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Low Voltage Network Operation with a High Density of Distributed Generation

D. GARCÍA VILLA, Rafael
TUTOR: D. Coto Aladro, Jose

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1. Abstract.

Renewable energies are becoming more important every day due to the increasing environmental concern in our society, the liberation of the electricity sector (for generation and commercialization) and the reduction of energy dependence. For this reason, governments and scientists work to maximise the use of renewable energy sources and get best benefits from them.

Looking to the future, one of the most innovative and interesting ways to harness renewable energies, is by means of the emerging concept 'Distributed Generation'. If we apply this concept to low voltage electrical networks, the most common way on which we will be able to work is with photovoltaic solar technology, since it can be widely deployed in towns and cities.
Grid-connected photovoltaic systems offer the opportunity to generate significant quantities of high-grade energy near the consumption point, avoiding transmission and distribution losses. These systems operate in parallel with existing electricity grids, allowing exchange of electricity to and from the grid.

The objective of this project is to analyse what would happen in the grid in case of having a high density of distributed generation interconnected with the low voltage network. For this purpose, miscellaneous studies will be carried out, using a software which simulates, as closely as possible, a model of a real existing network on which several photovoltaic systems will be incorporated.

2. State of the art.

2.1.- DISTRIBUTED GENERATION.

A few years ago, new generating systems, known as Distributed Generation (DG), began to be introduced in lower voltage networks (distribution grids) instead of connect them to transmission grids, mainly in shopping centers, airports, hospitals, etc. Little by little and thanks to the policies of incentives (consisting mainly in primes or subventions for renewable energies), these new technologies were introduced in the electrical generating system.

In general terms, DG refers to any technology scattered on the electrical system, whose purpose is obtaining electrical energy near the point of consumption and can be integrated within distribution systems (in plants of the distribution company or in consumer installations). Storage systems may be utilised to accommodate the variable output of some forms of generation. [1]

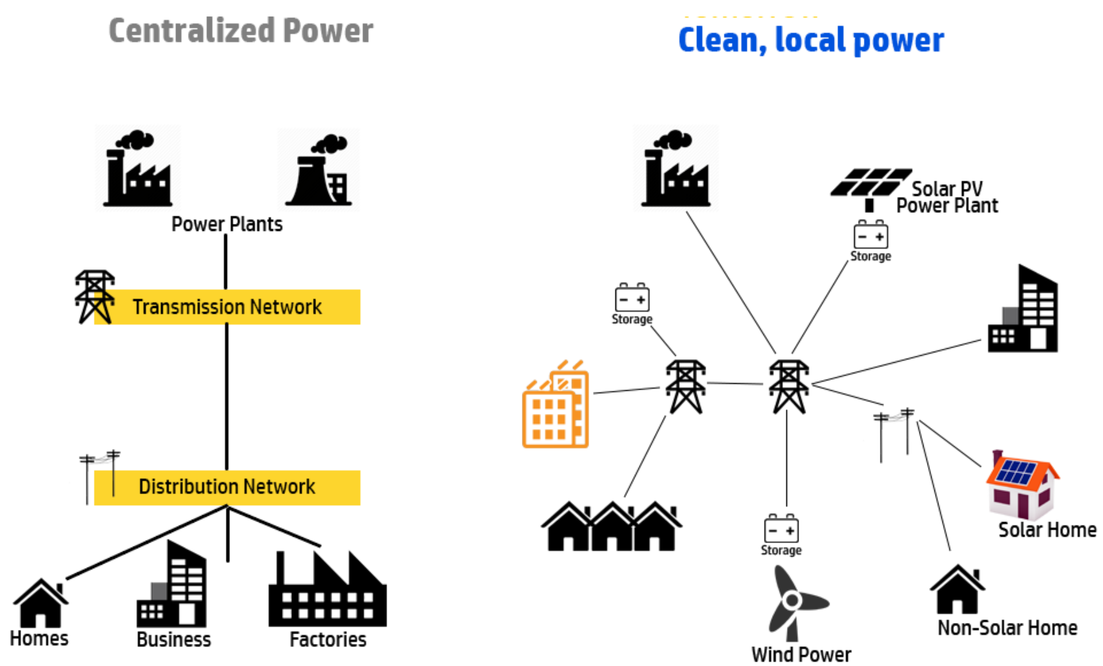

Figure 2.1.- Different generating models. Source: Sceola Energy.

As seen on Figure 2.1., DG systems have the capability of parallel operation with the utility distribution system. They can also be designed to operate separately from the utility system, being able to feed a load that can also be fed by the utility electrical system.

The figure below shows the difference between the energy flows with and without DG interconnected with the distribution network:

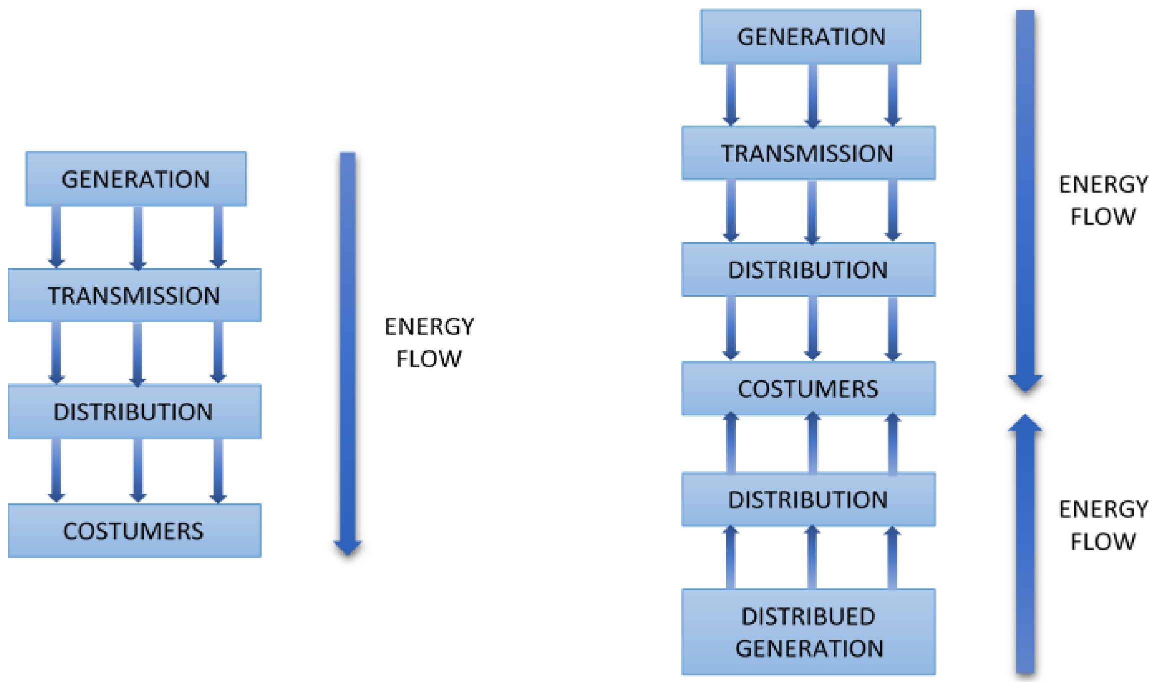

Figure 2.2.- Different energy flows

There exist some disagreements with the power that generators can cover in DG. For instance:

- Willis & Scott in "Distributed Power Generation: Planning and Evaluation" [2] determine that power ranges from 15 kW to 10 MW. However, they include another concept to refer to small generators: Dispersed Generation, covering powers ranging from 10 to 250 kW. They are intended to supply energy to residential consumers or small business and are connected to consumer installations or isolated from the grid.

- In contrast, Gonzalez-Longatt [3] defines on his document the following statemnts: Micro distributed generation: 1 W - 5kW; Small distributed generation: 5 kW - 5 MW; Medium distributed generation: 5 MW – 50 MW; and Large distributed generation: 50 MW – 300 MW.

Particularly, in Spain, according to regulating aspects in its electrical system, we can conclude that Distributed Generation is any set of systems of electrical power generation that are connected to distribution lines, since generators are low powered and are located in places close to the point of consumption. [4] Its main characteristics are:

- Capability of being connected to the distribution network.
- To have the possibility of direct consumption of the energy produced at the same time that is being generated and be able to export the excess to a distributing line.
- There is no centralized planning of that generation.
- Generating power is normally lower than 50 MW.

These systems provide an interesting alternative with respect to the usual centralized production method, where energy is generated at high scale to supply electrical power to a large number of customers, far away from the point of use. This requires transportation and distribution in high voltage (HV), medium voltage (MV) and low voltage (LV) to disperse electricity.

According with that, we can highlight some technical benefits of DG [5]:

- It is known that around 10% of the electricity generated in centralized production systems is lost in transmission and distribution. As explained before, DG generates energy close to the point of use, so these loses are significantly reduced.
- The use of local sources, as occurs in DG, increases the reliability of the power supply provided to customers. This system can also improve the voltage profile, power quality and support voltage stability of the power system.

- Distributed generators can help to cover the electrical demand in peak hours, when most people are consuming power, providing in many cases a relatively low capital cost response to incremental increases in power demand.
- Several power generating technologies used in this system are renewable sources. They allow to reduce the energy dependence from other countries, since fuel imports from other places that are required in other plants, such as thermal or nuclear power, are reduced.
- DG systems are modular and provide flexibility to the electrical distribution system. This implies a simple installation and in a short time. It also provides a great advantage in the operation and maintenance system and in the flexibility of its total capacity, increasing or decreasing the number of modules.

2.2-DISTRIBUTED GENERATION IN LOW VOLTAGE: SELF-CONSUMPTION.

The increase in electricity prices and the cheapening of certain renewable technologies due its development and policies to foster clean energy, have promoted the idea of energy self-sufficiency among worldwide consumers. Production of electrical energy, generated within the network of a consumer for his own use, has become an attractive alternative for many people.

Additionally, the global energy situation is changing as a consequence of technological advances, climate change and resource constraints, demographic changes, a shift in global economic power and an acceleration of urbanization. These megatrends affect in different ways to different areas of the energy sector and are evolving certain business models and markets: changes in customer behaviour, new ways to compete, distributed energy, etc. They are creating new challenges and opportunities in the sector.

Particularly in Spain, the electrical sector has experienced continuous regulatory changes during last years, especially focused on reducing the tariff deficit (*Tariff deficit: the difference between the collection rights recognized to electricity companies and incomes obtained through electricity tariffs. In other terms: what Spanish consumers pay today in the electricity bill is not enough to cover what it costs to electrical companies to provide electrical energy consumed in homes and businesses. And that difference, that money, is owed from consumers to electricity companies*.)

The new sector law establishes a guiding principle of economic and financial sustainability. Currently, under the legal framework of this law, it has been developed in Spain a new regulation on the consumption, the RD 900/2015 [6]. Its purpose is to establish the administrative, technical and economic conditions for the consumption procedures existing in Spain and, according to its preamble, it is intended to ensure an orderly development of the activity, consistent with the need to ensure the technical sustainability and the economic power system.

2.2.1- Renewable energies for self-consumption.

With global energy demand in continuous growth, the need for a safe and affordable supply worldwide has never been greater. In addition, the measures taken to reduce pollutant emissions from centralized energy sources, have special impact on the activity of this sector.

According to the World Energy Outlook 2014 (WEO 2014) [7], an annual report published by the International Energy Agency, a significant transformation in the horizon 2040 in the generation mix is expected.

Inside it, a decrease in the importance of fossil fuels from the highs of 2018, mainly due to the lower contribution of coal and fuel, is estimated. Therefore, renewable energy generation will be almost trebled in the 2040 horizon.

On the other hand, the installed capacity in the world will increase more than 35% over the next 10 years (due to the demand increases) of which almost 50% is renewable (including hydropower). The evolution towards a lower carbon economy is unstoppable.

These assumptions, contrast with those expected by EREC - the European Renewable Energy Council [8] - together with its member associations, based on experiences and cumulative knowledge, lead to assumptions on expected annual installations growth rates for different technologies and show that by 2040, a share of renewable energy up to 50% worldwide is possible.

The development of these renewable technologies, will lead to installations of two different scales: on one hand, there will be large-scale installations (utility scale) with power levels greater than 1 MW and on the other hand there will be residential/commercial installations (on which this project will be focused), of smaller size, generally focused on self-supply. The further development of a typology or another will be conditioned by various aspects, such as costs, regulation, development of electrical systems, etc.

Self-consumption, defined as the production of renewable electricity generated within the network of a consumer for his own use, has become an attractive and viable alternative in various electrical systems for all consumer segments. In fact in some cases, as places where it is very difficult or even impossible the construction of power lines, it may be the only alternative. This has been true thanks to a reduction in costs of certain technologies over recent years, the ease of installation of these technologies, as well as the existence of regulated schemes that foster it.

Self-consumption will play a key role in the energy mix of many countries in the future because:

- In case the sources are based on renewable technologies (not always so), it facilitates compliance with the objectives of reducing emissions established in many regions.
- These technologies are suitable for off-grid services, serving those in remote areas of the world without having to build or extend expensive and complicated grid infrastructure.

- It helps to reduce to some extent, the external energy dependence, in case of own consumption schemes connected to low voltage networks (distribution lines).

2.2.2.- Application areas of renewable technologies.

The market for PV systems is broken down into off-grid and on-grid systems, according to whether they are connected or not to the power grid [9]:

- Systems are off-grid when they have no connection to the public power grid, which implies that they cannot inject or consume energy with that grid. They are usually the sole power supply for stand-alone systems. In order to be able to make power available on a continuous and safe basis, the power must be stored in a battery.
  The PV generator must be dimensioned so that during the productive phase, that is, when there is direct sunlight, the electrical loads can be supplied and the batteries can be charged at the same time. Thereby, in moments when there are no sunlight or it is very low and therefore is not possible to generate electricity, we can consume the energy stored in the accumulators.

- A grid-connected system allows to provide electric power to households or small business with renewable energy during those periods (daily as well as seasonally) when the sun is shining. Any electricity excess produce is fed back into the grid. When renewable resources are unavailable, electricity from the grid supplies the needed electricity, enabling the possibility of eliminate the expense of electricity storage devices like batteries.
  The desired *net metering* modality of electrical supply allows consumers to produce electrical energy intended for self-consumption, combining its production curve with its demand curve.
  That is, it allows to inject to the power grid the excess of energy produced by a system of own consumption in order to be able to use that excess later. Thus, the electric company that provides electricity when demand exceeds the production of the self-

consumption system, will deduct from the electricity bill the excess of energy injected to the network.

In contrast most developed countries, in Spain, the net metering is pending of regulation and blocked by political interests. The "Real Decreto 1699/2011" [10], provides that the consumer connected to the network can give to the commercializing company, without monetary compensation, the energy generated inside their network which cannot be consumed, generating deferred consumption rights which can be used for example up to 12 months after generation.

2.3.– SOLAR ENERGY.

Demand for solar energy is experiencing strong growth worldwide, especially in the EU. PV is now, after hydraulics and wind power, the third most important source of renewable energy in terms of installed capacity in absolute terms.

In late 2011, the installed capacity of photovoltaic systems amounted to more than 50 GW in Europe. With increasing contributions from southern European countries, it could already generate over 60,000 million kWh annually, which was enough energy to supply more than 15 million European households. About 75% of world PV market growth in 2011 took place in Europe, where there was also 75% of the worldwide installed photovoltaic capacity.

Nowadays, although Asia is the fastest growing region, Europe still the most developed continent, with 88 GW or half of the global total of 178 GW. Solar PV now covers 3.5% and 7% of European electricity demand.

2.3.1.- Solar photovoltaic technology.

Photovoltaic cells are based on semiconductors material properties such as silicon. When the sunlight impacts on the surface of the photovoltaic cell, photons of sunlight transmit their energy to the electrons of the semiconductor so that they can circulate within the solid. All photovoltaic (PV) cells have two semiconductor layers, one positively charged and another with negative charge. When the light shines on the semiconductor, the existing electric field at the junction between these two layers causes electricity to flow, generating a current. Therefore, a photovoltaic system does not need bright sunlight to operate, electricity can be also generated on cloudy days [4].

For the transformation of the solar radiation into electrical energy a system comprised of photovoltaic components is necessary. These components will be different depending on the type of installation (isolated or connected to the grid).

Solar PV energy offers a list of advantages over other power generating technologies, including other renewable sources:

- Simplicity: PV systems generates electricity directly from the sunlight, no mechanical mechanisms or systems need. Therefore, there are no moving parts subjected to wear, a later breakage and a final replacement of the component. Only minimal maintenance is required to ensure the functioning of the system.
- Modularity: A photovoltaic system will always be able to expand with new elements. Therefore, they can be installed quickly anywhere. The photovoltaic modules are manufactured so that they can withstand all types of adverse weather events. Manufacturers guarantee lifetimes of panels from 20 to 40 years.
- Security: In a photovoltaic system there is no potential risk that may affect people or equipment. There are no flammable items and do not attract lightning strikes. Inverters, which connect the photovoltaic system to the grid, work with chips that make them very reliable.

- Reduced environmental impact: For photovoltaic solar energy the main environmental impact occurs in the processes of raw material extraction. Anyway this impact is limited, given that nearly 90% of photovoltaic cells are made from silicon, a material made from sand, and is the second most abundant material in the Earth's mass. The transformation process necessary for solar grade silicon requires a significant amount of energy, but in itself does not produce any waste or polluting effect.
- Reduced visual impact: The main impact on the insertion phase is the visual effect on the landscape. However, it can be reduced in most facilities in a simple way, with proper integration into the landscape or buildings. As can be installed almost anywhere where there is sun light, there exists a great potential for use in the roofs or facades of public, private and industrial buildings, as occurs in the case of distributed generation in low voltage networks.

2.3.2.- The solar radiation, irradiance and irradiation.

Solar radiation is the energy from the Sun in the form of magnetic waves which is received in a certain area and time. The Sun generates its energy by nuclear fusion reactions which are carried out at its core.

