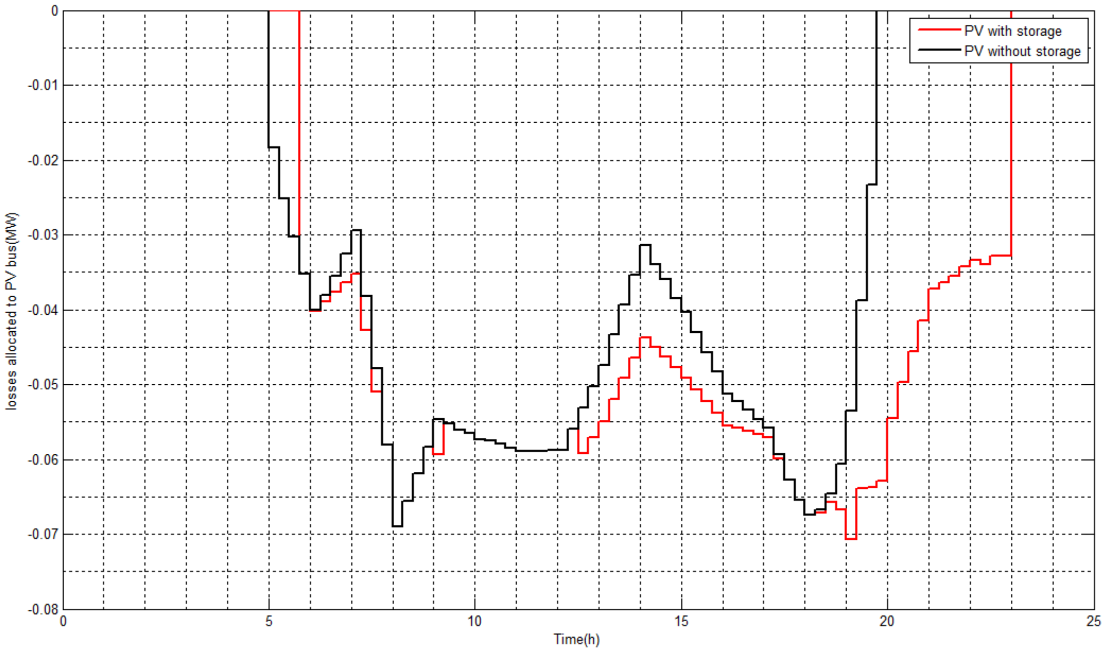

Figure 4.26 - Contribution of the PV generator to reduce losses in each period in the three cases studied for June

Finally the figure 4.27 show the optimal production in each period of the day for each month, determined by the tool developed.

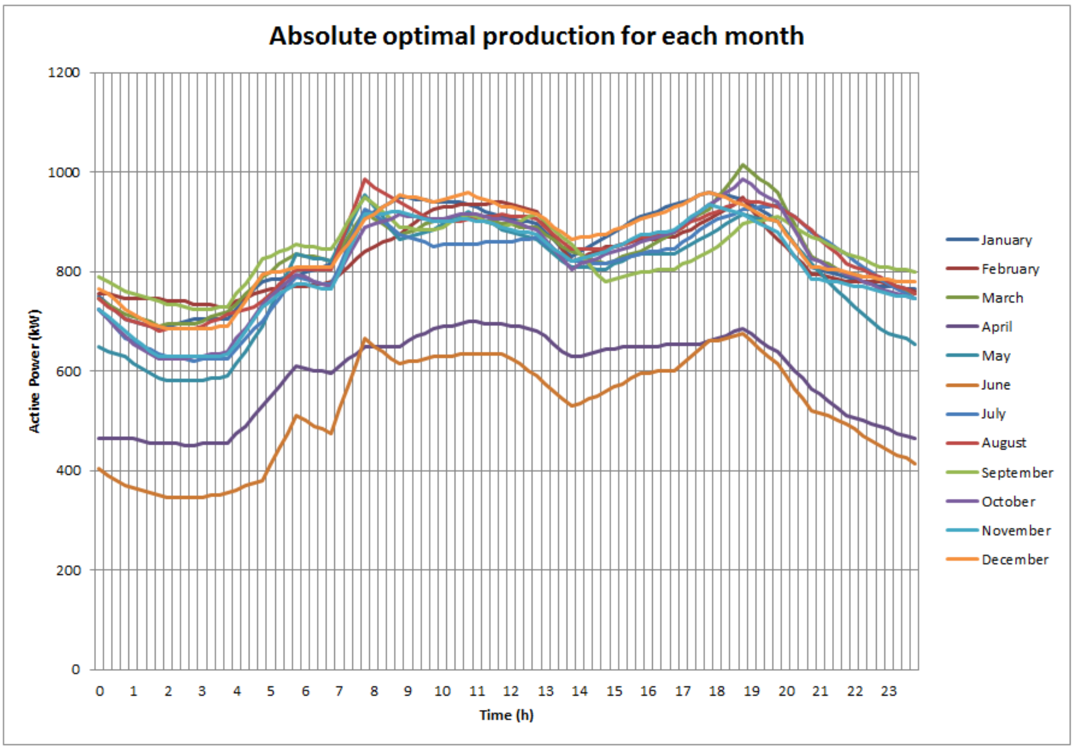

Figure 4.27 - Absolute Optimal production for each month

Chapter 5

Concluding remarks

5.1 - Final conclusions

The main objectives proposed for this work has been achieved as the contribution of the PV plants with storage to reduce losses was maximized in every month tested. Although the efficiency of this tool can be reduced as it is dependable by the profile of the load curves and the solar production. So the results clearly demonstrate that if the PV plants owners add a storage unit coordinated with generator through the loss allocation method, they can extract better profits if there are incentives to reduce such losses.

But the application of this tool showed that not only the PV owner can be benefited. The optimal contribution of a PV plant with storage can also lead to more technical/economical impacts on the distribution network. These impacts are:

- The contribution of the PV plant is not restricted to local loads as each consumer would have a less impact on losses. The decreased in losses mean that the penalty they paid for that impact is reduced
- As the impact on the losses of each bus is decreased, the power flow on the network is also decreased which result in a better capacity for the DSO to receive new consumers without the need to expand or update the actual infrastructures
- The investment costs on the implementation of the battery with a control system can be over the time compensated by the income received from reducing losses
- The integration of the PV plant does not have any impact on the ambient. The production that compensates the losses in the distribution network is supplied through the slack bus. This means that the tradition large power plants that provide this power reduce their production. As most of these plants are fossil fuel dependents, the pollution they produce is decreased

5.2 – Limitations, future development and uses

The actual energy policies already include benefices taking into account the potential contribution of renewable sources to the loss reduction [32]. Although, this benefices are constant and do not quantify the real contribution during the operation. In the future, if this type of compensation changes in order to be sensitive to the real improvements on the loss reduction purposes of each producer, the application of this tool will allow the monitorization and control of PV/storage systems.

In this case, this tool cannot work alone. It must be coordinated with various elements such as communication devices, control and automation systems. The implement and operational costs of such systems need to be considered. Also, it will need a good interface with the users to be easily run.

Another issue is the fact that the storage systems available in the market do not have 100% efficiency. So the amount of power supplied to them is not the same that the battery supplies. This efficiency is also dependable on the type of energy used as addressed in section 2.2.6. The tool developed does not contemplate this efficiency. For further development and implementation, this efficiency needs to be taking in count and the efficiency of other elements such as the inverters or the transformers.

This work does not contemplate any economic studies for the use of this coordination between PV and storage units. This is mainly because actually there are no references for the economic benefits to be paid to PV plant owners. The PV owner must have access to an economic study to decide if the addition of the storage system meets their requirements.

Finally, the algorithm developed can be improved taking into account the analysis of voltage profiles. So, voltage limits can be added as a restriction of the optimization problem.

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Annex A

Network data

Table A.1 - Data of the branches

From bus	*To bus*	*Resistance (ohm)*	*Reactance (ohm)*
1	2	0.0922	0.0470
2	3	0.4930	0.2511
3	4	0.3660	0.1864
4	5	0.3811	0.1941
5	6	0.8190	0.7070
6	7	0.1872	0.6188
7	8	0.7114	0.2351
8	9	10.300	0.7400
9	10	10.440	0.7440
10	11	0.1966	0.0650
11	12	0.3744	0.1238
12	13	14.680	11.550
13	14	0.5416	0.7129
14	15	0.5910	0.5260
15	16	0.7463	0.5450
16	17	12.890	17.210
17	18	0.7320	0.5740
2	19	0.1640	0.1565
19	20	15.042	13.554
20	21	0.4095	0.4784
21	22	0.7089	0.9373
3	23	0.4512	0.3083
23	24	0.8980	0.7091
24	25	0.8960	0.7011
6	26	0.2030	0.1034
26	27	0.2842	0.1447
27	28	10.590	0.9337
28	29	0.8042	0.7006
29	30	0.5075	0.2585
30	31	0.9744	0.9630
31	32	0.3105	0.3619
32	33	0.3410	0.5302
6	34	0.6188	0.1872

Table A.2 – Maximum active power and reactive power consumed by the loads

Bus no.	P_{Lmax} (kW)	Q_{Lmax} (kvar)
1	0	0
2	100	60
3	90	40
4	120	80
5	60	30
6	60	20
7	200	100
8	200	100
9	60	20
10	60	20
11	45	30
12	60	35
13	60	35
14	120	80
15	60	10
16	60	20
17	60	20
18	90	40
19	90	40
20	90	40
21	90	40
22	90	40
23	90	50
24	420	200
25	420	200
26	60	25
27	60	25
28	60	20
29	120	70
30	200	600
31	150	70
32	210	100
33	60	40
34	0	0