The incident solar radiation on Earth has led to the definition of the solar constant. The solar constant is the flow of energy from the sun, which strikes on a perpendicular surface to the direction of propagation of solar radiation, located at the mean distance from the Earth to the Sun, out of the atmosphere. The value of the solar constant varies according to the year and the seasons.

To reach the Earth's surface, the radiation must pass through the atmosphere where it undergoes various phenomena of reflection, absorption and diffusion decrease the final intensity. The global solar radiation is the sum of these three types, and corresponds to which we can leverage for the energy production process.

The irradiance is the term used to determine the amount of incident power per surface unit, as is to say, the amount of solar radiation which strikes over an Earth surface, measured in kW/m^2. The irradiance will be conditioned by the climate of the geographical area and the shadows that interfere with the uptake of it, produced by natural obstacles (a mountain) or by artificial causes (for example: the movement of the followers can cause shading of some panels over others).

It is necessary to differentiate between solar irradiance and solar irradiation. The irradiation is the term used to describe the power produced per unit area over a determined time. It is represented usually in kWh /m^2.

2.3.3.- Main components of a photovoltaic residential system.

A photovoltaic system for residential supply consists of the solar array and a number of components, often summarized as the balance of system (BOS):

- Solar panels: Solar cells, are encapsulated in a solar module to protect them from the atmospheric agents. The module consists of a tempered glass as cover, a soft and flexible encapsulant, a rear backsheet made of a weathering and fire-resistant material and an aluminum frame around the outer edge. Electrically connected and mounted on a supporting structure, solar modules build a string of modules, often called solar panel. A solar array consists of one or many such panels. A photovoltaic array, is a linked collection of solar panels. The power that one module can produce is seldom enough to meet requirements of a home or a business, so the modules are linked together to form an array.

  The modules in a PV array are usually first connected in series to obtain the desired voltage; the individual strings are then connected in parallel to allow the system to produce more current. Solar panels are typically measured under STC (standard test conditions) or PTC (PVUSA test conditions), in watts. Typical panel ratings range from less than 100 watts to over 400 watts. The array rating consists of a summation of the panel ratings, in watts, kilowatts, or megawatts. [11]

- Inverters: Grid-connected systems have to deliver the power generated into the electricity network. They need an inverter to convert the direct current (DC) produced from the solar modules to the alternative current (AC) of the utility grid. These inverters must supply AC electricity in sinusoidal form, synchronized to the grid frequency, limit feed in voltage to no higher than the grid voltage and disconnect from the grid if the grid voltage is turned off. A solar inverter may connect to a string of solar panels or in some installations, solar micro-inverters are connected at each solar panel.
  According to RD 1663, inverters must operate with a unity power factor, and it may be penalized if it departs from that value. For safety reasons a circuit breaker is provided both on the AC and DC side. Anti-islanding protection must be also included in order to avoid dangerous conditions for maintenance and operation staff of the distribution network. [12]

- Electricity meter: The metering must be able to accumulate energy units in both directions (energy generated by the installation which is injected into the public grid and energy demanded from the distribution network in order to supply electric power when is not possible to generate it) or two meters must be used. Many meters accumulate bidirectionally, some systems use two meters, but a unidirectional meter (with detent) will not accumulate energy from any resultant feed into the grid.

- Mounting: One of the most important elements in a photovoltaic installation, to ensure optimum utilization of solar radiation, is the support structure, in charge of supporting the solar modules, providing the most appropriate inclination for the modules to receive the highest amount of radiation along the year (they can be static or include a solar tracker). The mounting system must be designed in order to withstand adverse weather conditions (wind and snow), therefore they are usually made of hard and resistant materials impact and abrasion, such as galvanized steel, zinc-iron, etc.
  Modules are assembled into arrays on some type of mounting system, which may be classified as ground mount, roof mount or pole mount. For solar parks a large rack is mounted on the ground, and the modules mounted on the rack. For buildings, many

different racks have been devised for pitched roofs. For flat roofs, racks, bins and building integrated solutions are used.

- Cabling: The installation is composed by cables intended for pre-inverter parts, where the system works in DC, and those found after the inverter (AC). Because they must be able to work under adverse conditions, since they are placed outdoors, solar cables are specifically designed to be resistant against UV radiation and extremely high temperature fluctuations and are generally unaffected by the weather.

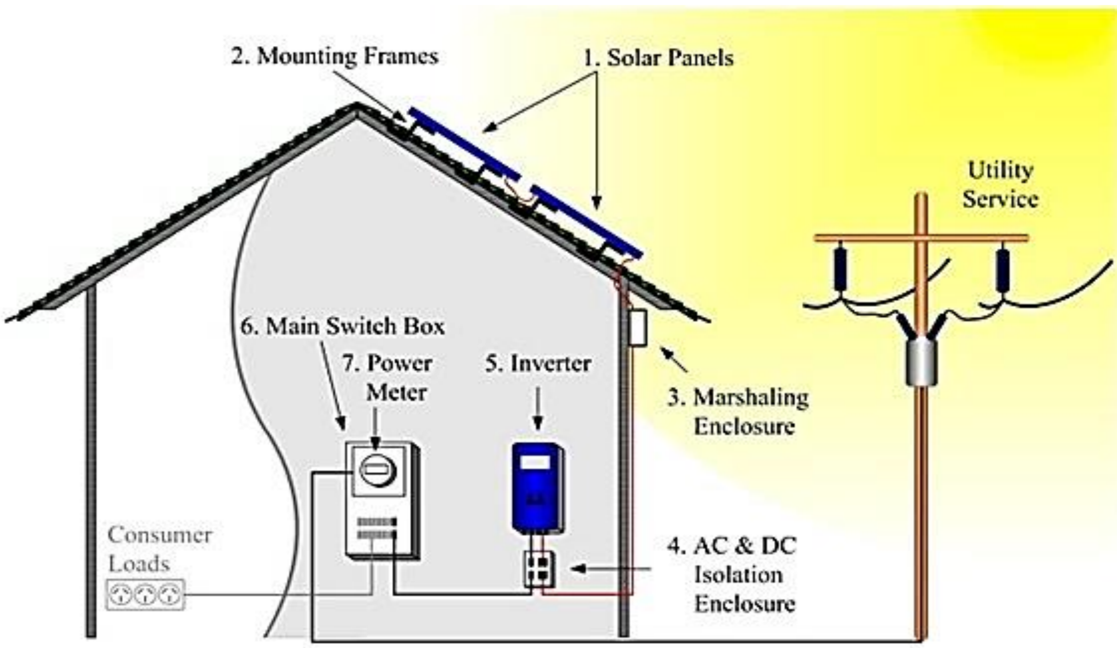

Figure 2.3.- Main components of a PV grid-connected house installation. Source: From Sun to Power.

The figure above shows the typical arrangement of a PV house installation, without storage systems. The PV-systems of the modelling program will follow this disposition.

2.3.4.- Economics and future of solar energy.

Recent years have seen rapid growth in installed solar generating capacity (both power plants and households), great improvements in technology that allows to reduce prices, performance enhancements, and the development of creative business models that have spurred investment in residential solar systems.

It's not just a European commitment, but a growing reality worldwide, which will continue without interruption reducing costs, as it occurred in recent decades. Nonetheless, further advances are needed to enable a greater increase in the solar contribution at socially acceptable costs. [13]

The expected evolution for the price of photovoltaic panels by 2050, is shown in the following graph:

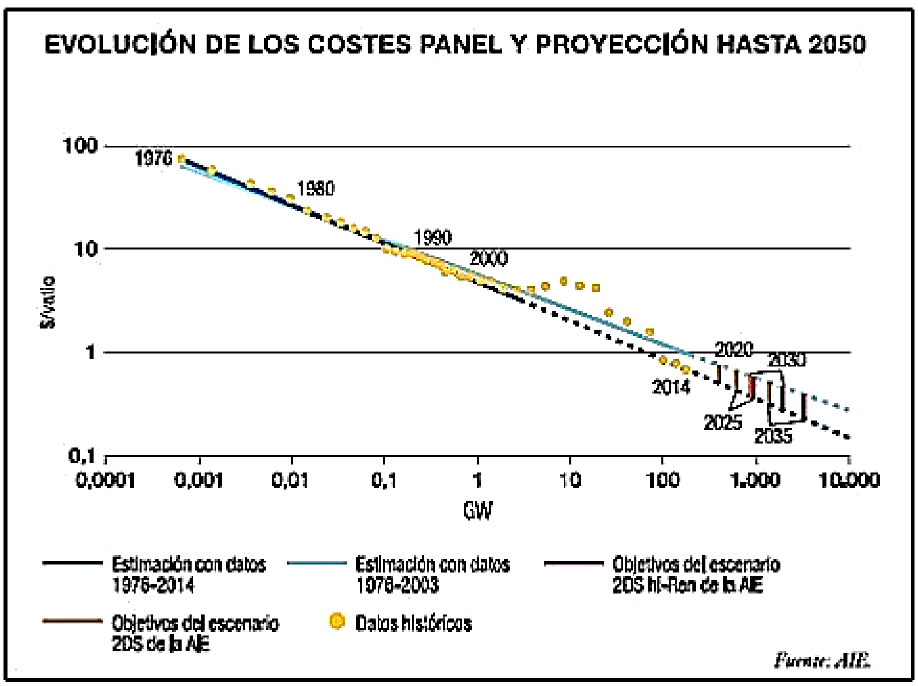

Figure 2.4.- Evolution of the PV panel costs until 2050. Source: IEA.

The main international agencies (IEA, IRENA [14]) estimate that in 2020 the global installed capacity will reach 540 GW, compared to 230 GW existing at the end of 2015, with an annual increase of 45-50 GW/year. This growth is mainly based on the development of technology in China, as well as other growing markets such as India, Japan and the USA, leading to a continued reduction in the price of the solar watt, as highlighted in the figure.

When talking about costs, it is also important to take into consideration the difference in costs between residential systems and power plant systems. According with the Study of the MIT 'Future of Solar Energy', it is estimated that the installed cost per peak watt for a residential PV system is approximately 60% greater than that for a utility-scale plant, with costs for a typical commercial-scale installation falling somewhere in between.

This difference is not produced by modules costs, since they do not differ significantly across sectors, the major driver of cost inequalities in different market segments is in the BOS component (The balance of system encompasses all components of a photovoltaic system other than the photovoltaic panels. This includes wiring, switches, a mounting system, one or many solar inverters, a battery bank and battery charger), which accounts for 65% of estimated costs for utility-scale PV systems, but 85% of installed cost for residential units.

About economic competitiveness of solar energy, with respect to other electrical power generating methods, depends on its cost and on the value of its output in the particular power market in which it is sold.

It is common to compare different generating technologies with the levelized cost of energy (LCOE). However, according to the MIT study of solar energy [13], LCOE is an inadequate measure for assessing the competitiveness of PV, or for comparing PV with CSP or conventional generation sources, because the value per kilowatt-hour (kWh) of PV generation depends on many features of the regional electricity market, including the level of PV penetration. As said before, the more PV capacity is online in a given market, for instance, the less valuable is an increment of PV generation. Other essential keys lie in the low-cost processes for making polycrystalline silicon (basic material on this technology), to use plastic instead of glass in certain elements, to include a minor amount of silver, to improve manufacturing processes or to make thinner panels. Thanks to these advances, in some countries, photovoltaic generation plants start to be competitive with conventional generation sources without fees or premiums.

In the case of residential solar generating, the reduction in BOS costs to the levels more typical of PV installations, would bring residential PV closer to a competitive position, but residential PV would still be more expensive than utility-scale.

2.3.5.- Photovoltaic solar energy in Spain.

Spain was initially one of the first countries worldwide in research, development and utilization of solar energy. Thanks to a favorable legislation, Spain was in 2008 one of the countries with the largest installed photovoltaic power in the world, with 2708 MW installed in one year.

However, further legislative regulations decelerated the implementation of this technology. These amendments on the legislation of the sector slowed the construction of new photovoltaic plants in successive years so that in 2009 only 19 MW were installed, in 2010 just 420 MW and 354 MW in 2011. The installed capacity of photovoltaic solar energy in Spain reached 4672 MW at the end of 2014 and 4721 MW at the end of 2015. [15]

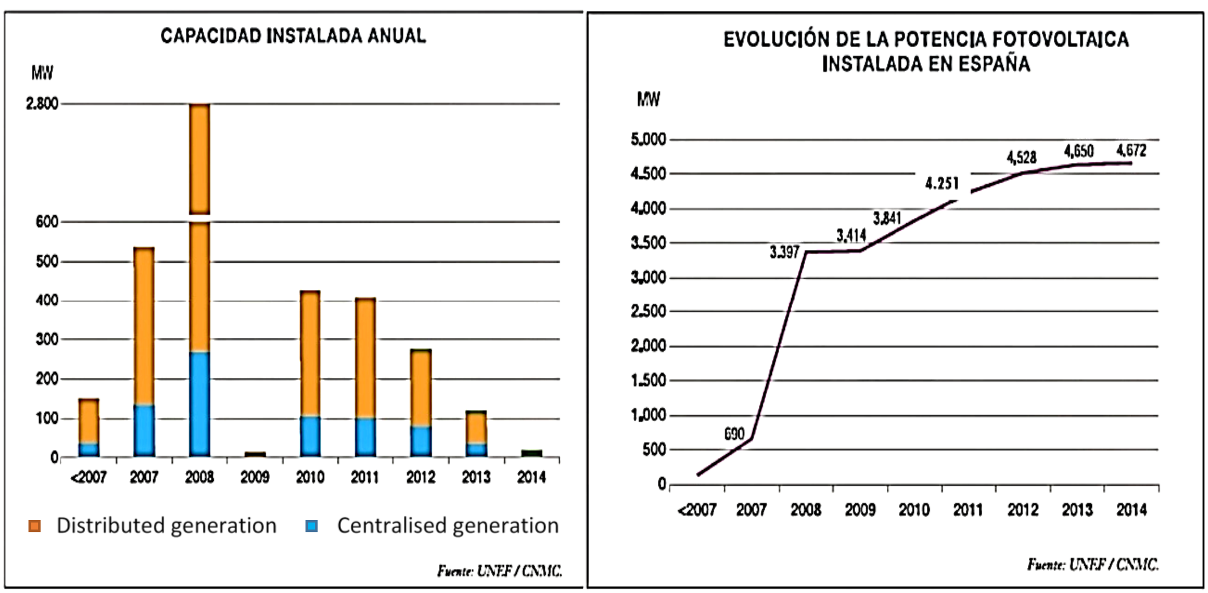

Figure 2.1.- PV capacity and evolution of last years. Source: Unión Española Fotovoltaica.

A recent study by Ernst & Young for Solar Power Europe points to Spain as one of the markets that will further grow in the next five years. The study predicts a recovery in the sector, which will facilitate the installation of 2,100 MW and the creation of 5,500 new jobs by 2020.

At present, the cost of photovoltaics has declined enough to start being competitive (currently, around 0.12 €/kWh on average in Spain). Over the coming years, the cost will continue to decline to become fully competitive and be able to take the place that corresponds in the energy generation sector.

In the coming years, it will be necessary to explode the new business models arising from the new energy paradigm. New energy services, smart grid management, efficient storage systems… are just a few examples of the opportunities that the changes that await us open to the industry.

According with the statements made on the journal 'Vértices' [16], the Spanish government has already recognized this reality in the Renewable Energy Plan 2011-2020, which provides a reactivation of the photovoltaic industry and the development of renewable sources well above 20% of primary energy consumption by 2020 from the current 14.2%.

Renewable energy technology, including photovoltaic of course, is one of the areas that offer the most promising business opportunities in Spain and Europe.

3. Objectives.

The incorporation of Distributed Generation to the low voltage network is a complicated procedure that requires a complete analysis to evaluate the behaviour of the new electrical system before a real implementation.

This evaluation is carried out with simulating programs, that allows to represent a grid which includes: substations, transformation stations, lines, loads, nodes and all parameters that these elements includes. For this study, an electric simulation program called *PowerFactory*, designed by *DigSilent*, has been selected.

The purpose of this project focuses principally on the study of three essential issues that DG presents when it is interconnected with the low voltage network (the excess of energy is transmitted to the grid):

- Load flow studies: These studies will provide information about the voltage levels of all nodes of the system, power flows in the networks and current levels flowing through the feeders. After the performance of power flow analyses, it will be possible to evaluate:

  - Voltage variations during a complete day: The increase of power generation sources that are incorporated to the electric grid, will lead to possible variations of the voltage levels in the nodes of the system.
    On a 230-volt base, the standard European voltage limits requires that the service entrance voltage be between 220 volts and 240 volts. Voltage conditions that are out of the normal operating range can lead to poor operation of the power system and customer loads, damage to utility equipment and customer loads, and in extreme cases can even be a safety hazard.
    In radial power systems, the voltage regulation is usually carried out by changing the load-tap of the transformers of the substations or transformation centres, and the

power only takes one path from the substation to the loads of the system. This assumption leads to the situation on which the voltage will always drop from the initial feeder to the final loads of the distribution network, principally due to the line losses since the distance from the substation increase. The only exception in this statement is when there exists a large reactive compensation (capacitor banks). The incorporation of new distributed sources in radial distribution networks will impact with this assumption. [17]

High voltages may be caused by reverse power flow. During moment of large PV generation, which coincides with no so high consumption levels, the voltage rise can be enough to push the voltage above nominal limits. It is possible to estimate the effect of a generator by using the standard voltage drop equations with reverse power flow. The voltage drop along a feeder due to a load is approximated by equation 'XX':

$$V_{drop} = I_R \cdot R + I_X \cdot X_L \tag{3.1}$$

Where:

V_{drop} = voltage drop along the feeder.

R = line resistance, ohms.

X_L = line reactance, ohms.

I_R = line current due to real power flow, amps (negative for a generator injecting power).

I_X= line current due to reactive power flow, amps (negative for a capacitor).

During moments where the new DG sources are transmitting energy to the grid, the voltage will be increased principally if X/R ratios are low (largest voltage rises when the line resistance is high). If the DG is injecting reactive power like a capacitor, the voltage rise will be even larger. Under the right circumstances, this voltage rise is beneficial (voltage support), but if too much rise occurs or it occurs on a section of

feeder where the voltage was already near the upper normal limit before the DG started, then a high voltage problem may be created.
If voltage rise can be a problem, there are several options. One would be to limit the size of the generators to below the level necessary to cause problems. Another would be to relocate the DGs to a more suitable location on the distribution circuit.

- Study of the load capacity of the present electrical lines and transformers of the selected network: As seen before, the power flows will suffer significantly variations during the operation times of the DG sources. Power flow analysis will also permit to verify whether the current lines and transformers can work without suffering overloads produced by the excess of energy transmitted to the grid due to the new sources. If this was not possible, it would be necessary to redesign the lines and transformers, modifying some of its features so that any failure does not occur.

- Analysis of the behaviour of the electrical protection devices of the electric transformation stations, as well as those of the substation. The function of power system protection is to detect a fault condition (perhaps due to a lightning strike or equipment failure) and isolate the faulted section of the system as rapidly as possible while restoring normal operation to the rest of the system.
  The aim of this part is to evaluate whether the fuse (that correspond to the low voltage part of the station) and the circuit breaker (corresponding to the medium voltage part) can operate in a correct way, making sure that they fulfil their function properly and pose no risk to the installation.
  If this were not so, it would be necessary to change the electrical protective devices characteristics for others adapted to the new electrical operating system.

- Harmonic analyses: Harmonic contents are always present in power systems to certain extent. They are usually caused by no lineal-loads such as fluorescent lights, AC to DC conversion equipment, variable-speed drives, switch mode power equipment, arc furnaces, etc. A wave that does not follow a "pure" sinusoidal wave is regarded as harmonically distorted (See Figure 3.1.).

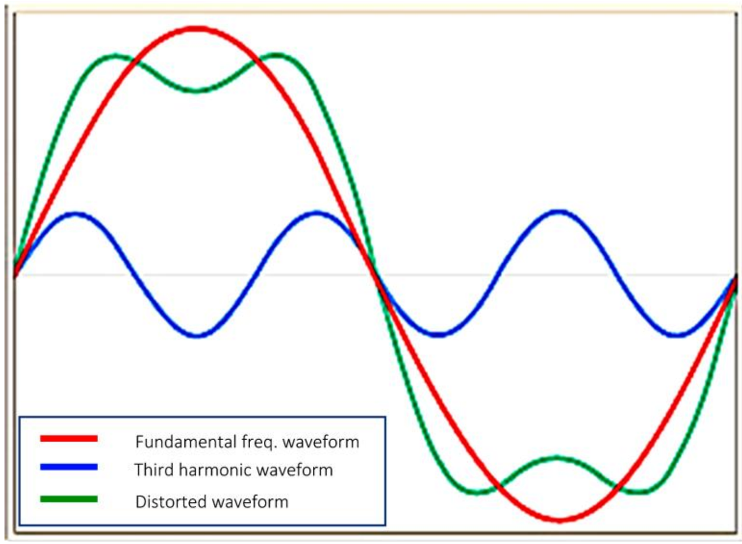

Figure 3.1.- Distortion of a voltage waveform due to harmonics.

Therefore, DG can cause important injections of harmonic contents to the distribution grid. In this case, they are generated by the inverter needed to transform the DC current and voltage produced by the PV-systems into a suitable AC current and voltage on which the distribution systems operate. Harmonics can cause significant thermal damages in conductors, transformer windings and in the neutral wire. They can also affect to the protective equipment, cause vibrations and resonance.

In this part, it will be necessary to determine whether the system fulfil the conditions stablished on existing international standards (IEC 61000-3-2 [18] and IEEE Std. 929-2000 [19]):

- The total voltage wave generated by the inverter, THD, harmonic distortion is a measure of the quality of the power generated by the inverter. In the standards, it is indicated that the THD must be lower than 5% when the total harmonic distortion of the voltage wave of power grid to which it is connected is less than 2%, plus each individual harmonic is less than a certain value.

- Furthermore, the harmonic distortion (HD) of each harmonic component cannot exceed 3%.

There exist other important aspects which would have to be analysed for a real implementation of this idea. The most important, has reference with the economic aspects of the modification of the current components of the electrical system.

This part will not be evaluated in this project, as it is focused on the technical point of view, corresponding to the part mentioned above.

4. Modelling of the program.

In order to evaluate the integration of Distributed Generation in low voltage networks, a case study will be used. A model of a real existing electrical system will be used to analyse this issue. The software selected for this analysis is Power Factory, designed for a complete implementation of electric networks among other things.

The programme allows to build your own grid, introducing the particular data and characteristics of each element and device. It permits to use a wide variety of electric analysis, including: load flows, short circuits, power protection studies, harmonic analysis, etc.

The case study of the project involves a typical residential site on the North Coast of Spain, particularly in Asturias. The place is located on the outskirts of a city, consisting mainly on private chalets. This situation would be suitable to incorporate particular sources of DG, intended for the own consumption of each chalet, but interconnected with the network. In this way, the excess of energy generated by the DG sources, would be injected to the common grid, leading to the issues previously mentioned. During this project, such problems will be analysed.

The site of study presents the following characteristics:

- It is a residential area with 106 residential units, that are represented as low voltage loads.
- The LV grid works at 230 V (phase to neutral voltage) / 400 V (phase to phase voltage).
- The MV grid works at 22 kV.
- The system operates at 50 Hz.
- The model includes a single substation and five transformation stations or transformation centres (TCs).
- The LV grid is a three-phase network with neutral.
- The loads are connected with overhead cables.
- The LV grid is owned by the distribution company *Eléctrica de Portugal (EDP)*, and is fed from the MV network by the transformation stations.

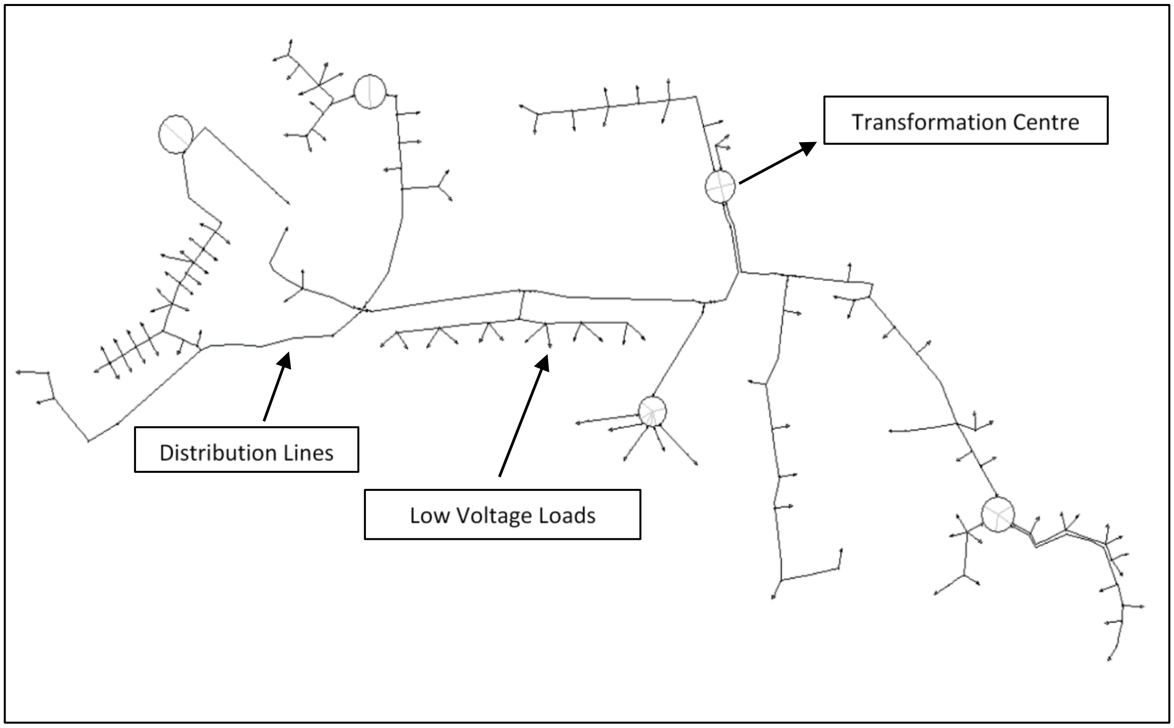

Figure 4.1.- LV network model.

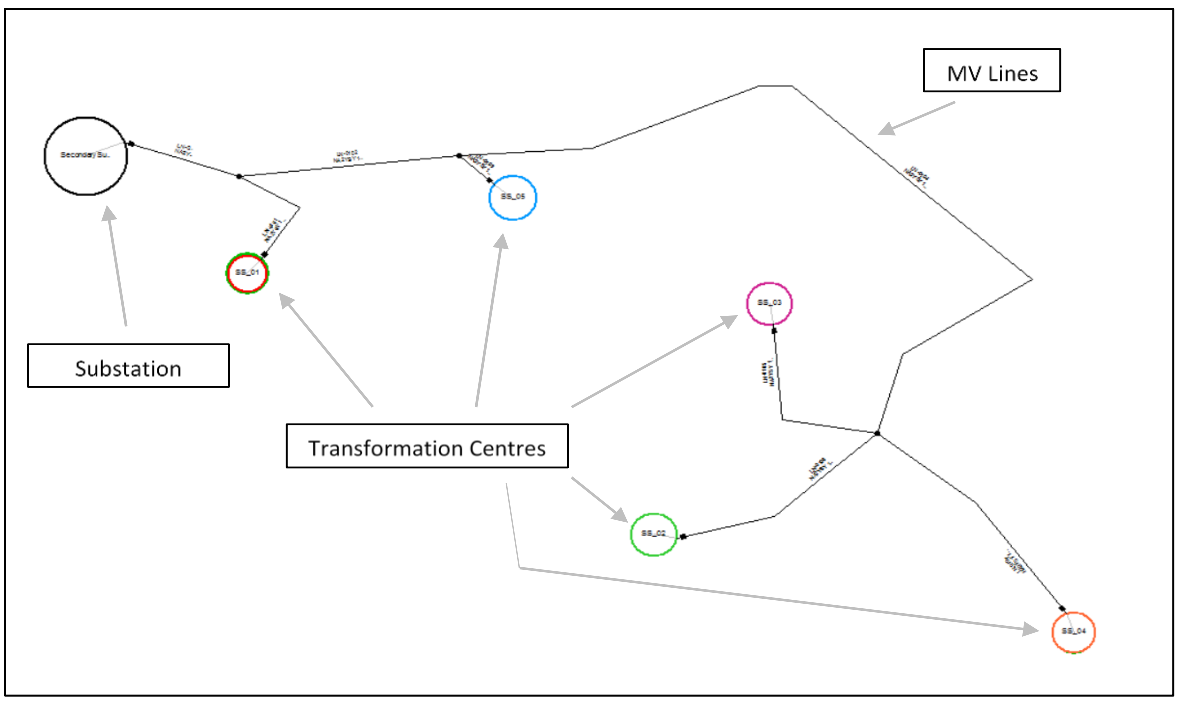

Figure 4.2.- MV network model.

In the figures above, the LV network, as well as the MV network are represented, including all TCs and the substation, which supplies power to the TCs through the MV lines.

In the first step, the network of the place of study will be modelled without any modification. The most similar data of the system as possible will be used according with the real existing data. In some cases, it was not possible to use the same equipment as the real place has, since the program does not have all brands and models stored in its database. Because of that, some elements have had to be modified by hand to satisfy the required specifications.

Once it has been determined that this model operates in the right way, several sources of distributed generation will be introduced in the system. These sources will be added gradually, in such a manner that the number of households that incorporate DG interconnected with the network increases progressively. This approach will allow to implement diverse analysis and check what difficulties appears when the number of generation sources increases.

Then, the results of the simulations performed in the program will be represented. To do this, several graphs of the different studies will be used. This manner allows to see the results in an easier and clearly way.

Finally, the conclusions drawn from the simulations performed will be included. In this part, the necessary modifications to make in the system for it to work properly, when the new generation points are integrated, will be also included.

The technology employed in this project to represent the DG consists of photovoltaic solar panels (PV systems). These structures can be integrated seamlessly into the site where the study takes place, either flat on the ground of the property or on the rooftop of the houses. A different number of them can be incorporated on each home, allowing to vary the power that each user transmits to the network. Their data can be modified by hand in the program and the power they generate is selected in each case by its rated power. Thus, the excess energy to be transmitted to the network is also known.

4.1.- COMPONENTS OF THE SYSTEM.

4.1.1.- Transformation centres components.

When representing the grid in the program, it is preferable to build two separately grids to work in a simpler manner: the LV network in one hand, and the MV on the other hand. Thus, they are represented in two different screens, making the project more visual and easy to understand.

The elements that connect both parts are called 'transformation stations', and are represented by a circle in the graphic window of the program. Then, a new window can be opened to edit its components and characteristics. The function of these installations is to change the voltage level from medium to low, by means of a transformer. They also include a power system protection for both sides, consisting on fuses of different characteristics for each voltage level.

In this case, a single transformation station has been designed, following the characteristics given by the distribution company of the site, and used for the five existing stations of the study case, as the structure of them is the same. The software has a very useful tool available for this purpose, called 'Template'. It allows to create components composed by several elements and store and organise them for re-use in the power system model.

The program includes some basic substation models in the 'Templates' folder. For this project, one of this models has been used to represent the transformation stations. Several modifications have been performed on the predefined template to adjust it to the required characteristics of the real system.

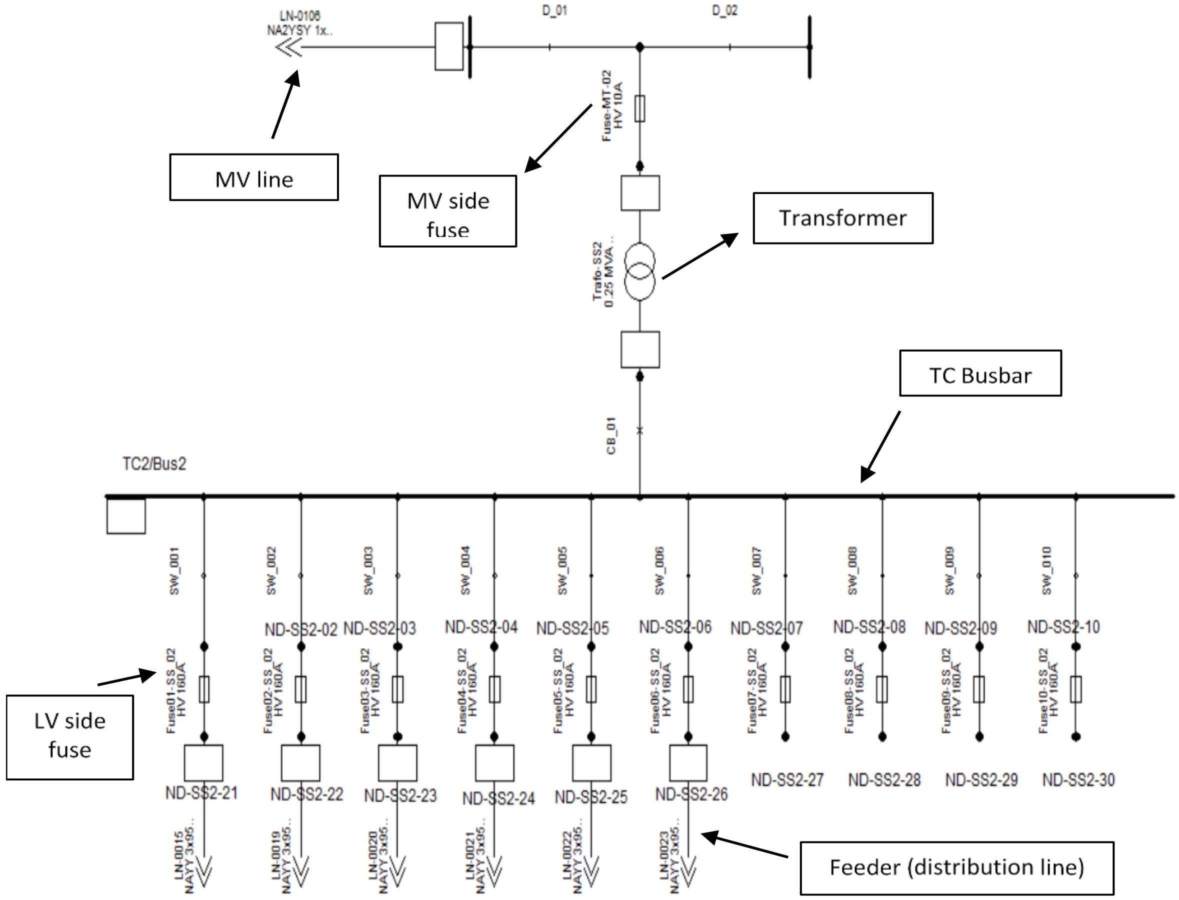

Figure 4.3.- Transformation centre model.

The transformation station is formed by the following main elements:

- Transformer:

Their main characteristics are exposed on the table above:

Technology	Rated Power (MVA)	Nominal Freq. (Hz)	MV Side (kV)	LV Side (kV)
3PH Transformer	0.25	50	22	0.4

Table 4.1.- TC transformer parameters.

It is necessary to regulate the transformer taps inside its characteristics menu. This tool is used when the transformer is overloaded after performing a load flow calculation and the system has not been modified yet (no new power sources have been introduced). To perform this regulating action, the 'Load Flow' window of the transformer must be opened. Then, the 'Tap Position' option has to be modified, in this case, increasing its value to one or two. This function allows to increment the voltage carried by the transformer in normal conditions. In particular, for each upper tap, the transformer voltage level increases by 5% respect with the nominal value.