Where “P_{Lmax}” is the maximum value of the active power load and “Q_{Lmax}”

Annex B

Additional results

March:

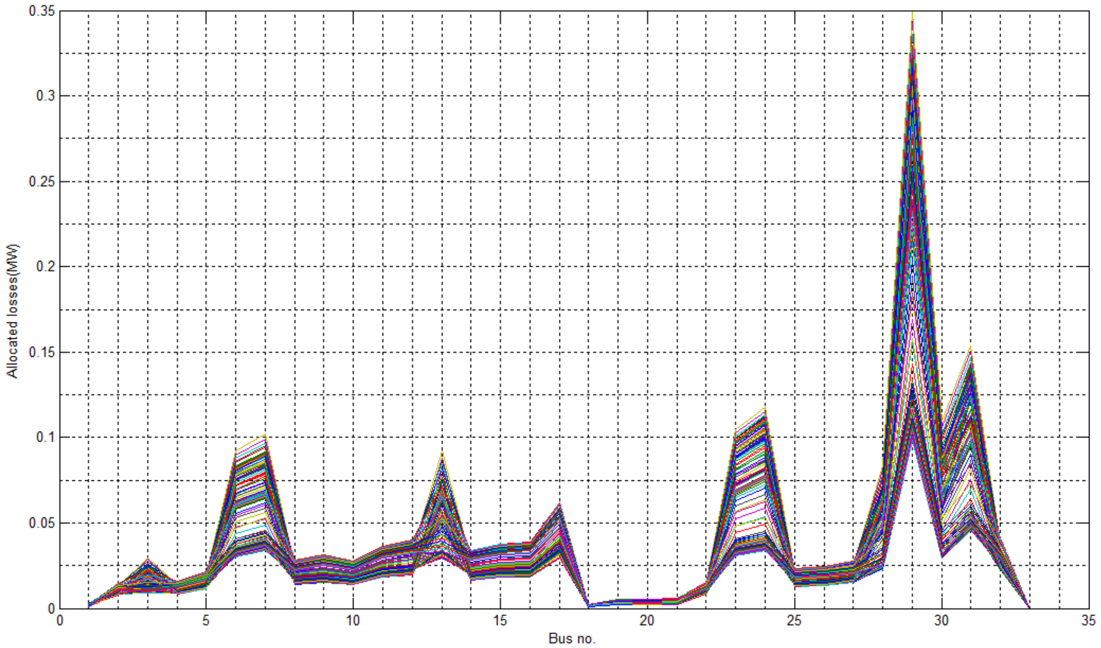

Figure B.1 - Allocated losses in the network for each period of time without the PV for the month of March

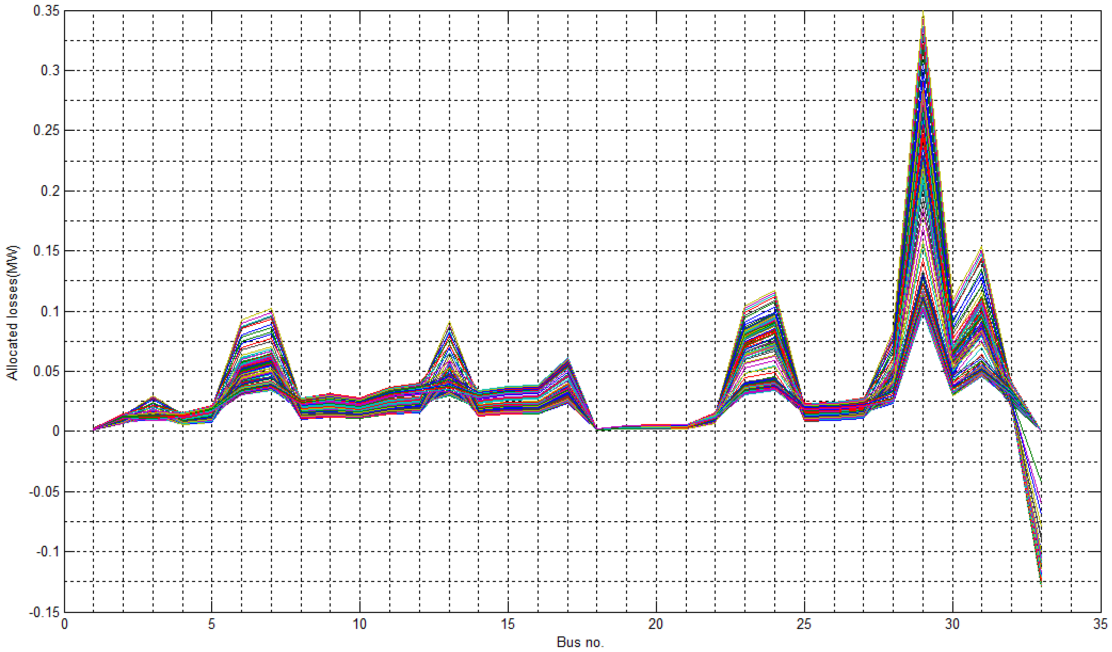

Figure B.2 - Allocated losses in the network for each period of time to a PV without storage for the month of March

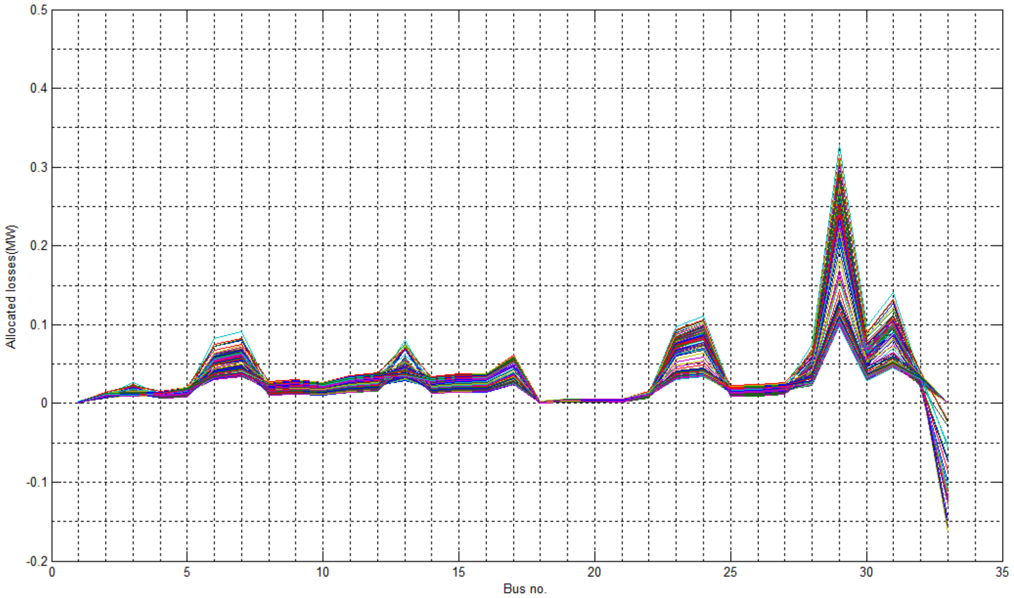

Figure B.3 - Allocated losses in the network for each period of time to a PV with storage for the month of March

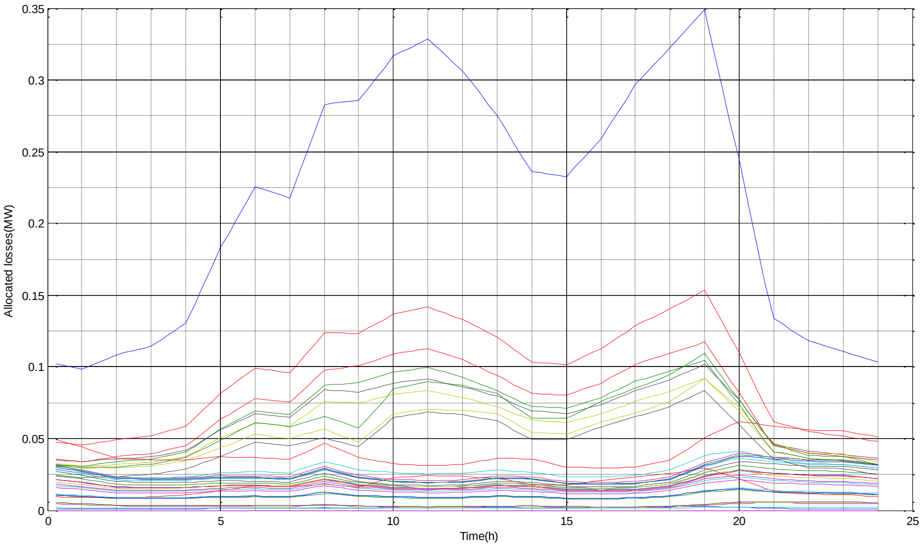

Figure B.4 - Allocated losses in the network in each bus without a PV for the month of March