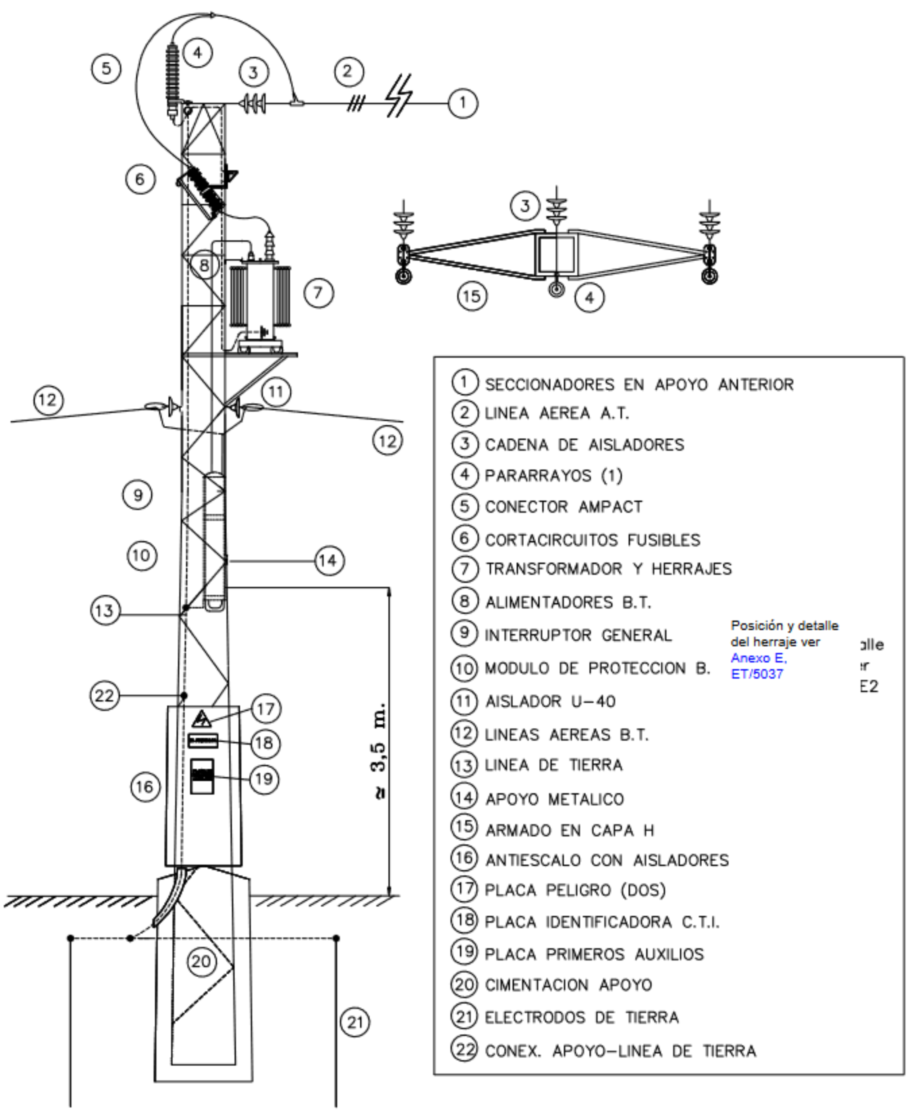

Figure 4.4.- Transformation centre disposition. Source: EDP.

The figure above shows the typical disposition of the location of the transformer on an outdoors transformation centre. This type of TC is the real existing one of the analysis site.

- Busbar:

Corresponding to the LV side (0.4 kV). It acts like a node, where different lines, transformers and protection devices are joined in a more visual way.

- Fuses:

The transformation station is composed by several fuses. We can distinguish between those belonging to the low voltage side, after the busbar (one fuse is needed for each line which exits the station and distribute power to the LV network) and those of the high voltage side of the transformer.

The fuse is a device used to protect electrical components, in this case the transformers of the transformation stations. This element allows the current to flow while it does not exceed an established value, which is determined by the rated current of the fuse. The fuse is constituted by a foil or metallic wire which melts with the heat produced if the flowing current exceeds such value. In this way, the circuit will open and the current flow would be interrupted, preventing the protected element from damage.

The most important feature when defining the fuse is its rated current. In this case, fuses of 160 A have been used for the low voltage side, while 10 A rated current fuses have been selected for the higher side. There exist other options to define inside the 'Basic Data' of the fuse element dialog which are enabled for this project: [20]

- Closed: If this is checked, the fuse will be in the closed (non melted) state for the calculation.
- Open all phases automatically: If this option is enabled, then should the fuse be determined to melt, the software will automatically open all three phases on the switch

during a time domain simulation or short circuit sweep. This field has no effect on the load flow or short-circuit calculations.

- No. of Phases: This field specifies whether the fuse consists of three separate fuses (3 phase), two fuses (2 phase) or a single fuse (1 phase). For this project, a 3-phase fuse has been selected in all cases.
- Compute Time Using: Many fuses are defined using a minimum melt curve and a total clear curve. The idea is that for a given current, the fuse would generally melt at some time between these two times. In Power Factory it is possible to choose whether the trip/melt time calculations are based on the minimum melt time or the total clear time. The total clear curve must be selected to implement time-overcurrent plots, which will be evaluated in this project.

The time-overcurrent plot is a very useful tool that can be used for graphical analysis of an overcurrent protection scheme to show multiple relay and fuse characteristics on one diagram. These plots can be used to determine relay tripping times and hence assist with protection coordination and the determination of relay settings and fuses' characteristics. They will be explained in detail later.

4.1.2- Substation components:

In this project, the substation is modelled following a similar structure than the TC does. Of course, it is necessary to change the voltage levels and rated power of its components. Its main components are the following:

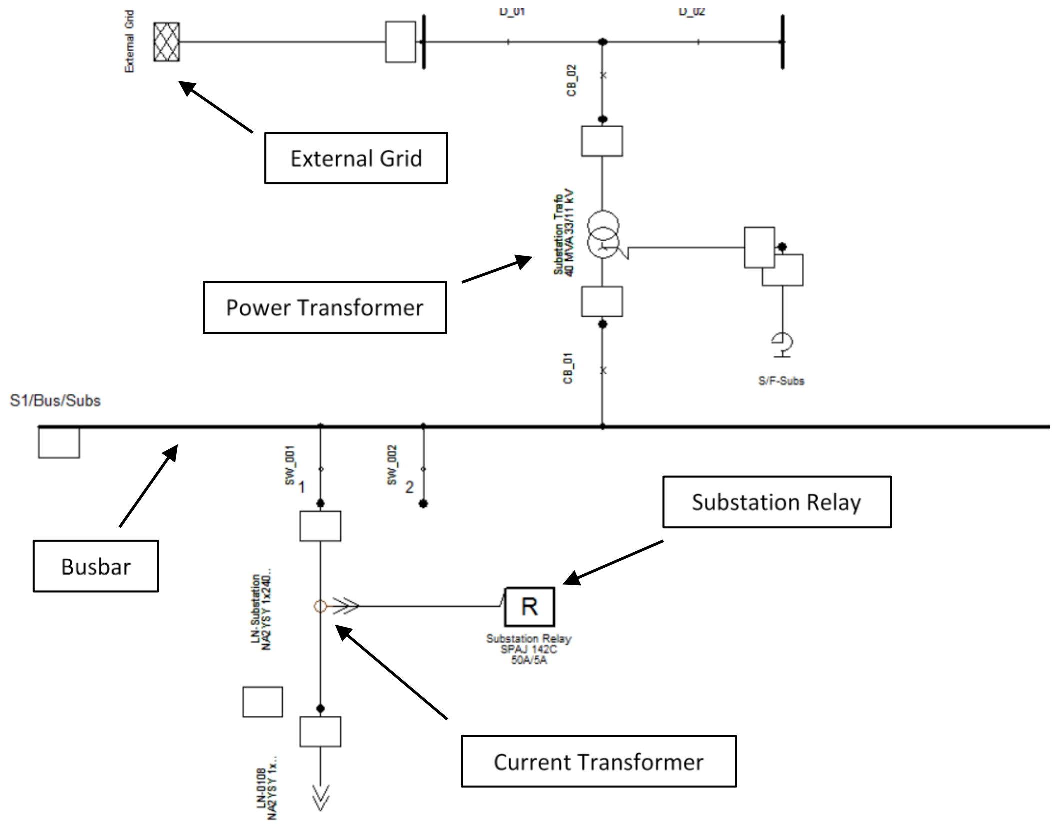

Figure 4.5.- Substation model.

- Power transformer:

Technology	Rated Power (MVA)	Nominal Freq. (Hz)	MV Side (kV)	LV Side (kV)
3PH Transformer	0.25	50	22	0.4

Table 4.2.- Substation transformer parameters.

- Busbar:

Corresponding to the MV side (22 kV). It acts like a node, where different lines, transformers and protection devices are joined in a more visual way.

- Relay:

The relay is a protective device designed to activate a circuit breaker when a fault is detected (over-current, over-voltage, reverse power flow, over-frequency, and under-frequency). This element is located at the low voltage side of the substation, just after the LV side of the power transformer. This component needs to include a current transformer (CT) which gives the input signal to the relay. The CT is connected at the beginning of the exit line, and it is purpose is to reduce the current at the relay input.

The first step the user has to perform when modelling the relay, is to select its type. In this project, an overcurrent relay will be used. An overcurrent relay is a type of protective relay which operates when the load current exceeds a pickup value. When this occurs, one or more contacts will operate and energize to trip (open) a circuit breaker.

Once the relay type is selected, several slots, which are based on the configuration of the relay type, appear on the 'Basic Data' of the relay dialog. The values to define in each slot are shown in the following table:

Relay Type	**Phases**			**Neutral**		
	I>	**Curve**	**I>>**	**I_0>**	**Curve**	**I_0>>**
SPAJ 147C $I_{af}=I_{an}=5A$	50	0.10	100	10	0.10	20

Table 4.3.- Relay parameters.

The combined overcurrent and earth-fault relay are connected to the protected object (power transformer in this case) through the current transformer. The three-phase overcurrent unit and the earth-fault unit continuously measure the phase currents and the neutral current of the high side of the power transformer. When a fault is detected, the relay starts, trips the associated circuit breaker, initiates auto-reclosing, provides alarm, records fault data etc. in accordance with the application and the configured relay functions. The following figure shows the block diagram of the relay, which allows the user to understand better its working principle:

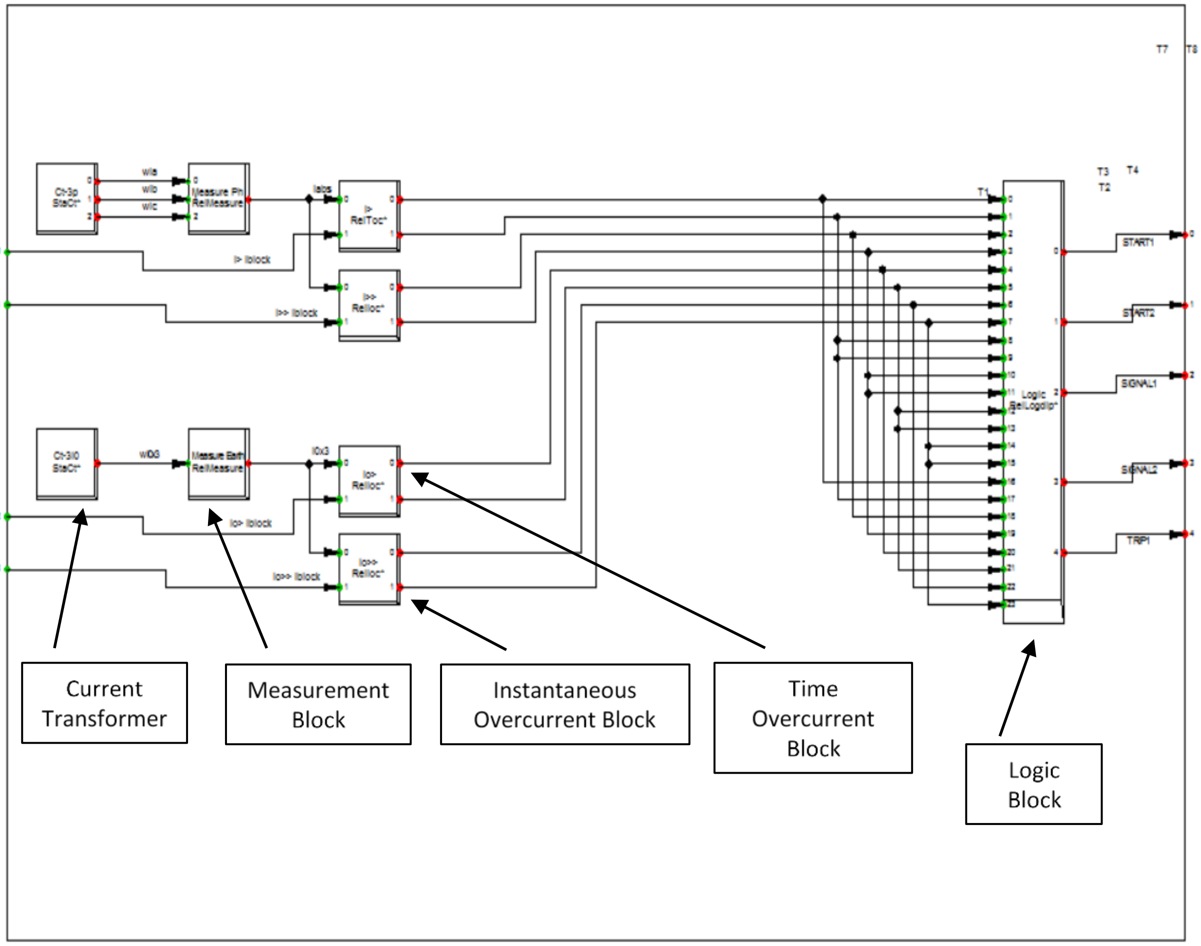

Figure 4.6.- Block diagram of the relay.

The following paragraphs provide a brief overview of some of the basic protection blocks that can be used to develop a relay model in this program: [20], [21]

- Measurement blocks: The measurement block takes the real and imaginary components of the secondary currents from CTs, and processes these into the quantities used by other protection blocks in the relay model. Quantities calculated by the measurement block include absolute values of each current phase and the positive and negative sequence components of current.
- Instantaneous overcurrent block: The instantaneous overcurrent block is a protection block that trips based on current exceeding a set threshold. This block also supports the

inclusion of an optional delay time and directional features. Hence this block can be used to represent instantaneous, definite time and directional overcurrent relay functionality. The total tripping time is the sum of the delay time and the pickup time also configured within the relay type.

There exist two different types of instantaneous overcurrent blocks:

- I0>: When the earth-fault current exceeds the set start current of the low-set stage I0>, the earth fault unit starts delivering a start signal after a pre-set start time. When the set operate time at definite time operation or the calculated operate time at inverse time operation elapses, the earth-fault unit operates.
- I0>> In the same way the high-set stage I0>> of the earth-fault unit starts delivering a start signal after a pre-set start time, when the set start current is exceeded. When the set operate time elapses, the earth-fault unit operates.

- Time overcurrent block: The time-overcurrent block is a protection block that trips based on current exceeding a threshold defined by an I-t characteristic. Most relays support the selection of several different I-t characteristics. These characteristics can be shifted for higher or lower delay times by altering the time settings or shifted for higher or lower currents by altering the pickup current.

  There exist two different types of time overcurrent blocks:

  - I>: When the phase current exceeds the set start current of the low-set stage I>, the overcurrent unit starts delivering a start signal after a pre-set start time. When the set operate time elapses, the overcurrent unit operates.
  - I>>: In the same way the high-set stage I>> of the overcurrent unit starts delivering a start signal after a pre-set start time, when the set start current is exceeded. When the set operate time elapses, the overcurrent unit operates.

- Logic block: The logic block is responsible for two functions in the relay. Firstly, it combines the internal trip signals from the other functional blocks, and produces an overall trip status and time for the relay in a single output. Secondly, it controls one or more switches in the power system model that will be opened by the relay in the time determined by the logical combination of the various tripping signals. In this case, for the logic block, a switch breaker has been assigned, placed just between the power transformer of the substation and the current transformer linked to the relay.

- Current transformer:

The next step is to make the configuration of the CT which connects the relay with the power transformer output. First of all, it is necessary to choose the CT type. Then, the user will have to set the primary and secondary ratio through the drop down menu next to tap. The available ratios are determined by the selected CT type.

In this case, a ratio of 50-100/5 has been defined, according with the data given by the distribution company. If the selected CT type has not the required taps, the user can include additional primary or secondary taps by inserting more rows to the taps table and entering the needed values.

In this project a new CT has been created by selecting 'New Project Type' in the type field and inserting 50 and 100 on the primary taps columns and 5 on the second one. Then, it is necessary to select the tap for the primary side, in this case it can be 50 or 100 A.

- External grid:

The substation is fed from the centralized generation points through high voltage electric lines. In the program, this is represented with an 'External Grid' that supplies energy directly to the substation. Thus, there is no needed of representing the large generation centres and their corresponding HV lines.

An important feature to choose when programing the 'External Grid' is the option: Bus Type (inside 'Load Flow' options). There exist three options which the user can select, depending on the analysis you want to realize. In this case, the 'Slack' (SL) type will be used, allowing the user to fix the voltage magnitude and angle. The program uses the angle of the external grid to refer all other angles to this reference.

Another essential parameter to define on the external grid is the short circuit current I''k max. To change its value, the characteristics window of the external grid element must be opened. Then, the correspond number (in this case: 17.5 kA) is introduced on the 'Short Circuit Current Max.', located on the 'Short Circuit' field.

4.1.3.- Overhead lines:

To join all elements of the system and allow electric power transmission, overhead lines of aluminium are used. Although copper is one of the most common materials used in electrical installations and electric power transportation, aluminium is considerably cheaper and lighter. It also offers good conductivity, so it is very common to use it in overhead electric lines.