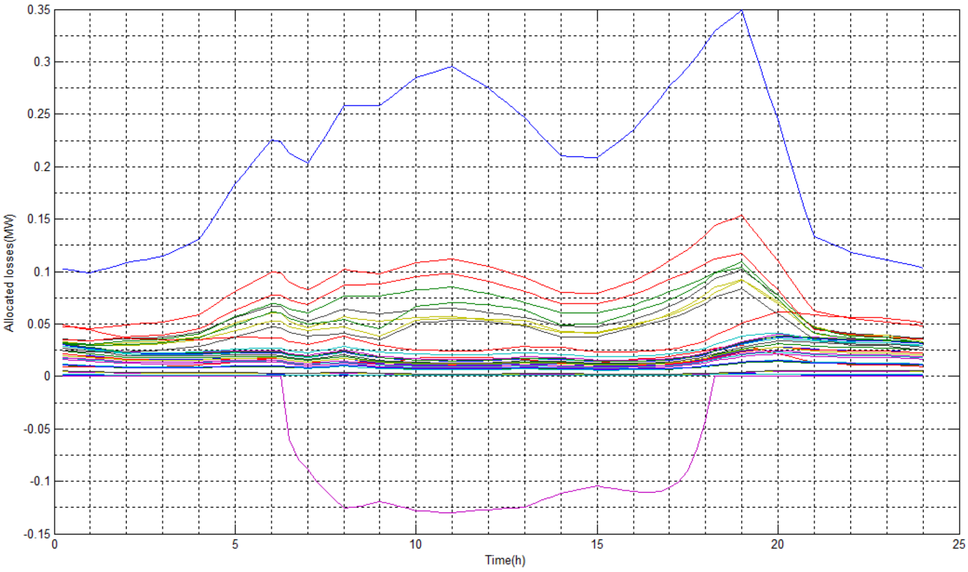

Figure B.5 - Allocated losses in the network in each bus to a PV without storage for the month of March

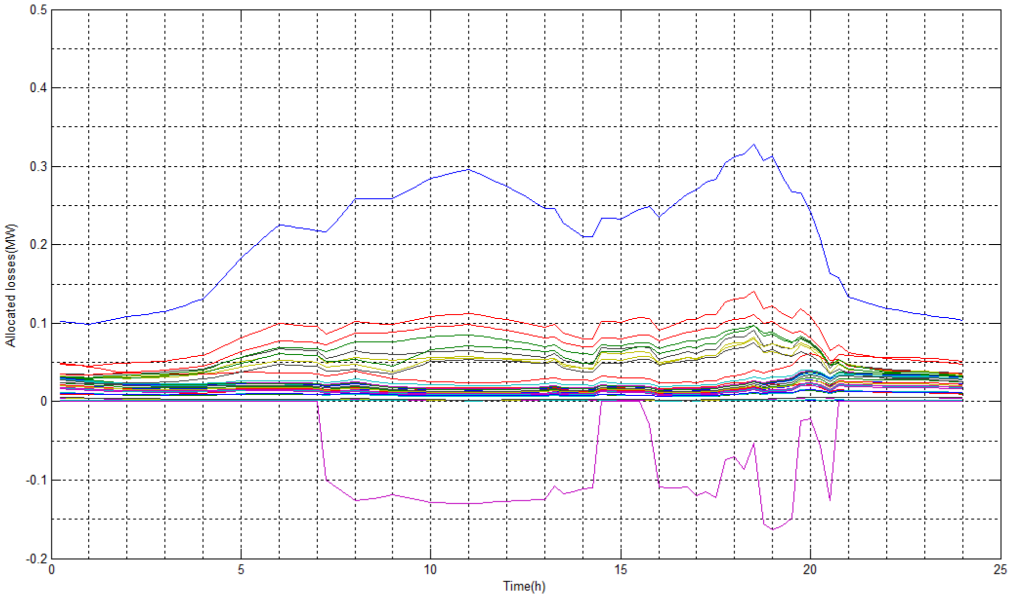

Figure B.6 - Allocated losses in the network in each bus to a PV with storage for the month of March

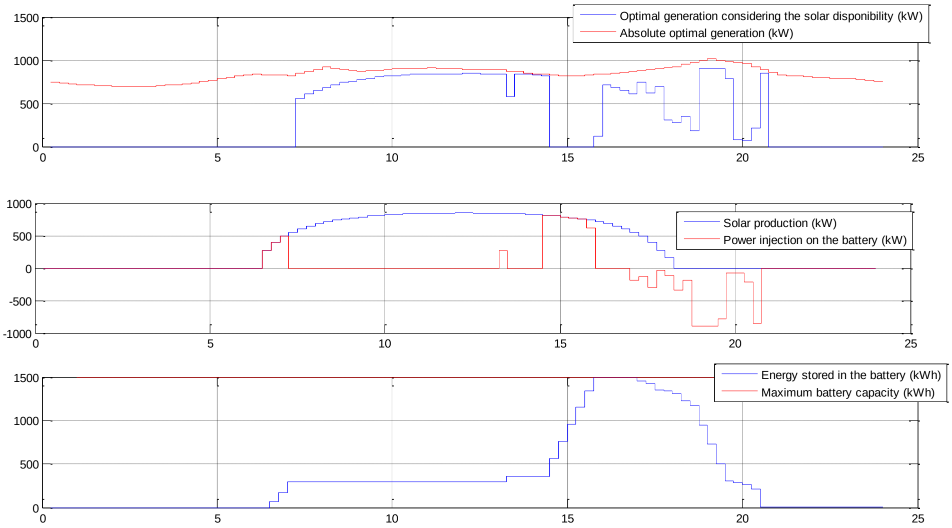

Figure B.7- Power flow on the PV/storage system for the month of March

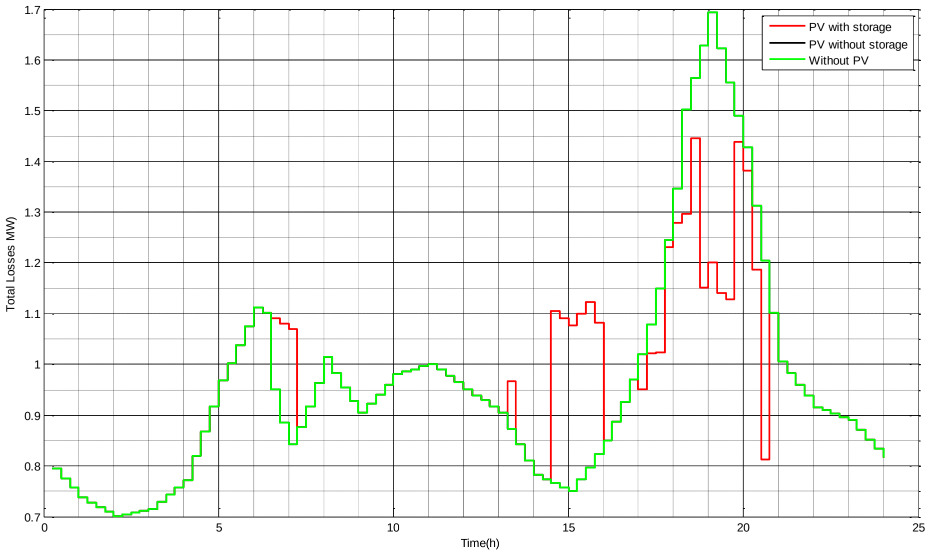

Figure B.8 - Total losses on the distribution network in the three cases studied for March

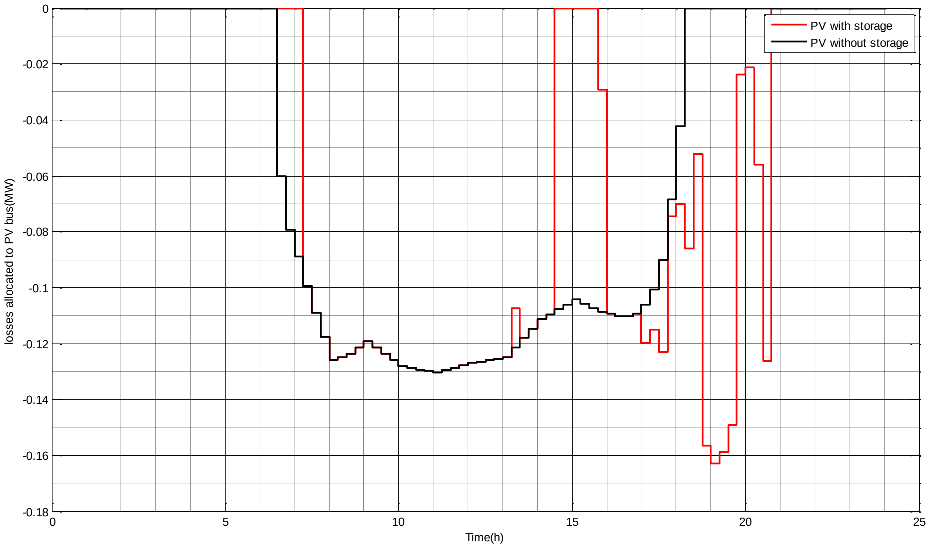

Figure B.9 - Contribution of the PV generator to reduce losses in each period in the three cases studied for March

August:

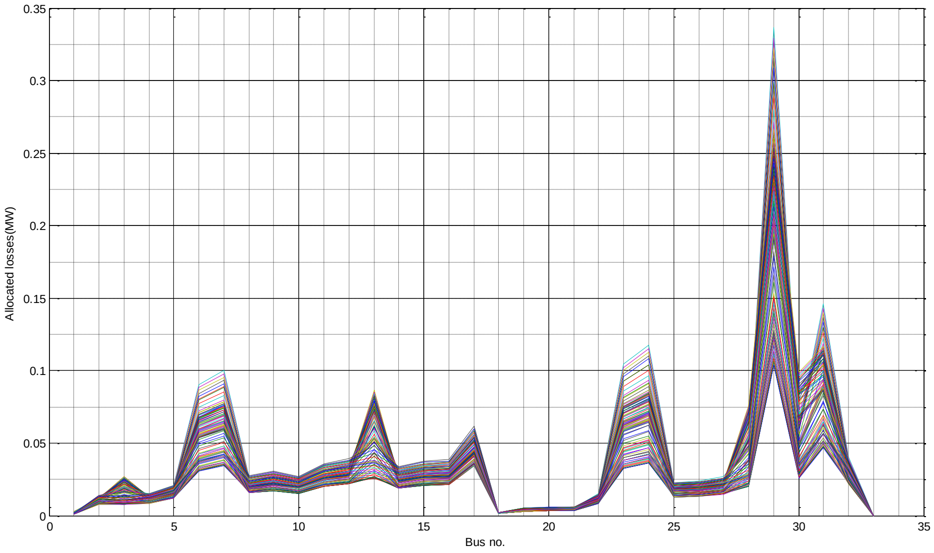

Figure B.10 - Allocated losses in the network for each period of time without the PV for the month of August

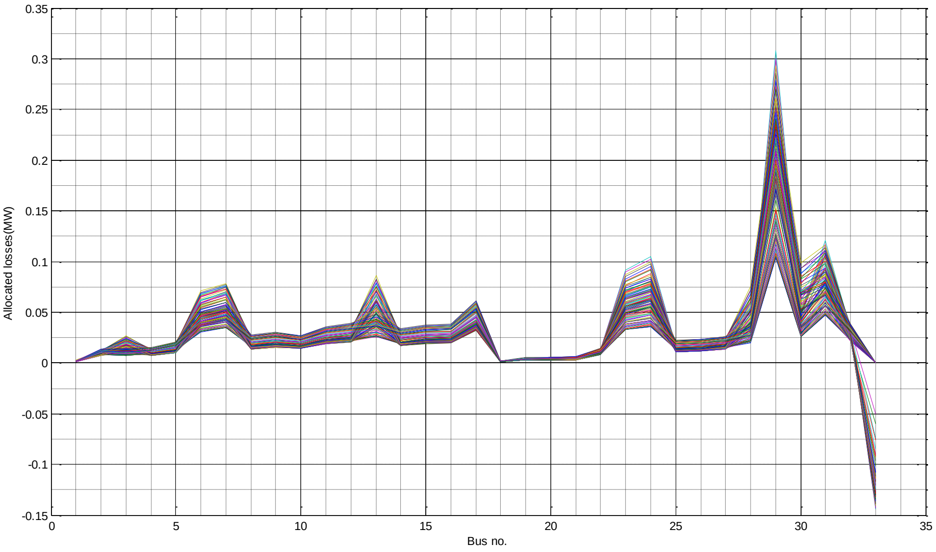

Figure B.11 - Allocated losses in the network for each period of time to a PV without storage for the month of August

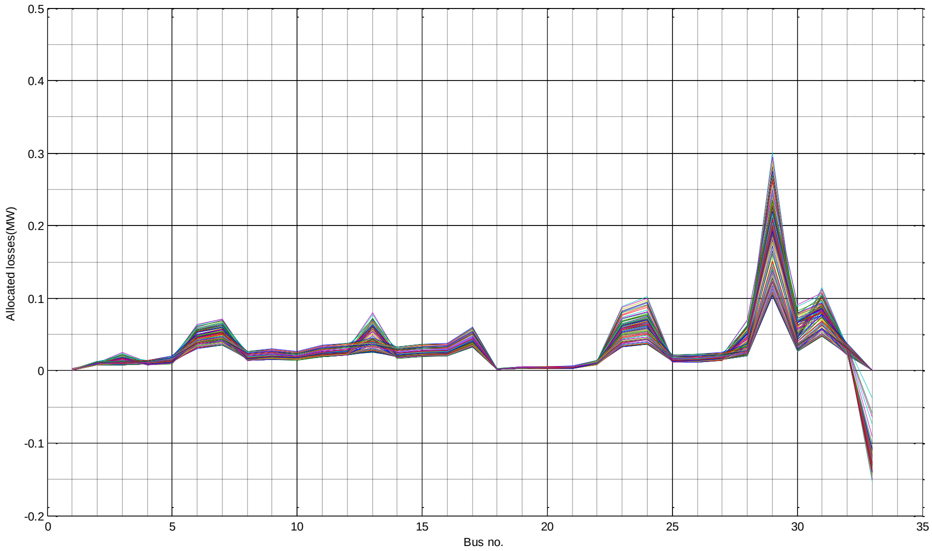

Figure B.12 - Allocated losses in the network for each period of time to a PV with storage for the month of August

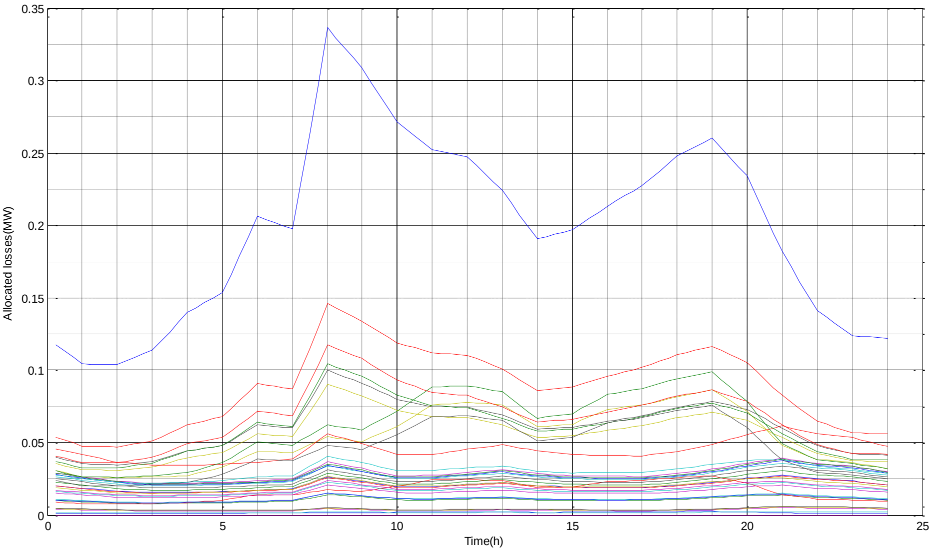

Figure B.13 - Allocated losses in the network in each bus without a PV for the month of August

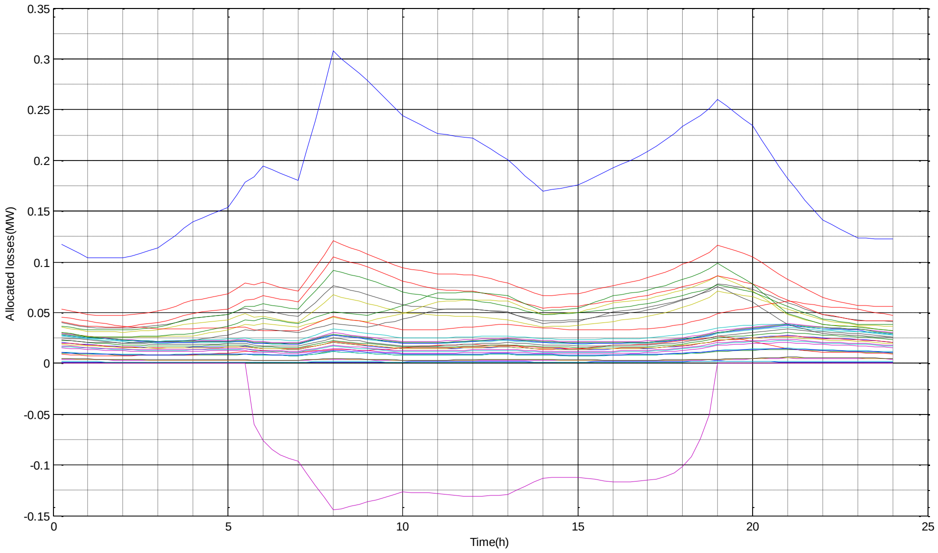

Figure B.14 - Allocated losses in the network in each bus to a PV without storage for the month of August

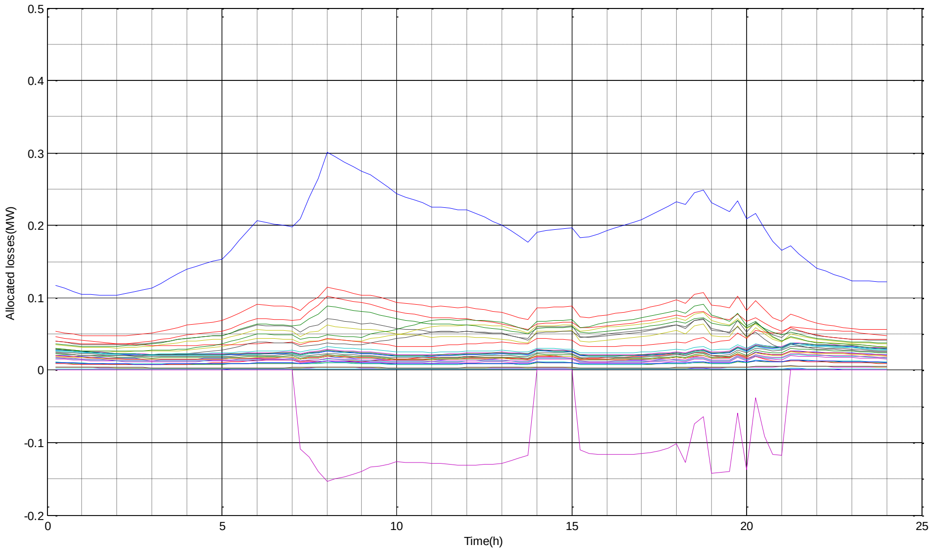

Figure B.15 - Allocated losses in the network in each bus to a PV with storage for the month of August