The most important feature when selecting the conductor in the program, is the cross section it is going to has. This characteristic will define the current that the conductor will be able to withstand without damage (called 'Rated Current' in the Table 4.4.).

To choose the characteristics of the conductors, we have to differentiate between those that belong to the LV network and those that are used in the MV system. Their main features are shown in the following table:

	LV Conductors	**MV Conductors**
Nominal Cross Section (mm^2)	150	240
Rated Current (kA)	0.19	0.425
Rated Voltage (kV)	1	22
Conductor Material	Aluminium	Aluminium
Insulation Material	PVC	Bare conductors

Table 4.4.- Conductors parameters.

Notice that the 'Rated Voltage' of the conductors exposed on the table above exceed the voltage level of the LV network or is the same (MV). The point is that there will be no problem with the voltage level because they can operate, (0.4 kV for LV and 22 kV for MV).

An important aspect to consider when some component (for instance loads) are incorporated to the lines is that this element is divided into different fragments automatically. It is necessary to regroup in the program the original line by terms of a branch. First is recommended to name the fragments created and then define all of them together in a branch, which will behave like a single line. It is advisable to use this option to avoid confusing lines and have everything more organised in the program.

When simulations are performed in the program, it is possible that the current that the conductors are able to withstand exceeded the maximum allowable value. This is because the new sources introduced on the system inject the excess of energy produced into the network, increasing the current flowing through it.

Therefore, it is possible that, in order to avoid damage to the conductors currently used, some modifications on its characteristics could be carried out. This will be evaluated in the next chapter.

4.1.4.- Low voltage loads.

In the electric system model, the energy that the neighbourhood consume is specified for each house. This is represented by 'Low Voltage Loads' in the LV network of the program. That means that the energy consumed by each user is depicted and defined for each user.

In a low voltage system every load may consist of a fixed component with a deterministic amount of power demand plus a variable component comprising many different, small loads, such as lights, refrigerators, televisions, etc., whose power varies stochastically between zero and a maximum value. [20]

Because of this fact, low voltage loads are represented in *PowerFactory* with fixed and variable (stochastic) components. The parameters which define these fixed and variable components are set in both the load flow command dialog, and in the load types' dialogs.

There exists the possibility to modify on the 'Fixed Load' field, the input of the Fixed Load which is the non-stochastic component of the load that is not subject to coincidence factors. First of all, the power factor has to be defined by the user. In this case a value of 0.95 was chosen as it is a common value. A high power factor indicates that the consumer has a better use of electrical power, since for the same electricity consumption the user needs less current that in the case of a low power factor. In electrical terms, it means that the user is consuming little reactive power from the supply company. Then, there exist the choice to set fixed values for: the apparent power, active power or voltage and current levels. These parameters represent the consumption of the load. The decision of selecting a parameter of those mentioned above, depends on the type of study that is going to be performed. In this project, the active power is chosen to set fixed, as it determines the consumption of each user and results very useful to create a consumption model for the analysis which will be performed later. Different nominal values of active power have been used to represent the fixed load parameter on this project, principally values between one and three kW.

In the case of the stochastic component of the low voltage load, the active and reactive power (calculated from the fixed load and power factor defined in the fields in the load flow page) are multiplied by the number of customers (defined in the load elements themselves), and are added to the fixed load defined for each low voltage load. The user has to introduce a numerical value in the variable load field to define the number of customers. In this project, different numbers have been used, ranging from 1 to 10, in order to have more variety on the power system.

The definition of 'Variable Load per Customer' frame allows the definition of the variable component of low voltage loads using the parameters available (average power, max. power per customer, power factor of variable part, and coincidence factor), or by specifically defining LV load types for the target loads.

In this project, a very useful tool for load flow calculations of low voltage networks is used. It is called 'Feeder' and permit the user to control some supply parameters. They are explained on the the next section. This tool has a function called 'Load Scaling', which has a relation with the load parameter values: it helps the user in adjusting the load values when they are not known, by scaling them to match a known feeder power or current that has been measured in the real system.

It is available on the 'Load Flow Calculation' command and it can be activated by selecting in 'Load Options' the 'Feeder Load Scaling'. When the load flow is performed, the program will adjust automatically the scaling of all adjustable loads in the feeder areas in such a way that the load flow at the feeder equals the current or power set-point. This function is explained in more detail below.

Note: The data and characteristics of the elements mentioned in section 4.1, correspond to the actual devices of the study site, so they are probably not suitable if some modification is carried out. This occurs when the DG sources are introduced. Therefore, it is possible that some components of the transformation station have to be replaced for others adapted to the new terms. It will be seen in the next chapter, where the analyses take place.

4.2- MODELLING TOOLS.

The program used in this project has a large number of tools which are really useful when preparing the electrical model of the system. In this section, a complete explanation of this functions is exposed:

4.2.1.- Feeders.

When analysing a complex network, is preferable to know where the various components are receiving their power supply from. This is achieved by using a tool called 'Feeders Definitions'.

The feeder is a virtual object which exists not as separate object in the single line diagram [20]. This approach will be used in this project since it allows the user to control the neighbourhood's consumption.

The feeders are defined in this project in the node of the corresponding transformation centre, particularly in a cubicle, which represent the specific place inside the node where the element is joined to it. Notice that a node can be composed by lot of cubicles since a cubicle is created for each element connected to such node. The element in this case is a line, which is connected to the LV side of the station, just after the fuse. A feeder must be defined for each line of each station, in such a way that is known where each line is fed.
In Figure 'xx', the different feeder domains are represented in different colours to distinguish their limits.

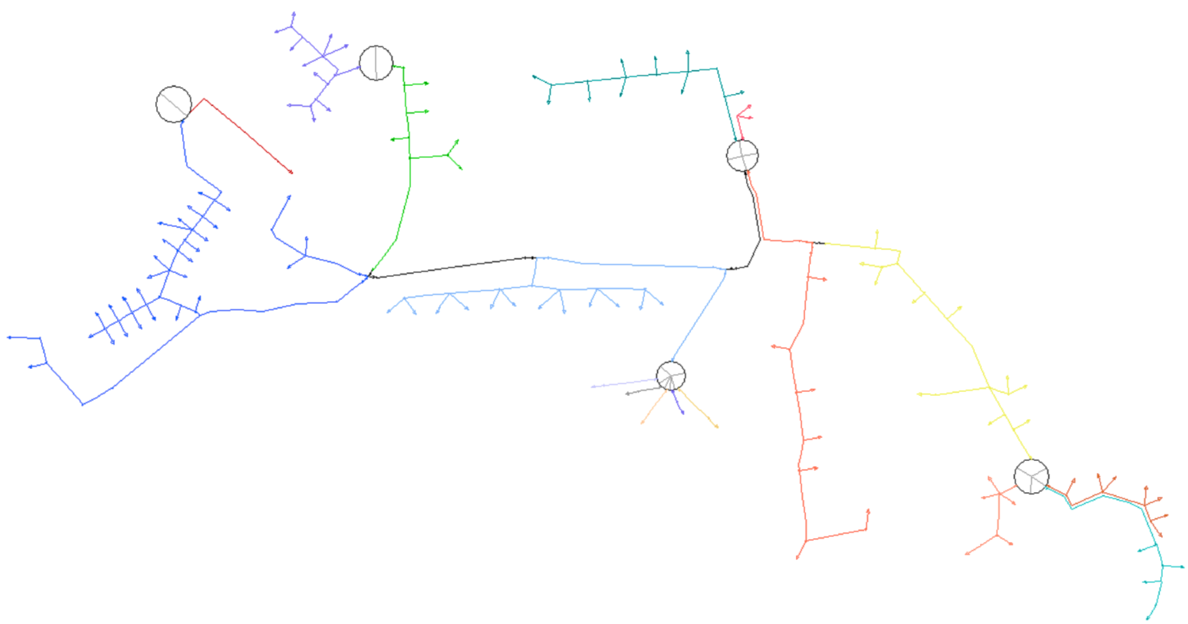

Figure 4.7.- Feeders' domains.

Once a feeder has been defined it may be used to scale the loads connected along it according to a measured current or power, to create voltage profile plots or to select particular branches and connected objects in the network. Following load flow calculations, special reports can be created for the defined feeders.

The load flow calculation will then adjust the scaling of all adjustable loads in the feeder areas in such a way that the load flow at the feeder equals the current or power set point (in this case current which exits through the LV side of the transformation station of each line). Therefore, it is necessary to let know the program that adjustable loads will be used in order to enable the feeders function. This is made by activating the 'Adjusted by Load Scaling' option, inside the low voltage load dialogue. This action has to be made in all the loads of the system.

When creating the feeder, is fundamental to modify the 'Scaling Factor' inside 'Load Scaling' of 'Load Flow' options. This parameter allows the user to control the active power that the transformation station is supplying to the covering electricity demands (or in other words, the electrical energy that the consumers are using in a zone defined by a feeder). To determine this consumption, the program offers the possibility to set fixed values for one of these parameters:

- The active power consumption of the feeder zone (although it seems to be a good option, it could be difficult to estimate).
- The current that the transformation station is supplying at the beginning of the defined feeder.
- Apparent power that is supplied to the feeder zone.
- By defining a value for the scaling factor.

For this project, the second choice has been selected (to set fixed values for the current). In order to activate this tool, the 'Feeder Load Scaling' option has to be enabled when performing the load flow calculation. This part of the project consists of keep testing consistent values for each feeder and adjust the results obtained by performing load flows, until the ideal status is achieved.

When modelling the feeders, some problems can appear if the values introduced manually for the parameter to set fixed are not adequate. First of all, it is essential to fulfil the maximum current which the LV system can operates with. This is imposed by the fuse located on the LV side of the transformation station. In this case, its rated current is 160 A. That means that the station cannot provide more than this value at the beginning of the defined feeder. Otherwise, the fuse would fulfil its function and the circuit would be opened. Once this restriction is satisfied, it is recommendable to start setting the current values to half the rated fuse current. As each feeder have different number of consumers, some problems will appear: different number of consumer implies different current consumption. So the next step will be to adapt the current value flowing at the beginning of each feeder for each case, depending on the number of consumer that the covered zone of the system has. To carry out this action, it will be necessary, obviously, to reduce de current sent to those parts with lower consumptions. If we do not do so, the transformer of the transformation station which the feeder belongs to, will be overloaded (the current exceed the maximum transformer withstanding value). When reducing the feeder current, adversely occurs that transformation station node voltage increases, so it is also necessary to take this fact into account. Otherwise, in the node there will be over-voltage. It also could be possible that the current sent to those parts with a greater number of consumers, needs to be increased for the system to work properly.

Generally, the feeder ends when a breaker switch is opened or when a higher voltage level is encountered. To distinguish the different feeder definitions, they can be coloured uniquely in the single line graphic. In this project, open breakers will be used to terminate the feeder domain. For this reason, it is necessary to incorporate breaker switches on the LV lines. They are placed just before the intersection node of two or more lines fed by different transformation stations of the system.

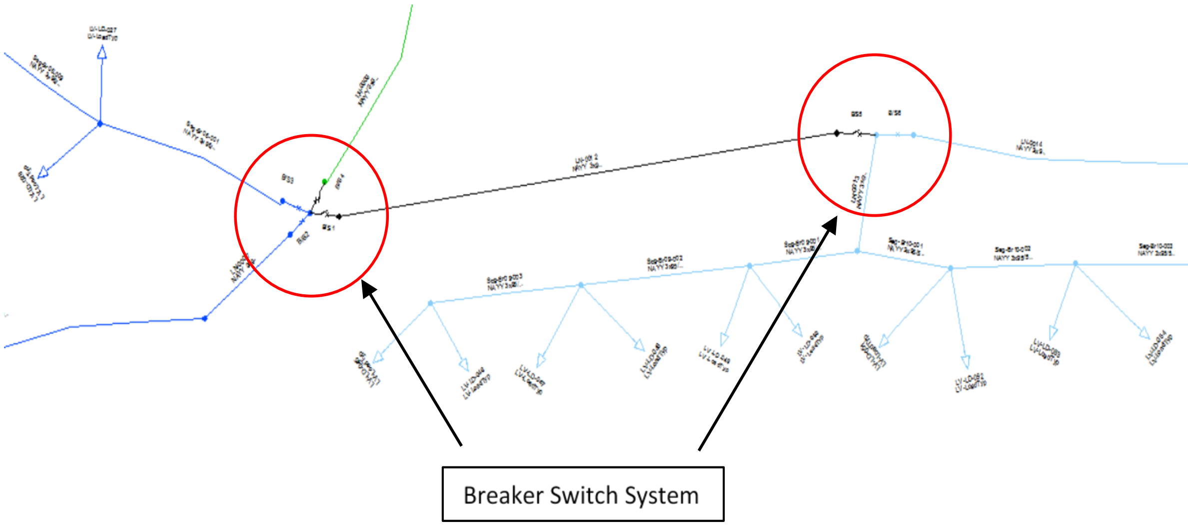

Figure 4.8.- Breaker switch system.

This disposition permits to separate the LV network in several parts. There exist various options to divide the system, since there are many alternatives when opening or closing the breaker switches.

The feeder set point is influenced by the zone scaling. This means that the current or power flow as calculated by the load-flow could differ from the set point in the feeder dialogue when the busbar where the feeder is defined is part of another zone. In this project, a feeder just operates in a single zone.

In order to verify that everything runs in the correct way, several load flows have to be performed during the modelling of the feeders. This step, of course, has to be made before introducing the PV panels on the network. Once the system is perfectly adjusted and no error or warning messages appear on the 'Output Window', where the program displays the results of the simulations, after performing the load flow calculations, the first part of the project will be done.

That means that a model of the real existing system will be reached. Therefore, the program will be ready to introduce new power sources which will modify the actual values of the elements belonging to the real existing system. Several analyses will be performed to evaluate the impact of DG in the modelled network. Although the model which is being used belongs to a specific area, the results will reflect what would happen in any other place on which renewable sources of these characteristics were incorporated.

4.2.2.- Zones.

In some applications of the program, as for instance the 'Quasi-Dynamic Analysis' tool, it is interesting to group all feeders belonging to the same TC. This action will allow the user to perform analyses which includes all elements of the LV network which are fed by such TC. In other words, these elements will determine geographical regions of the system which are receiving their energy supply by the same TC. As there are five different transformation centres, there will be five different zones. These five zones cover the whole LV network.

The function is called 'Zone' and can be easily activated in just two steps:

- First, all the desired components of the network have to be selected on the single line diagram
- Next, by right clicking on the mouse, 'Define Zone' must be selected in order to declare that such components belong to the new defined region.

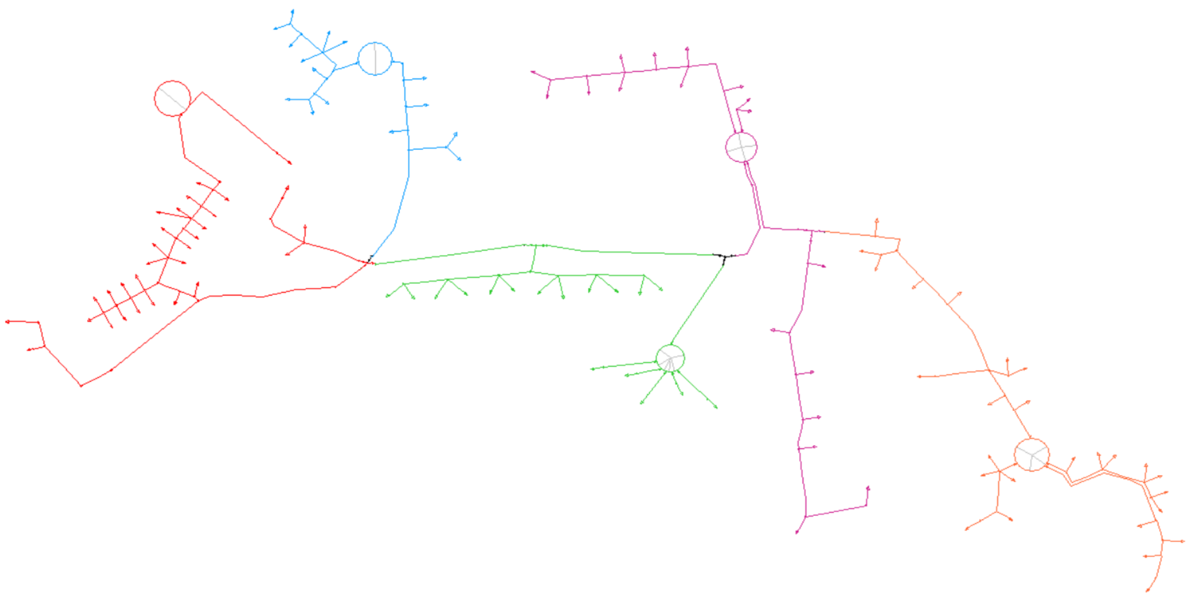

Figure 4.9.- Zones' domains.

This tool will be really useful for the analysis part, since it allows to 'divide' the LV network into several parts, and perform individual studies of each part fed from a single TC. Otherwise, only complete grid analyses could be performed.

4.2.3.- Variations and expansions.

Once the system has been properly adjusted and everything works correctly, the solar photovoltaic arrays will be added gradually to increment little by little the new generated power. The program includes 'Photovoltaic Systems' (PV systems) to represent this generation sources.

To carry out this action, *PowerFactory* includes a very useful tool, called 'Variations and Expansion'. It allows the user to incorporate to the created system more elements that store and implement required changes to a network and can be easily activated or deactivated. These objects permit the user to perform, in a very flexible way, the desired analyses, as several network configurations can be used. The term 'Variation' is used to collectively refer to Variations and Expansion Stages.

For this project, this idea results very attractive, as it permits the user to control the number of PV arrays working in the base system, just by creating different variations with different number of panels, placed in different sites of the network. The idea is to increment progressively the number of PV systems, so new variations will include the solar panels included in previous variations.