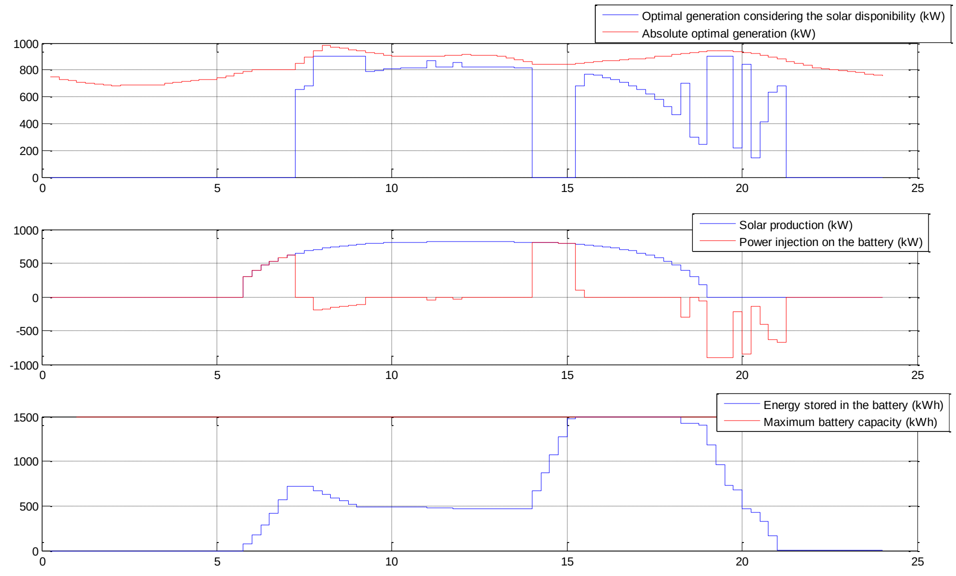

Figure B.16 - Power flow on the PV/storage system for the month of August

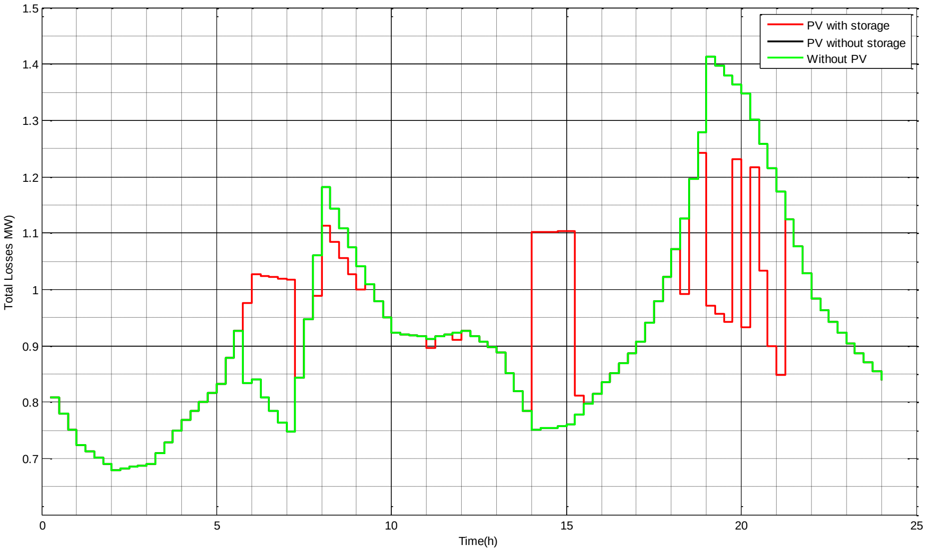

Figure B.17 - Total losses on the distribution network in the three cases studied for August

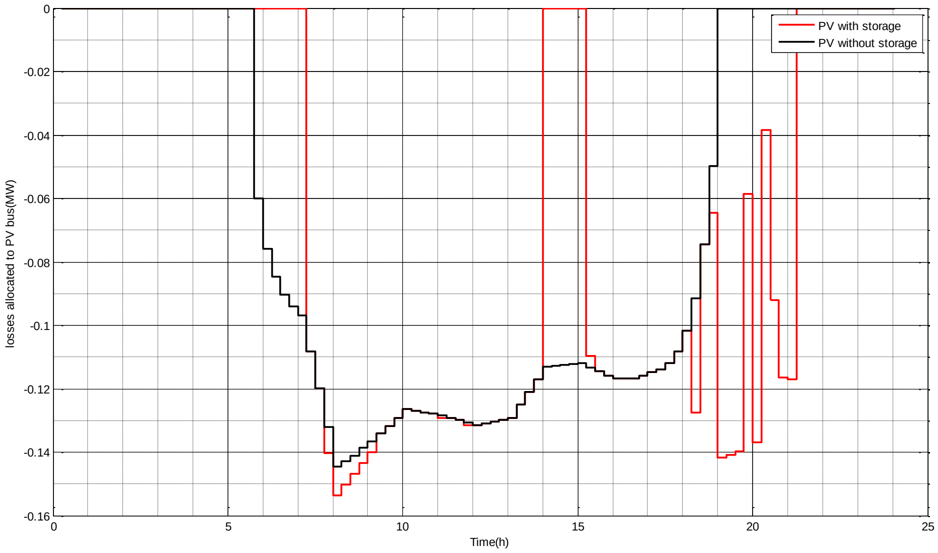

Figure B.18 - Contribution of the PV generator to reduce losses in each period in the three cases studied for August

Outubro

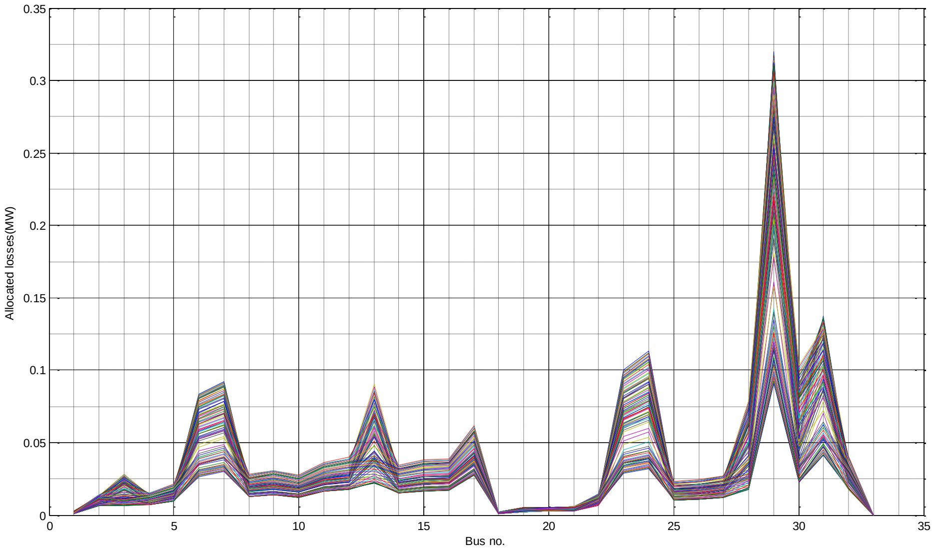

Figure B.19 - Allocated losses in the network for each period of time without the PV for the month of October

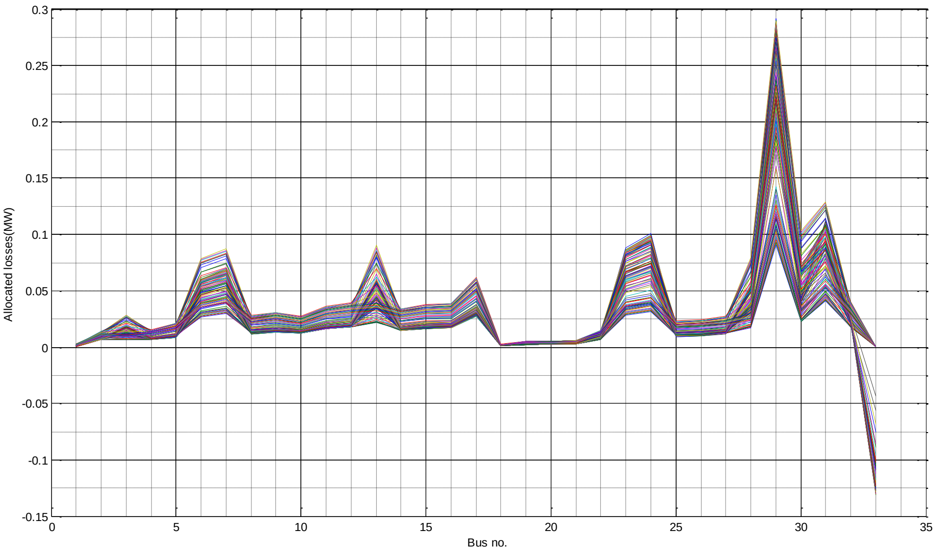

Figure B.20 - Allocated losses in the network for each period of time to a PV without storage for the month of October

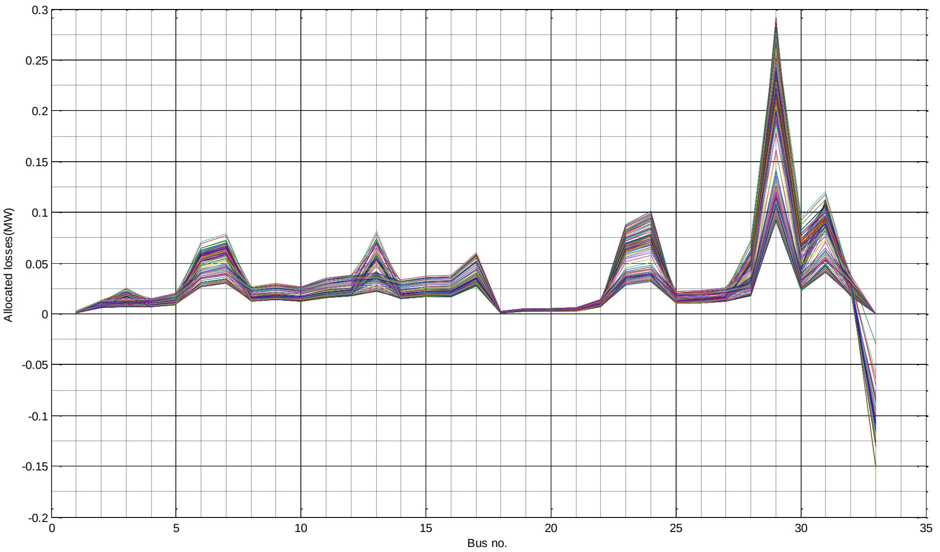

Figure B.21 - Allocated losses in the network for each period of time to a PV with storage for the month of October

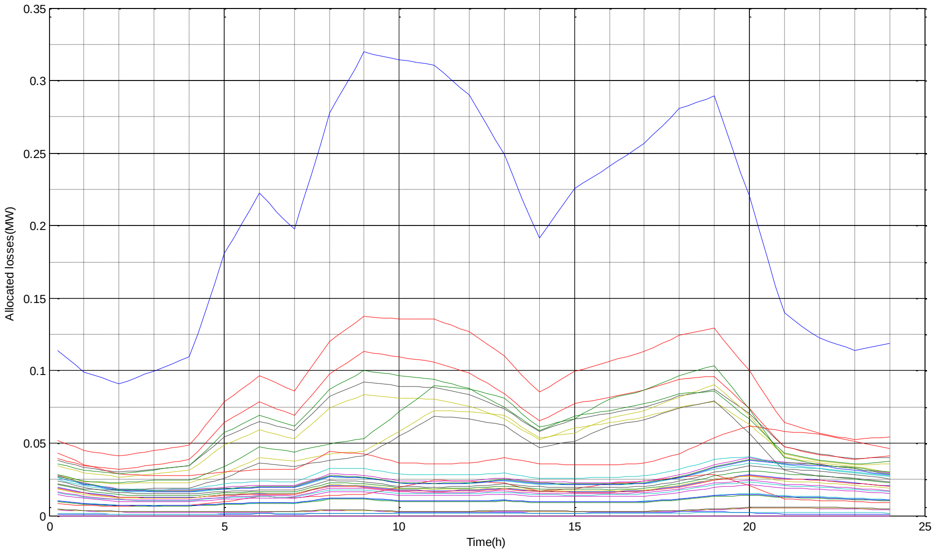

Figure B.22 - Allocated losses in the network in each bus without a PV for the month of October

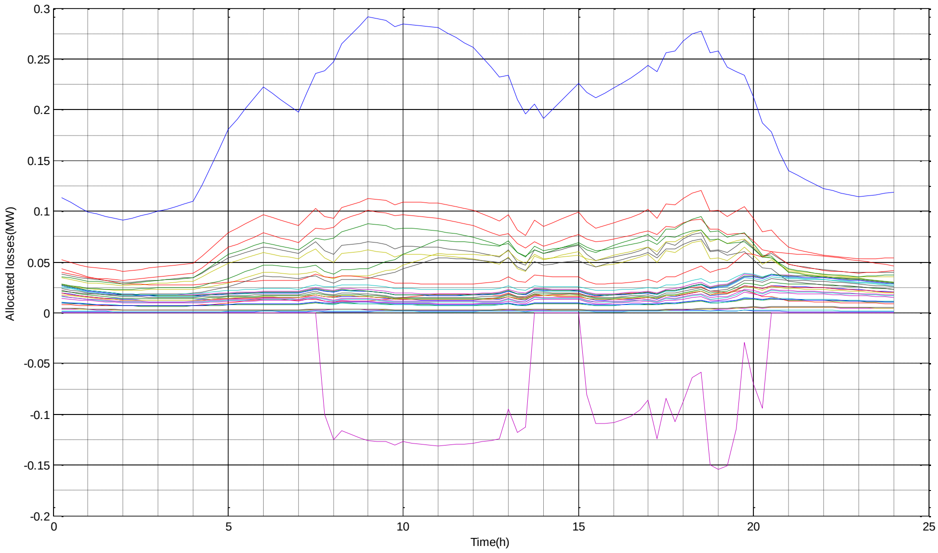

Figure B.23 - Allocated losses in the network in each bus to a PV without storage for the month of October

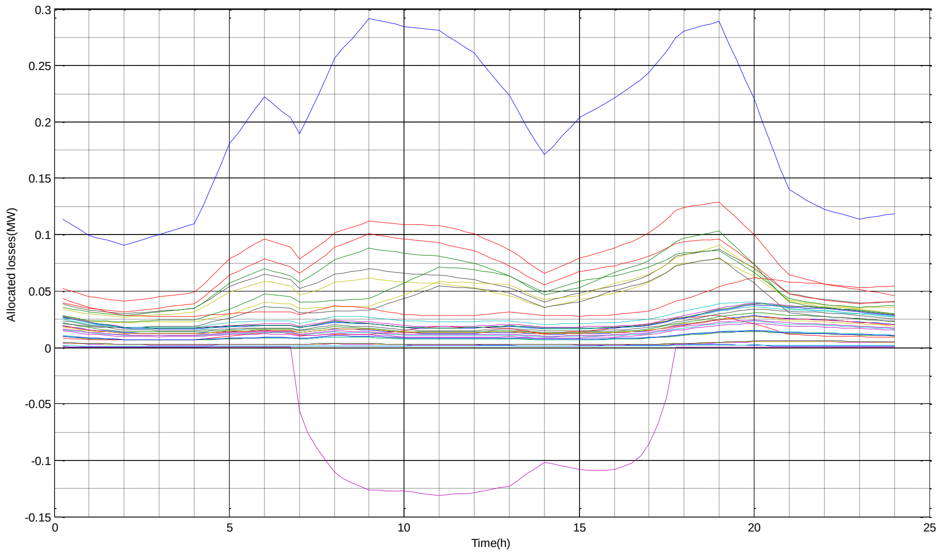

Figure B.24 - Allocated losses in the network in each bus to a PV with storage for the month of October

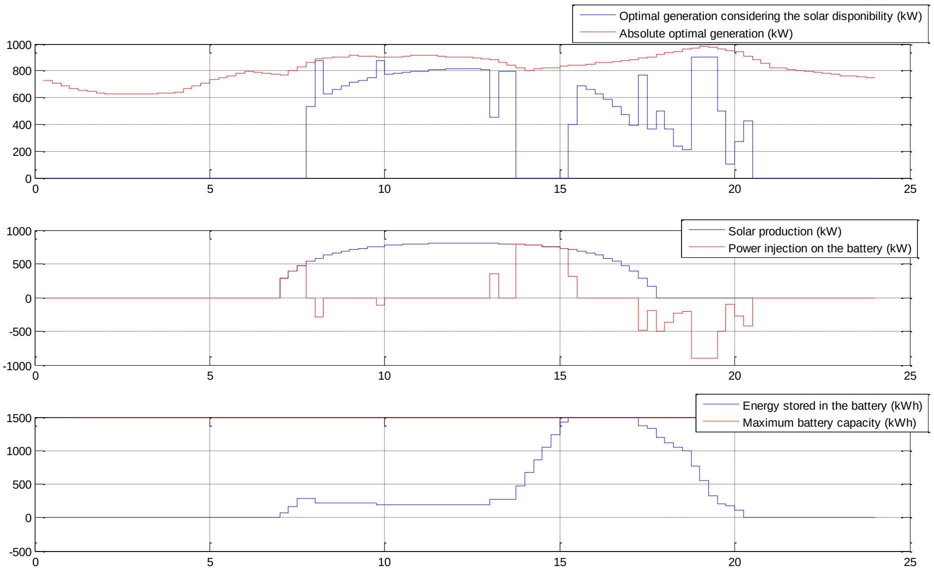

Figure B.25 - Power flow on the PV/storage system for the month of October

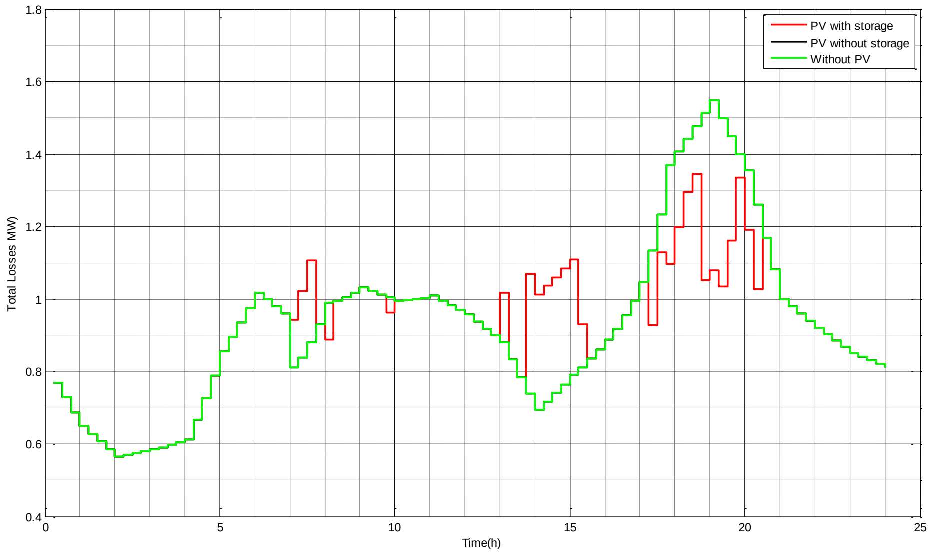

Figure B.26 - Total losses on the distribution network in the three cases studied for October