Some interesting aspects of variations are the following:

- The difference between variations and expansions is that an expansion is included inside a variation. Several expansions can be introduced inside a variation. The new expansions include the modifications defined in the previously created expansions.
- If the user wants to make changes directly on the base network model, no variation must be activated.
- This tool also allows to change, inside a variation, the characteristics of the required elements defined in the base model and do not store this changes outside the variation. This feature can be useful if some elements are not adequate (overloaded for instance) when increasing the number of generating sources, and it is necessary to change some of its data to carry on with further analysis.
- Several variations can be activated at the same time but there can only be one recording expansion stage per study case (modifications are stored just in one expansion when several are activated).
- When a Variation is inactive, it’s graphic is shown on the ‘Single Line Graphic’ in pale yellow.

To define a new variation, first the user has to insert a ‘New Variation’ from the ‘Data Manager’ menu. Then, the name of the created variation has to be defined. In this project, variations will be named as ‘PV-X’, where ‘X’ is the number of the variation (PV-1, PV-2, and so on). A colour can be selected to highlight the variation when it is activated. Finally, the ‘Study Time’ has to be defined, for the program to follow a chronological order of the different variations.

When a variation is defined, an expansion is automatically created. It is necessary to define the times when expansions are created. In this way, the user will be able to control properly the changes made in the previously defined expansions because they will be added in chronological order: "The 'starting' and 'completed' Activation Time are set automatically according to the Expansion Stages stored inside the Variation. The 'starting' time is the activation time of the earliest Expansion Stage, and the 'completed' time is the activation time of the latest Expansion Stage". [20]

In this figure, it can be seen in blue colour the activated PV-systems in the model. The light-yellow ones belong to another expansion, which is not activated at this moment.

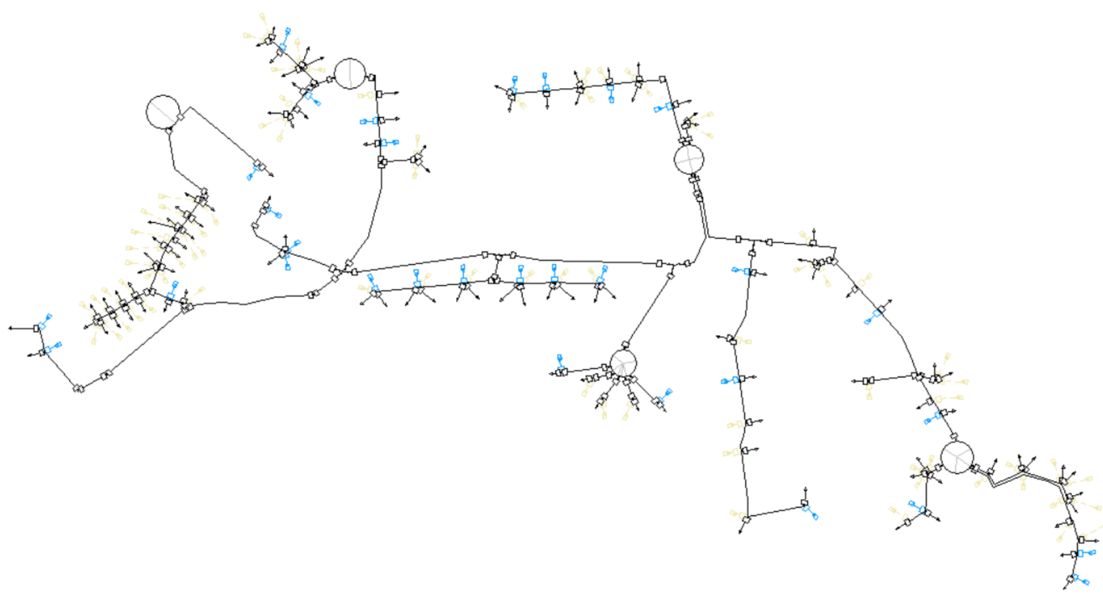

Figure 4.10.- Medium level of PV introduced to the LV network model.

In summary, the study time will determine which expansion stages are active: if the study time is equal to or exceeds the activation time of an expansion stage, it will be active. The study time can be changed in order to set the active expansion stages in the 'Date/Time of Calculation Case' icon, and as a consequence, set the 'Recording Expansion Stage', which is the latest expansion activated.

A 'Variation Scheduler' can also be used. This tool allows the user to determine which expansions are active, independently from its starting times. This function is useful when a non-chronological order has to be followed.

4.2.4.- Photovoltaic systems.

The PV system is an easy-to-use model based on the Static Generator element. The PV system element models an array of photovoltaic panels, connected to the grid through a single inverter. This disposition is ideal for LV networks, as it allows to include a reduce number of solar panels with a predefine inverter.

The main difference with the static generator, is that the PV System provides an option to calculate the active power generated with this devices, by inserting the necessary information according with solar parameters [20]. The option of inserting directly the active power that these elements generate, it is also available by using the 'Active Power Input' mode.

If preferable, the 'Solar Calculation' option can be chosen, and used to automatically calculate the active power according to solar parameters, as mentioned above. On this mode, the user has to define the solar panel type and other necessary data such as the arrangement of the solar array, the local time and date, and optionally irradiance data.

The software uses the following expressions to calculate the output active power, when the 'Solar Calculation' option is enabled:

$$P_{panel} = \frac{E_{g,pv} P_{pk,panel} \eta_{rel} \eta_{inv}}{E_{STD}} \tag{4.2}$$

And:

$$P_{system} = P_{panel} \cdot num_{panels} \tag{4.3}$$

Where:

- P_{panel} is the active power output of the panel in kW, after the inverter.
- P_{system} is the single system active power output in kW.
- num_{panels} is the number of panels per inverter.
- $E_{g,pv}$ is the global irradiance on the plane of the array in W/m^2.
- E_{STD} is the standard irradiance value of 1000W/m^2.
- $P_{pk,panel}$ is the total rated peak power of the solar panel in kW.
- η_{rel} is the relative efficiency of the panel, unit-less.
- η_{inv} is the efficiency factor of the inverter, unit-less.

In order to obtain the global irradiance on the panel surface, which is the term used to determine the amount of incident power per surface unit, several calculations have to be performed. The rest of the parameters mentioned above are characteristic data of the solar installation.

When modelling the solar array, the user has to introduce some input data on the ‘PV system’ dialog. The following parameters have to be defined:

- Latitude of the site.
- Longitude of the site.
- Local Time Zone.
- Mounting System.
- Orientation Angle.
- Tilt Angle.
- Efficiency Factor.

For this project, the first mode, which allows the user to define directly the output power of the ‘PV system’, will be used. This method results perfect to evaluate the integration of DG into the low voltage network in the program, since it allows to control in an easier and clearly way the power generated by the new sources.

The rated active power of each PV panel, intended for domestic applications, varies between values ranging from 0.1 to 0.3 kW, depending on the manufacturer. Photovoltaic installations can produce enough energy to cover the household demand. This fact implies that the installed power of the domestic installations can reach 5 kW or even more. Of course, the photovoltaic installation of each house is composed by several solar panels in order to increase the installed capacity. In the program, the whole particular PV installations (including the inverter) will be represented by a single PV-system.

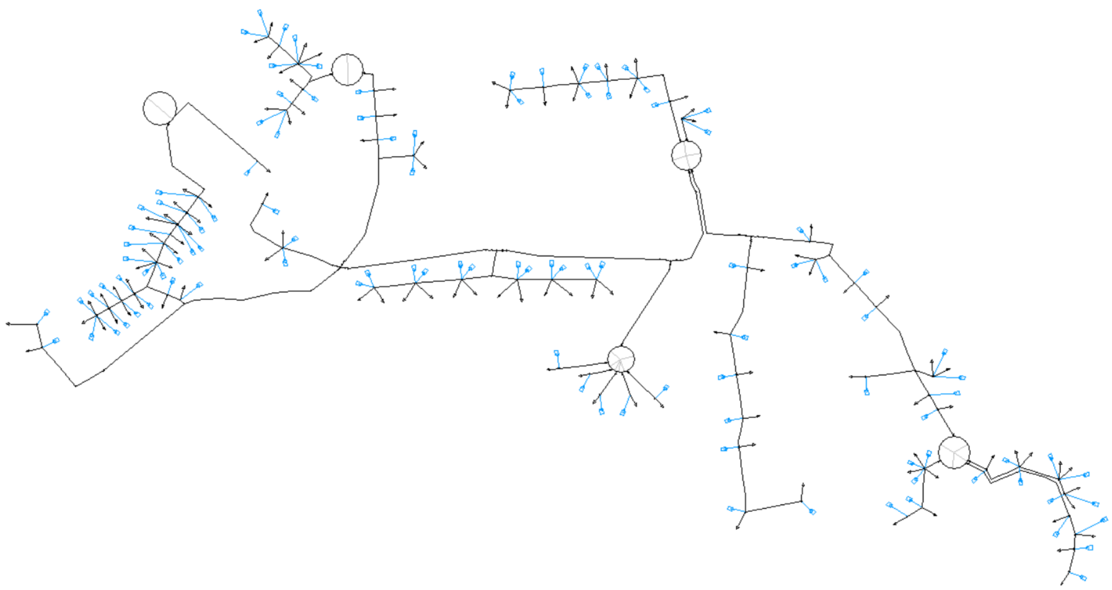

Figure 4.11.- High level of PV introduced to the LV network model.

For the evaluation of low voltage networks with high density of distributed generation, it is interesting to analyse the worst case. This means that the solar panels should be producing energy in a very sunny moment, as is to say, working with values close to its rated power. For this reason, the rated active power defined on each ‘PV system’ of the program will be placed between 3.5 and 6.5 kW, assuming that some part of the generated power is being consumed at the same time of producing.

4.3.- SIMULATING TOOLS.

Once the modelling stage have been completed, it will be possible to start with the analyses commented in section 3. In this project, several functions will be used to perform the necessary studies and obtain the output results, which will be represented by plots.

In this section, a complete explanation of such tools is performed, as well as a brief theoretical framework intended to understand well the analyses.

4.3.1.- Load Flow Analyses.

During the process of modelling of the network, it is necessary to check frequently that everything in the program works properly (voltages at nodes, currents, power transmission, etc.) and no error messages appear on the output window. This is an essential task when working with large networks with several components. Otherwise, the existing errors will be more difficult to find and correct. It is also fundamental to make analysis of these network parameters when the PV-systems are integrated, and make comparisons between the different situations (variations) studied.

To make sure that everything is going right, or in the case of having errors correct them, a specific function called ‘Load Flow Calculation’ will be used. Load flow calculations are used to analyse power systems under steady-state non-faulted (short-circuit free) conditions. Where steady-state is defined as a condition in which all the variables and parameters are assumed to be constant during the period of observation. We can think of this as ‘taking a picture’ of the power system at a given point in time. [20]

Basically, a load flow calculation will provide us information about the active and reactive power flows for all branches, and the voltage magnitude and phase for all nodes, although many other parameters can be displayed. The results obtained represent the values of the measured parameters in a determined moment of the day, since load flows are not calculated with respect to time.

In this project, the generator sources, as well as the loads, are known and defined in the program. This configuration allows to, from the input data of these generators dispatch, provide the active and reactive power of all loads of the model. The results of the load flow calculation should represent a system condition in which none of the branch or generator limits are exceeded. It is also important to take a look at the different nodes of the system and be aware of voltage drops, especially at the end of the branches. This fact, has to be checked frequently when modelling the network, as explained before, in order not to accumulate errors.

The results obtained after the performance of the load flow calculation, are displayed on the single line graphic by means of 'test boxes'. However, special reports, which collect the desired information of the desired component, can be drawn. For this project, two main tools will be used in order to get the specific information:

- Output Calculation Analysis (command): several reports can be created by using this tool. Some global analysis can be made easily, such as the 'Total System Summary' report, which includes the load flow information of the main components of the system. Another useful option is the 'Complete System Report', which outputs the results for all elements. This function includes an option which allows the user to define the element or elements that are going to be evaluated. That report will display just the results of that element/s.
- Verification Report: this fast function is activated by selecting inside the options of the 'Calculate Load Flow' dialogue. A report containing a table with a list of overloaded power system elements and voltage violations will be displayed directly on the output window. The user has to define the maximum allowable load for elements, as well as the lower and upper voltage limits.

These two report types, have to be performed after the load flow calculation, otherwise there will be no information to show. The results obtained can be exported from the output window to an excel file.

4.3.2.- Voltage Profile Plots.

After the performance of a load flow, it can result annoying to check the output voltage of every node one by one (on the single line diagram) in order to make a study of the voltage profile. This program includes a useful tool which allows the user to create a plot for the voltage profile and avoid the task mentioned above.

This function is called 'Voltage Profile Plot' and shows the voltage profile of a radial network based on the networks load flow results. The Voltage Profile Plot is directly connected to a feeder object defined in the network, so it can only be created for parts of the system where a feeder is assigned. Fortunately, in this project all the LV network has been previously divided by several feeders, which define different radial areas of the mentioned network.

For radial power systems, voltage regulation practices are based on a single source of power (the substation and the transformation stations) and the power taking only one path from the substation to all loads on the system. This condition leads to the assumption that the voltage will always drop from the beginning to the end of the feeder as the distance from the substation increases. The only exception to this assumption is when there is too much reactive compensation (a capacitor bank can causes a rise in voltage). The integration of DG onto the radial distribution system will impact on this basic assumption, since the grid loses its radial distribution behaviour (high voltages may be caused by reverse power flow). [17]

As mentioned above, several cases will be evaluated during this project, as different models are used when the PV-systems are integrated on the LV network. This function will be interesting from the point of view of comparing the voltage profiles generated by implementing load flows on the base model and on further modified models. This analyses will show if voltage conditions are out of the normal operating range when introducing the DG sources.

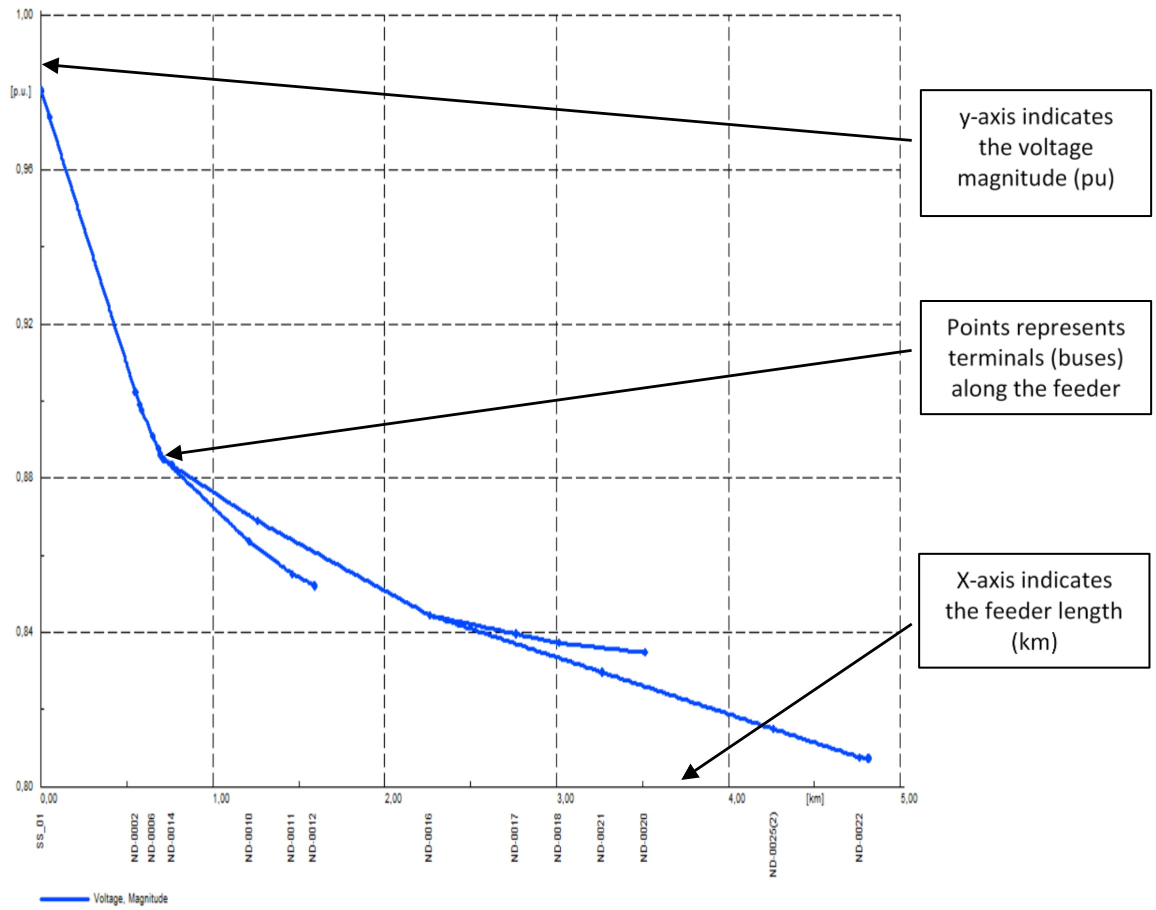

Figure 4.12.- Voltage profile plot.

The voltage profile plot shows the voltage of terminals or busbars along the length of a feeder. The variable shown by the plot can be changed. At first, it will display the voltage 'p.u.' on the 'y' axis and the distance covered by the feeder on the 'x' axis.

4.3.3.- Quasi-Dynamic Simulations.

Once all concepts of this chapter until now have been understood, it is possible to explain the 'Quasi-Dynamic Simulations'. This *PowerFactory* function is used to create more realistic representations of the electrical system as it allows to perform evaluations of the model during a whole day and thus, identify and evaluate the worst operational condition cases. This will introduce some changes to some of the parameters explained in previous sections.

This tool allows to define the energy consumption along the day of each user (LV-load) following a predetermined time-consumption data (which can be easily represented in a graph to obtain the time-consumption plot). The same occurs when talking about the PV-systems generation: they will produce different amount of energy according with the moment of the day, since it directly depends on the solar radiation. The production of a very sunny day will be considered in order to evaluate what would happen if the generation could reach the installed capacity on the production peak hours. This scenario, combined with moments with low consumptions, will lead to the worst operational condition cases from the point of view of the electrical system and it will represent the most interesting case of study.

In order to evaluate the behaviour of the system, with respect to load flow calculations, quasi-dynamic simulations will be used. This function principally performs several load flows in order to obtain a complete study of the model during a complete day, taking into account the different consumptions during the day and the different generation levels, providing a more realistic situation. Therefore, in this project we will use this tool to make evaluations of data provided by load flow calculations during a whole journey: loading levels of transformers, principal lines and nodes, busbars, etc.

Once these parameter values are modified on the program, all consumptions and generations will be modified with respect to moment of the day. This fact does not mean that all previously defined parameters on the sections before are not valid. New values will be defined satisfying a percentage of that previously defined values. As is to say, what it was defined at the beginning for this elements corresponds to the ‘rated values’ of the consumption and generation values, and form that values, percentages will be applied to them according with the moment of the day. Therefore, it will be necessary to start using the ‘Date/Time of Study Case’ command for the analysis on which it results interesting to evaluate just a determined moment of the day (otherwise, several analyses will be implemented). That analyses will be those regarding with the protections device elements and the introduction of harmonic contents to the network. On these analyses, specific times will be set on the time command mentioned above, of course always evaluating the worst cases (highest production levels combined with low consuming levels).

To prepare the scenario for the quasi-dynamic studio, first of all, it is necessary to introduce the values of the daily consumption and generation (in percentage terms) in both, the LV-load elements and the PV-systems respectively:

- LV-load: first, the LV-load options dialog must be opened. Then, on the 'Basic Data' field, where the fixed load value has been determined, now it is necessary to choose the 'Add Time Characteristic' option. This action will automatically open a window on which the consumptions for each hour of the day have to be specified. In order to determine the consumptions, information about these field have been searched on the 'Red Eléctrica de España' (REE) webpage [22]. An excel document where some average consumption profiles along the day, determined for each hour, have been used to have a reference of such values. These values are exposed on the following table, accompanied of their respective graph, which represents the consumption curve versus time:

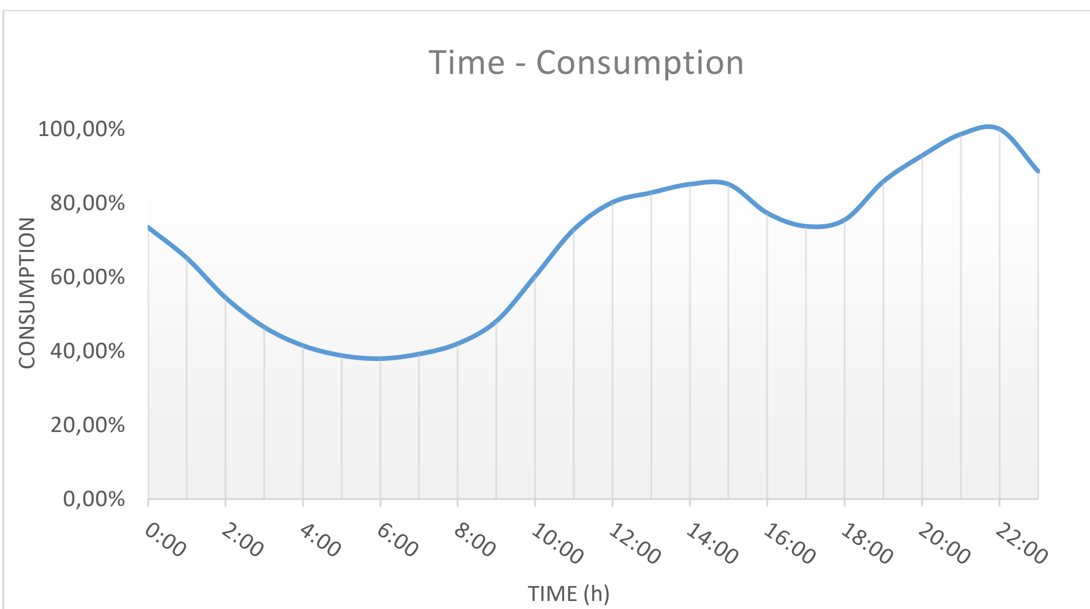

Figure 4.13.- LV loads time-consumption curve.

- PV-systems: similar to the consumptions previously determined, the energy generation along the day has to be defined. Once the PV-system dialog has been opened, we must select the 'Load Flow' field where the power generation have been previously defined (as explain in section '4.2.4.- PV-systems', between 3.5 kW and 6.5 kW), now, by right clicking on this value, the 'Add Time Characteristic' option must be selected. This action will automatically open a window on which the generation for each hour of the day have to be specified. In order to get a reference for the energy generated along the day, the data base of the daily solar radiation has been used [23]. These values are plot on the following graph, representing the time-generation curve:

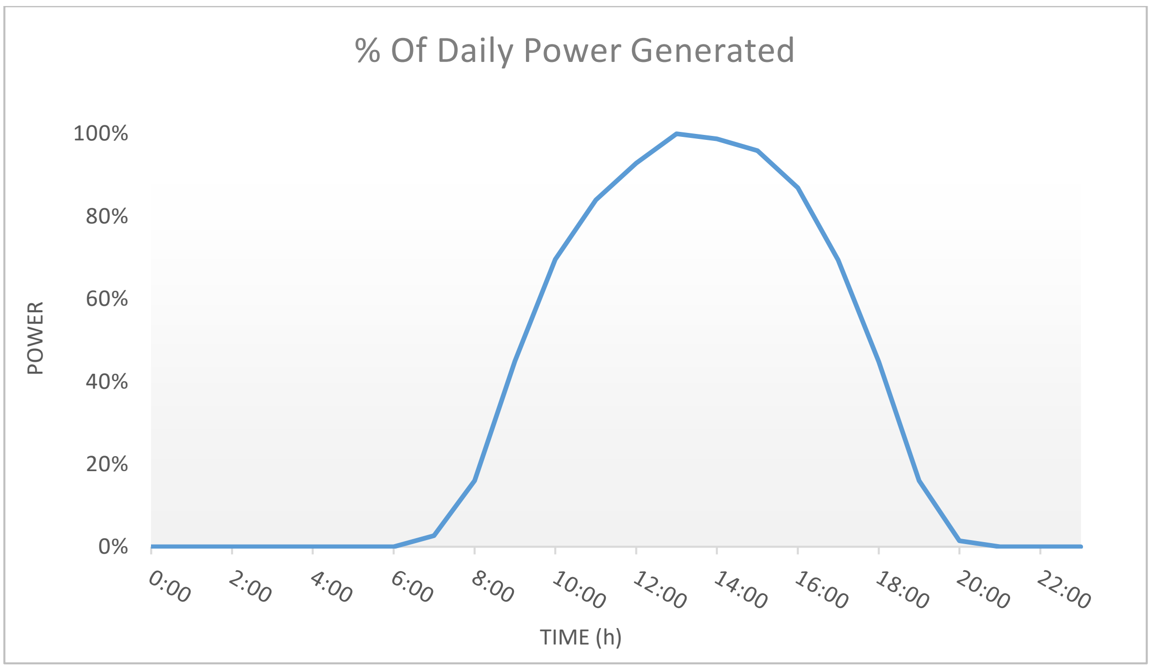

Figure 4.14.- PV time-generated power curve.

As mentioned above, these new values, that will change according with the moment of the day, are a percentage of the maximum value determined on the 'LV-Load section'. That is: the users will consume this exact value at the peak consumption hours (100% of consumption). The rest of the moments a lower consumption will take place, as represented on Figure 4.13. Although the percentages are the same for all loads, different consumptions will be maintained, since different 'rated consumptions' have been defined for each load.

The same occurs with the PV-systems production: the peak generation hour will correspond to the 'rated generation' level specified on the PV-systems section. Again, the production of each PV source will be different from others, since that values along the day are a product of the consumption percentage (different for each hour) and the particular 'rated generation' of each load.

4.3.4.- Short-Circuit Analyses.

The rest of analysis performed in this project until now, have been implemented under steady-state non-faulted conditions, as is to say, without short-circuit failures. A short-circuit is produced when two or more points between which there is a potential difference are contacted with one another. It is characterized by high circulating currents, which can produce irreparable damages to the equipment of the system. This failure will be used in this project to analyse the behaviour of the protection elements belonging to the transformation stations and substation (fuses and relay).

There are several short-circuit calculating options, but in this project, the 'Complete Method', available inside 'Short-Circuit Calculation' dialogue, will be used. The complete method (sometimes also known as the superposition method) is, in terms of system modelling, an accurate calculation method. The fault currents of the short-circuit are determined by overlaying a healthy load-flow condition before short-circuit inception with a condition where all voltage supplies are set to zero and the negative operating voltage is connected at the fault location.

The initial point is the operating condition of the system before short-circuit inception. This condition represents the excitation conditions of the generators, the tap positions of regulated transformers and the breaker/switching status reflecting the operational variation.

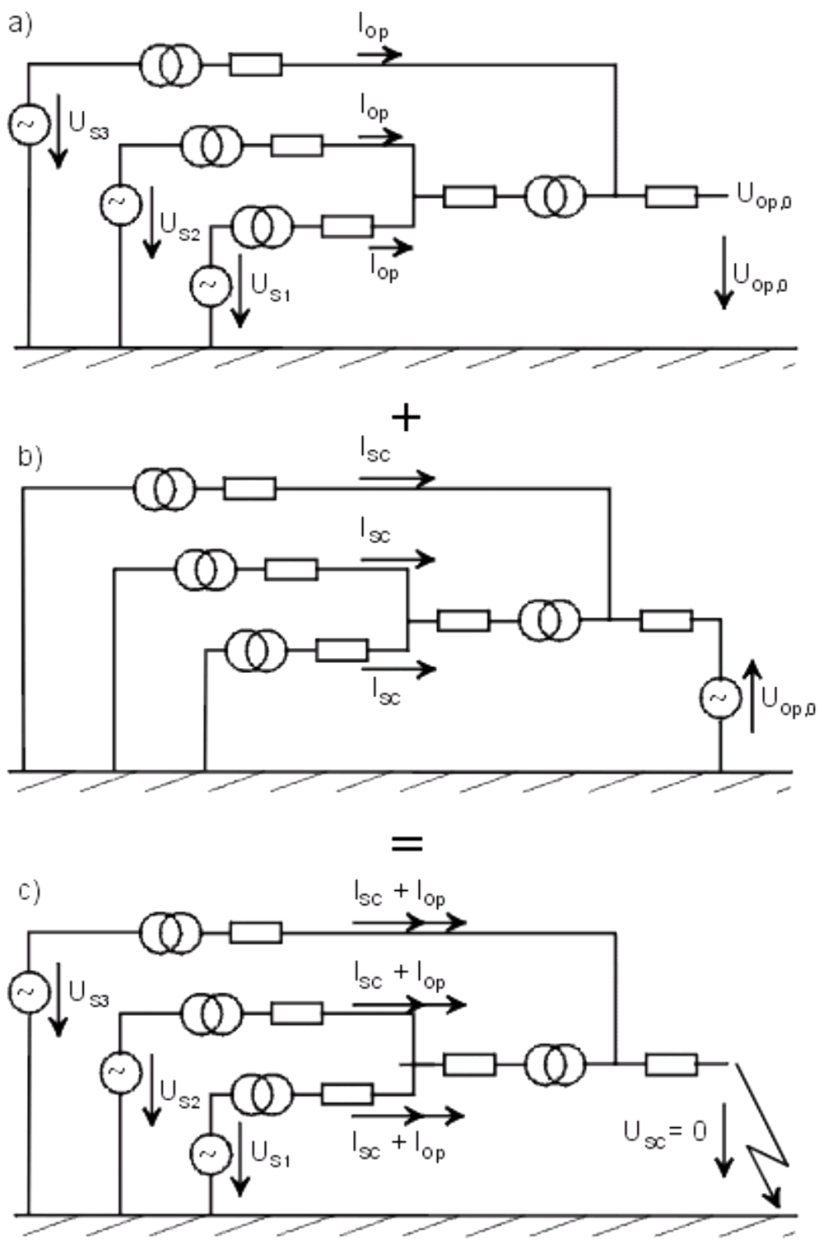

Figure 4.15.- Short-circuit calculation: 'Complete Method' representation. Source: DigSilent.

From these pre-fault conditions the pre-fault voltage of the faulted busbar can be calculated. For the pure fault condition, the system condition is calculated for the situation where, the negative pre-fault busbar voltage for the faulted bus is connected at the fault location and all other sources/generators are set to zero. Since network impedances are assumed to be linear, the system condition after fault inception can be determined by overlaying (complex adding) both the pre-fault and pure fault conditions.

4.3.5.- Time Overcurrent Plot.

The program includes an interesting tool intended for graphical analysis of protection systems which show multiple relay and fuse characteristics on one diagram. This function is called 'Time-overcurrent Plot', and can be easily implemented by right clicking the mouse on the protection element which the user wants to analyse.

These plots are used to determine relay tripping times by means of time-current graphs, and hence assist with protection coordination and the determination of relay settings and fuses' characteristics. For this project, is necessary to check that the coordination of the fuses belonging to the transformation stations and the relay of the substation are correct.

To evaluate more than one protection device at the same time, there exists a special function which allows to plot both elements together in a graphic. The user just has to implement a first over current plot and then select 'Add to Time-Overcurrent Plot'. This will open a list of previously defined protection representations from which any one can be selected to add the selected device to.

The time-overcurrent plot constitutes an essential protection analysis tool for the evaluation of load flows (steady-state non-faulted conditions) and short-circuit calculations (faulted conditions). The plots show the results automatically as a vertical 'x-value' line through the graph. If the intersection of the calculated current with the time-overcurrent characteristic causes the shown characteristic to trip, then the intersection is labelled with the tripping time.

Therefore, this function will be used in this project to evaluate the coordination of the protections, and to analyse the behaviour of the protection system when a short-circuit is produced. [20]

Interpretation of relay time-current plots:

A time-current curve plots the interrupting time of an overcurrent device based on a given current level. These curves are related with the electrical overcurrent interrupting devices, such as fuses and relays. The shape of the curves is determined by both the physical construction of the device as well as the settings selected in the case of adjustable relay. The time current curves of a device are important because they graphically show the response of the device to various levels overcurrent (faulted conditions). The curves allow to graphically represent the selective coordination of overcurrent devices in an electrical system.

The time-current curve diagram plots the interrupting response time of a current interrupting device versus time. Current is shown on the horizontal axis using a logarithmic scale and is plotted as amps X 10^X. Time is shown on the vertical axis using a logarithmic scale and is plotted in seconds X10^X. [24]

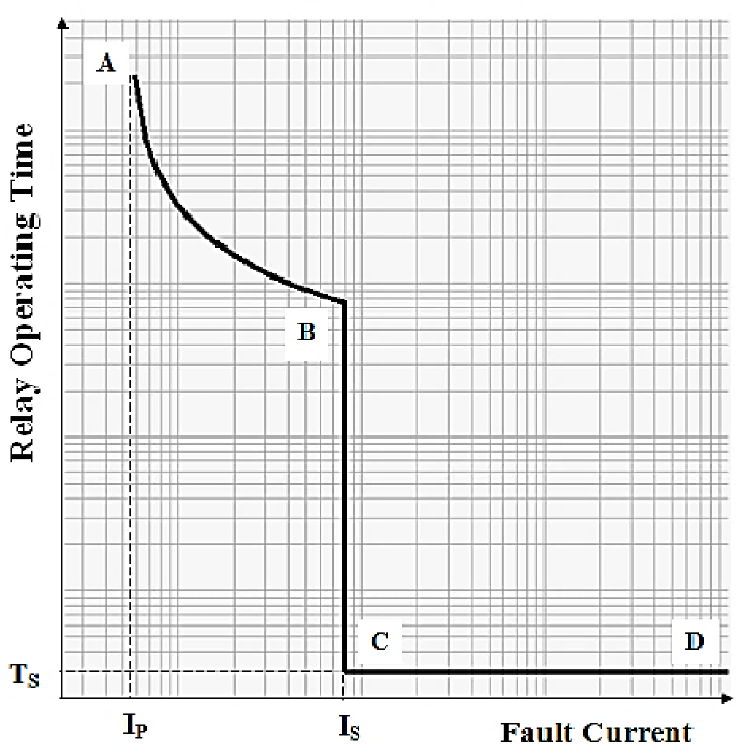

Figure 4.16.- Time-current plot. Source: ResearchGate.

The picture above shows current time characteristics of an over-current relay. Curve A-B is the normal inverse characteristic of the relay and is used to protect apparatus from excessive currents less than severe short circuit fault levels but large enough (I>), that if allowed to sustain for a certain period would damage the apparatus it is meant to protect. Moreover, Curve B-C-D is meant for instantaneous, high speed clearing of severe short circuits (I>>) by reducing the clearing time to only Ts. Currents before Ip will not be interrupted as they are not large enough to cause damages. The operating currents will be displayed as vertical lines on the analysis. In this way, it will be possible to determine the operating region. [25]

The normal or standard inverse characteristic of the relay is calculated as follows:

$$t = \frac{k}{\left(\frac{I_p}{I_s}\right)^{\alpha} - 1} \times \frac{T}{\beta} \tag{4.4}$$

Where:

- t is the operating time.
- I_p is the current value.
- I_s is the current set point.
- T is the time setting at I_p/I_s.

The parameters k, α and β are particular coefficients, which in this case their values are: [26]

k	α	β
0.14	0.02	2.97

Table 4.5.- Inverse characteristic parameters.

These coefficients have different values for other characteristic curves (very inverse, long time inverse, extremely inverse and ultra-inverse).

4.3.6.- Harmonic Analyses.

One of the most important aspects of power quality is the harmonic content of voltages and currents. For this project, this analysis results really interesting, since PV systems can introduce significant harmonic contents to the network. This fact is produced due to the current inverter, used to convert the direct current generated by the solar array into alternating current at the convenient frequency that can be fed into a commercial electrical grid.