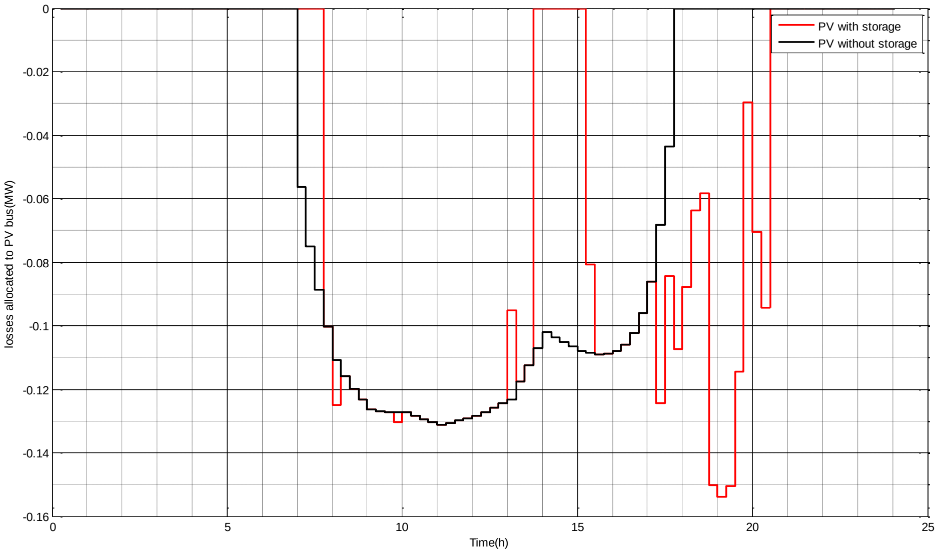

Figure B.27 - Contribution of the PV generator to reduce losses in each period in the three cases studied for October

December

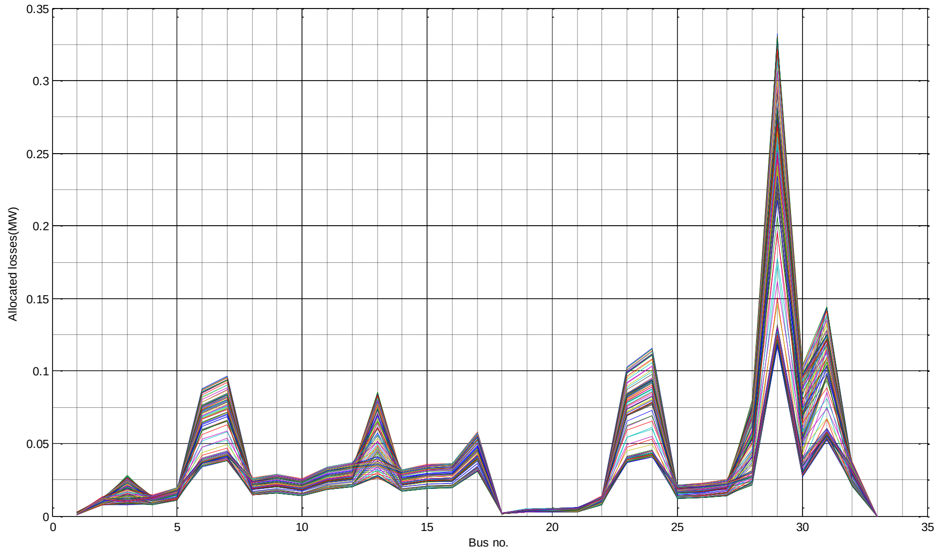

Figure B.28 - Allocated losses in the network for each period of time without the PV for the month of December

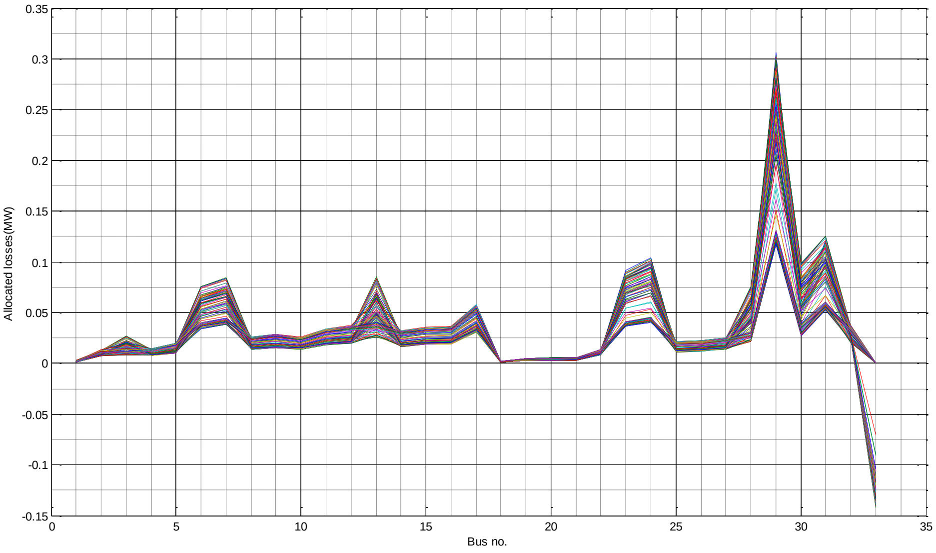

Figure B.29 - Allocated losses in the network for each period of time to a PV without storage for the month of December

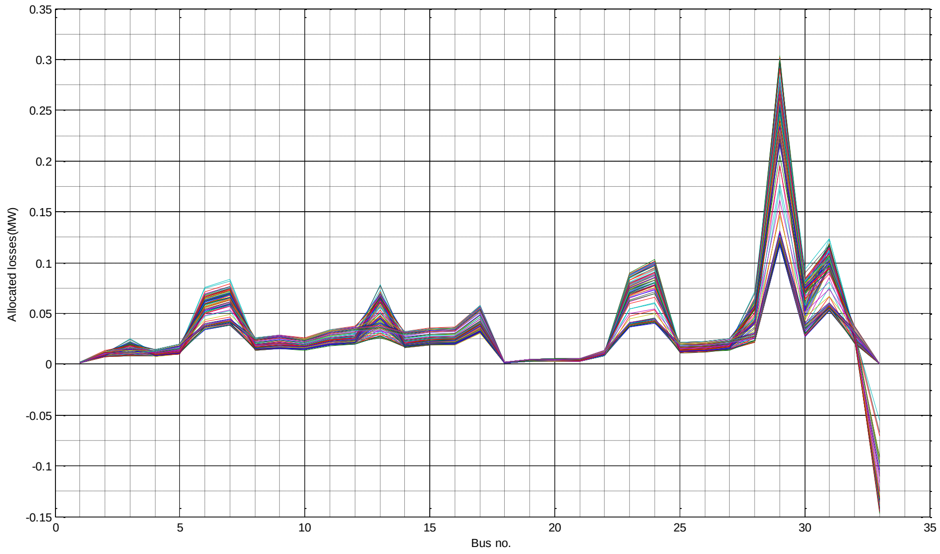

Figure B.30 - Allocated losses in the network for each period of time to a PV with storage for the month of December

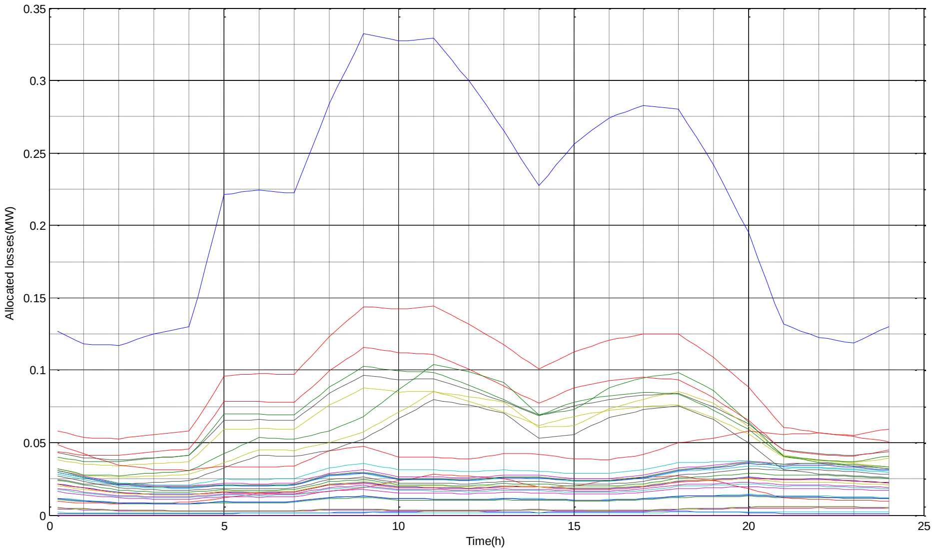

Figure B.31 - Allocated losses in the network in each bus without a PV for the month of December

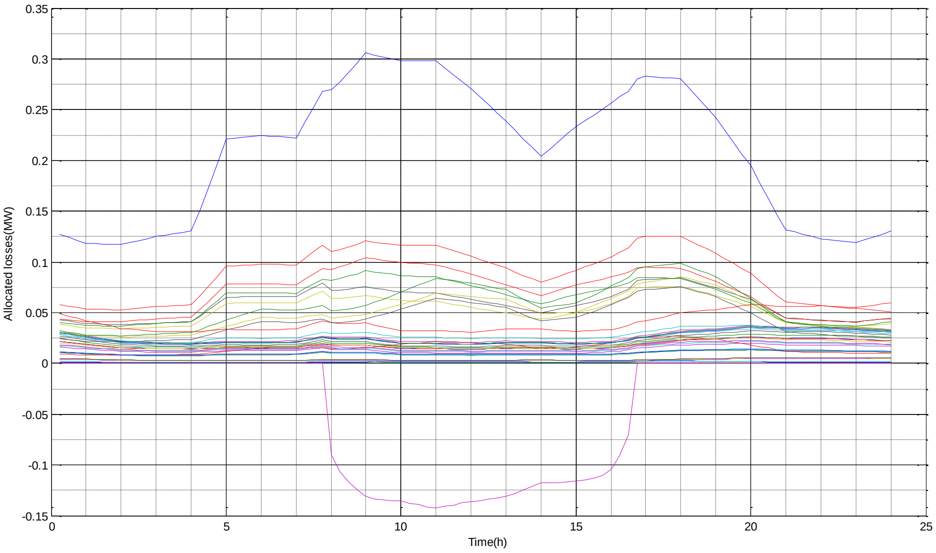

Figure B.32 - Allocated losses in the network in each bus to a PV without storage for the month of December

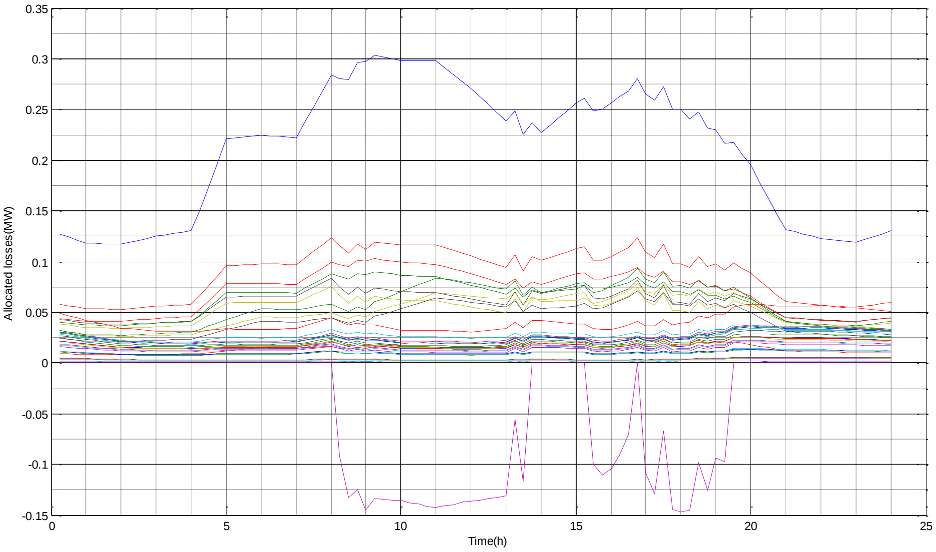

Figure B.33 - Allocated losses in the network in each bus to a PV with storage for the month of December

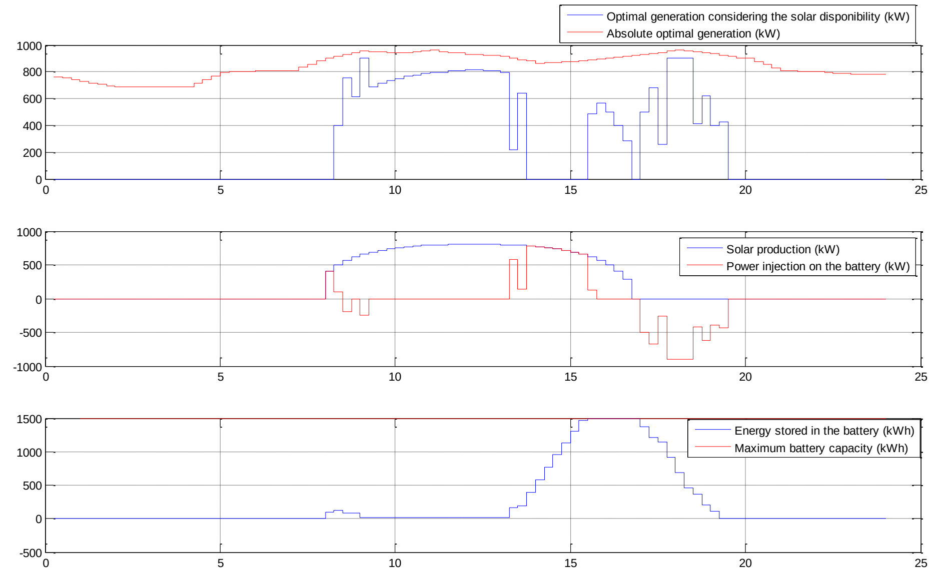

Figure B.34 - Power flow on the PV/storage system for the month of December

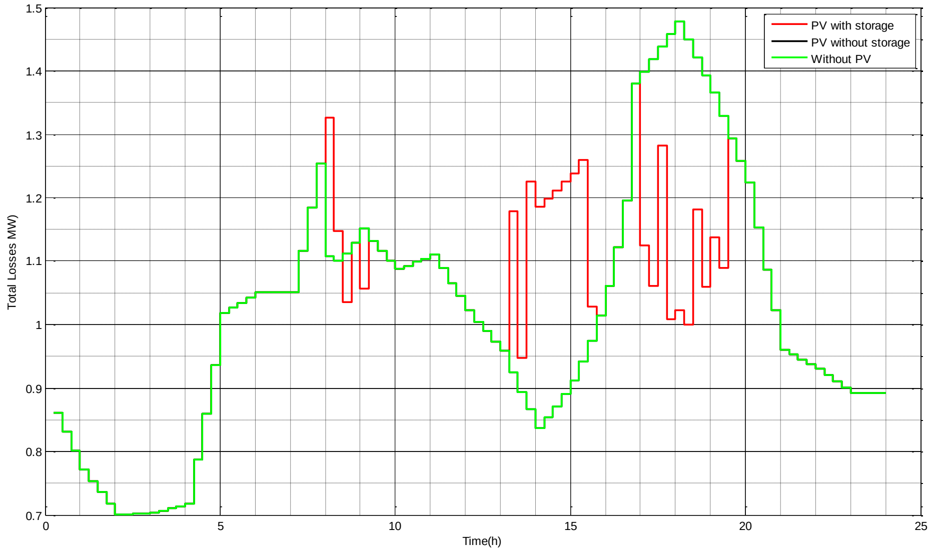

Figure B.35 - Total losses on the distribution network in the three cases studied for December

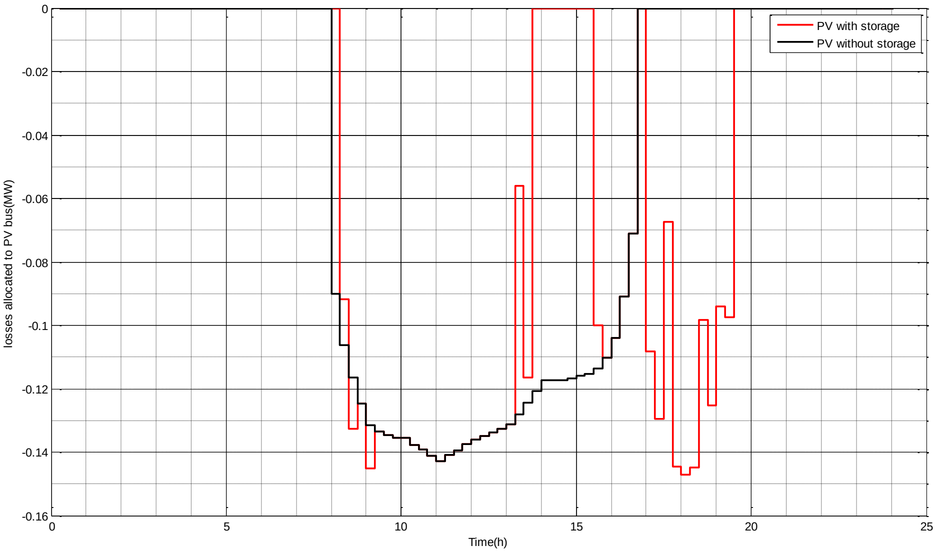

Figure B.36 - Contribution of the PV generator to reduce losses in each period in the three cases studied for December