First of all, a brief overview of electrical harmonics will be given:

A harmonic current or harmonic voltage is a sinusoidal signal whose frequency is an integer multiple of the fundamental frequency of the supply signal. According with Fourier, any periodic signal, no matter how complex, can be decomposed into the sum of sinusoidal signals whose frequency is a multiple of the fundamental.

$$s(t) = \sum_{1}^{n\to\infty} (A_0 + A_1 \cdot \sin(2\pi f_1) + A_2 \cdot \sin(2\pi \cdot 2f_1) + \cdots + A_n \cdot \sin(2\pi \cdot nf_1)) \quad (4.5)$$

This mathematical expression allows to decompose any signal into a sum of sinusoidal signals, where f1 is the frequency of the fundamental component and A0, A1, A2, ... are the amplitudes of the various sinusoids.

In general, harmonics are produced by non-linear loads, which means that its impedance is not constant (is a function of the voltage). These non-linear loads, in spite of being fed by a sinusoidal voltage, absorb a non-sinusoidal current, making the current becomes out of phase with respect to the voltage. To simplify calculations, it is considered that the nonlinear loads behave as current sources, injecting harmonics on the network. The components that often cause harmonics are: variable speed drives, electronic ballasts, computer equipment and generally any type of active component, such as diodes, transistors, thyristors, etc. [27]

A series of concepts is defined below. They result interesting for the analysis that will be carried out later:

- Harmonic order (HD): represents the integer number of times that the frequency of that harmonic is greater than that of the fundamental component, that is, the ratio of a harmonic frequency and the fundamental frequency.
- Harmonic spectrum: allows to decompose a signal into its harmonics and represent it by a bar chart, where each bar represents a harmonic with a frequency, an effective value, magnitude and phase lag.
- Harmonic Distortion: the harmonic distortion of a waveform represents the harmonic content that has that signal. The amount of distortion which presents a waveform of voltage or current is measured by an index called total harmonic distortion (THD) defined for voltages and currents by equations (4.6) and (4.7), where V_1 and I_1 are the fundamental components of voltage and current respectively, and V_h and I_h 'h' harmonics. All in effective terms.

$$THD_v = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \tag{4.6}$$

$$THD_i = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \tag{4.7}$$

Finally, it should be mentioned that the power factor is closely linked to harmonic distortion. The greater the harmonic distortion, the higher the total current (I_s) is with respect to its fundamental component 'I_1' (since the rest are harmonics), so that the power factor decreases.

$$PF = k \cdot \frac{I_1}{I_s} \tag{4.8}$$

Therefore, the presence of harmonics in the current has a very negative effect on the efficiency at which the equipment provides power to the network and is a very important aspect to control not only at security but also the level of effectiveness.

The *PowerFactory* harmonics functions allow the analysis of harmonics in the frequency domain, by means of 'Harmonic Load Flows'. The harmonic load flow calculates actual harmonic indices related to voltage or current distortion, and harmonic losses caused by harmonic sources (converters). In the harmonic load flow calculation, *PowerFactory* carries out a steady-state network analysis at each frequency at which harmonic sources are defined.

In order to work with this analysis mode, the 'Tool Box' icon of the program must be changed to 'Harmonics/Power Quality'. This action will allow the user to have all harmonic analysis options available.

To perform a harmonic load flow, some parameters must be defined on the 'Harmonic Load Flow' dialog command. There are several fields to cover: [20]

- Network representation: for this project, the 'Balanced' option will be chosen. In the case of a symmetrical network and balanced harmonic sources, characteristic harmonics either appear in the positive sequence component (7th, 13th, 19th, etc.), or in the negative sequence component (5th, 11th, 17th, etc.).
- Calculate harmonic load flow: This option will perform harmonic load flow calculations for all frequencies for which the inverters are defined. These frequencies are gathered automatically prior to the calculation. The results can be then used to make graphical representations by means of bar charts.
- The nominal frequency is set to 50 Hz, as only fundamental harmonic frequencies can be calculated. The output frequency is also set to 50 Hz in order to have a proper display of the results on the single line graphic.
- Harmonic order: in this case is set to 1, as the harmonic order multiplied by the nominal frequency always equals the output frequency.

Once the harmonic load flow is executed, a tool called 'Filter Analysis' can be used to create a report with the results obtained. It outputs a summary of the harmonics for the terminals/busbars and branch elements at the frequency specified before, in the output frequency field of the harmonic load flow command.

Before performing harmonic load flow, it is necessary to define the harmonic contents generated by the inverter of the solar arrays. These harmonic injections are defined using the 'Harmonic Sources' field of the 'PV-system' dialog, inside 'Harmonic/Power Quality'.

Then, the 'Balanced, Phase Correct harmonic sources' option must be selected. In this way, the user will be able to define the magnitudes and phases of positive and negative sequence harmonic injections at integer harmonic orders.

After the performance of the harmonic load flow calculation, many results for the network are displayed. On this project, the harmonic distortion and the total harmonic distortion of the voltage will be analysed at the busbars of the TCs.

The harmonic distortion of a current or of a voltage can be quantified in terms of the HD. To describe the overall distortion, the THD index has been introduced. All distortion indices are described by their equations for the current, but may be similarly described for voltage distortion.

In order to display the waveform of a voltage or a current harmonic load flow calculation, the waveform plot is used. The harmonics are typically emitted by a harmonic voltage or current source, as occurs with the PV-systems.

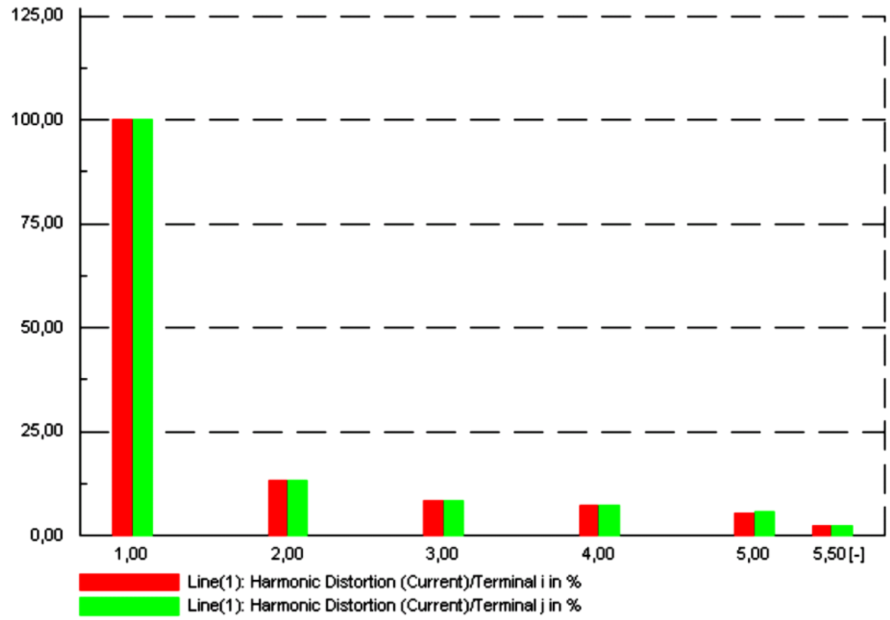

Figure 4.17.- Harmonic Distortion plot.

In this plot, a waveform is generated using the magnitude and phase angle of the harmonic frequencies. With this diagram, a variable such as the voltage or current, which is defined in a harmonic source (a power electronic device in this case), can be easily shown as a time-dependent variable. This way the real shape of the voltage can be seen and analysed.

4.3.6.- Comparison between calculations.

As explained before, the base model of the real network simulated on the program will be filled progressively with low voltage DG sources, by terms of PV-systems. These approach will lead to several variations or expansions, which in turns will generate different result values after the performance of a load flow, short-circuit calculation, etc. The problem is that, when activating an expansion, the previously displayed results are automatically delated. This fact produces an uncomfortable way of working.

The program has available a special tool called 'Comparison Between Calculations' which allows the user to see the output results, displayed on the single line graphic or the output window, comparing two similar cases. In this project, this function will be used to compare the results obtained between the base network model and the further models created by incorporating PV-systems to the base model.

The user will have to follow the steps below in order to use this tool:

- To start with, the desired calculation has to be performed. This will create the first case of the comparison.
- Then, the 'Comparing of Results' on/off button must be pressed. The results of the first calculation are ’frozen’. All subsequent calculations will then show their results as deviations from the first calculation made.
- If relative results are also required for a particular calculation report (displayed on the output window), as for example a specific busbar report, that report has to be generated for the first case by pressing the icon of 'Output Calculation Analysis' on the main toolbar and selecting the required report.
- The next step consists of activate the desired variation or expansion, and to perform the second calculation.
- The result boxes will show the relation between the two different scenarios. If other cases are calculated, the program will compare the latest results with the first case.

The output results provided by this function, as explained above, will be intended to compare similar cases, which differences become of interest. The way in which the program will show the difference between both cases, will be in a percentage form. For example: if we evaluate the behaviour of a node on which, at the first case the active power is 2 kW and in the second case is 2.3 kW, the program will display: 13%. This value represents the relation between these two values in form of percentage: $\frac{2.3-2}{2.3} \cdot 100$.

5. Simulations and results.

On the previous chapter, a description of the elements and components of the electrical model were included and explained in detail, as well as all the necessary functions and tools needed to make a successful evaluation of the system.

Once the base model has been created and verified that everything works properly, an expansion consisting of large number of solar arrays were included. This scenario can be enabled or disabled whenever it is needed, and there also exists the option of create more expansions to make the desired variations (include or remove elements).

5.1.- SIMULATING SCENARIOS.

In order to analyse the behaviour of the network if a high density of distributed generation (in terms of PV-systems) were integrated within the low voltage network, several scenarios will have to be tested. This models will vary according to the level of incorporated DG. Therefore, the study cases will be:

5.1.1.- Case 1: base model.

The aim of the base model is to represent the real existing electrical network of the study site. This means that no solar panels have been included yet on the system.

It has been created following the indications given by the distribution company. Although not all the necessary information could be obtained, the base model constitutes an accurate representation of the real one and thus, the results obtained will be really close to the existing ones. This fact is also important for further operating scenarios, since they will be constructed over the base model.

The base model will be used to compare the results of the current system with those obtained when the solar panels are included into the LV network. In this way, it will be possible to evaluate the issues that a high level of DG could generate and introduce on the real existing system.
Therefore, these normal operating conditions of the real network will be represented frequently in order to provide a reference of comparison for the rest of cases.

5.1.2.- Case 2: medium density level of DG model.

The second model represents a scenario on which half of the users, more or less, would have a PV installation interconnected with the LV network. A first expansion was created in order to integrate the solar panels on the base model. On this case, not all branches or feeders have the same number of PV-systems. This fact will lead to relevant differences between areas that have a greater number of DG with others on which there is a lower density of it.

On this system, the energy generated by the new DG sources never exceeds the demand generated by the LV loads (consumers). This approach makes that 'Case 2' constitutes an intermediate scenario between 'Case 1' and the final one, 'Case 3'. Therefore, it will be used to observe how the output results, obtained from the program, change when incorporating a medium level of DG on the site of study.

Although an important amount of energy will be integrated on the system, the worst operating conditions will not be achieved on this scenario. Hence, it will be studied whether the system could be prepared to operate under this conditions or not.

5.1.3.- Case 3: high density level of DG model.

On this model, a high penetration of PV-systems will be represented, creating another expansion, this time over the second model. This fact means that all consumers will have solar panels interconnected within the LV network, injecting the excess of energy produced to the electrical system.

This scenario will represent the worst network operational conditions, since large amounts of energy will be introduced (without control) to the network that all consumers use. Therefore, several analyses will have to be performed in order to evaluate the behaviour of the new hypothetical conditions by using the different types of simulations, explained on the previous chapter.

This model in turn, constitutes the most interesting case of study for this project, which tries to simulate and analyse a real network under extremely conditions from the point of view of DG. On this case, the PV generation will exceed in some moments of the day the load demand of the consumers. Hence, most important conclusions will be drawn by means of this model.

In order to compare results and draw conclusions in a more easy and visual way, several plots will be represented on the same graphic if possible. To do this, data from the output results (obtained from the program), will be exported to excel files, from which nicest representations could be achieved.

5.2.- SUMMARY OF ANALYSES TO PERFORM.

The analyses which have to be performed in order to obtain a proper evaluation of the possible issues of the system were explained in detail on the previous chapter. On this section, a summary of these analyses is exposed:

- Load Flows: This function simulates a normal operating situation of the case which is being analysed, as is to say, without any faulted condition. It provides information about the power flows of the system, as well as voltage and current levels at any point of the system.

It can be used to evaluate a certain moment of the day, by setting the time of study at the desired hour, or a special function called 'Quasi-Dynamic Simulations' can be used. This latter function will provide information about a complete day of network operation, according with the data introduced for the power consumption and PV generation, which varies with time.

- Behaviour of the protection elements: Short-circuit analyses will be used in order to know how the protection systems behave under the new operating conditions of the three different cases. In particular, they will be used to evaluate the performance of the relay belonging to the substation which feeds the whole MV and LV networks.

  Given that the new DG sources will introduce modifications to the grid operating conditions, the relay trip could be negatively affected. This fact is due to the variation on the current levels when a high penetration of DG is set. These new sources generate more energy than consumed in some cases, which increases the flowing current through the distribution grid. Several analyses will be carried out by using time current plots.

  In order to check the behaviour of the fuses, it is enough to watch over the current flowing through them. Its value cannot exceed their rated value; otherwise, the fuses will be overloaded.

- Harmonic Analyses: On this part, the voltage harmonic content introduced by the new generating sources by means of the converter used, will be studied.

  It will be tested whether the harmonic contents in the network exceed or not the maximum allowable values. This will be possible by using the THD and the HD for each rated frequency value.

5.3.- LOAD FLOW ANALYSES.

On this part, the behaviour of the whole systems and the main parts (substation, TCs, feeders, etc.) will be evaluated, under the operating conditions of the three different cases, by means of load flows.

As explained on previous chapter, several tools will be used in order to make a proper study of this matter. The main aspects that could be observed on the system when including the PV-systems are: the power flows through the different TCs and feeders, as well as the current levels; the reactive power flows and therefore the voltage levels on the different TCs and nodes of the system.

5.3.1.- Study of the power consumption, PV power generation and network power flows.

On this part, various analyses of the load consumption, the energy generated by the PV-systems and the power flows of the network, will be represented on a graph. The parameters will be represented with respect to time, since different consumptions and PV generating levels are produced depending on the moment of the day.

These three parameters (belonging to the same case) will be represented in the same plot in order to compare them in an easier way. These sections will be divided according to the location of the analyses: the whole system and the five different TCs. The three different cases will be included on each section.

5.3.1.1.- Analyses of the whole system.

First of all, an analysis of the complete grid is performed. On this study, a representation of the three mentioned parameter analysis is exposed on the following plots, according to the different cases:

- Case 1:

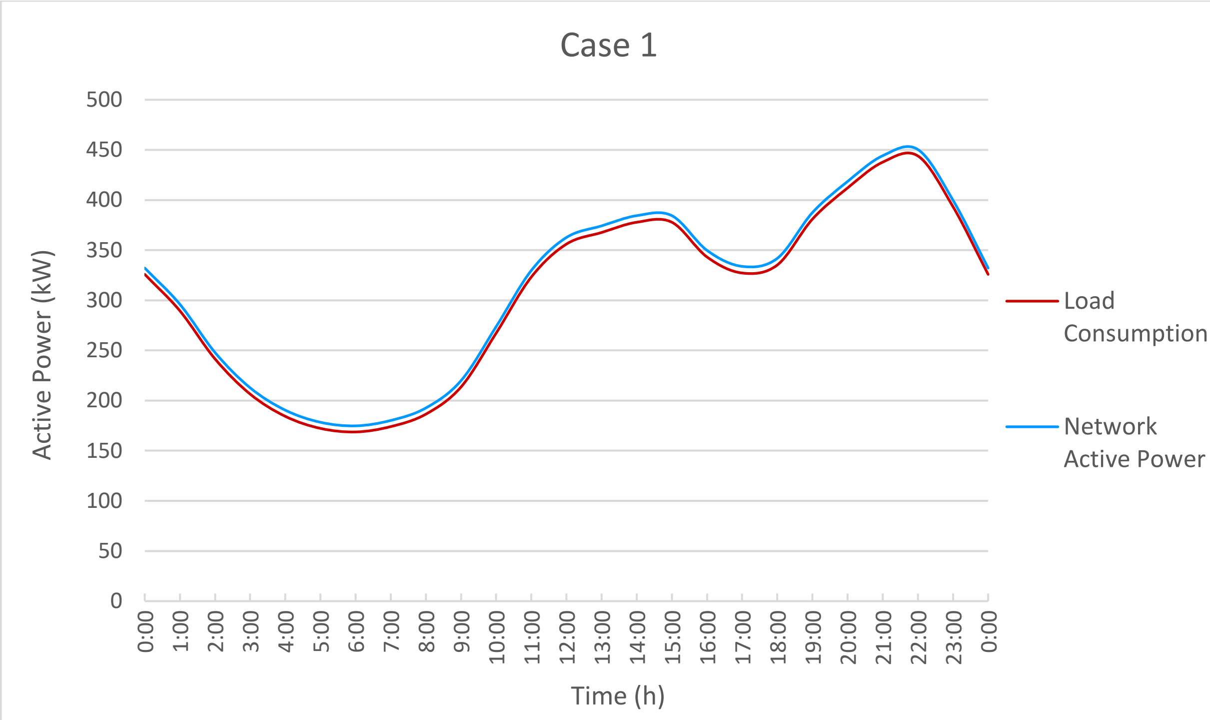

Figure 5.1.- Load consumption and network active power of the whole system during a complete day, without PV generation.

This first chart shows the load consumption curve, which represents the total consumption of the users, and the network active power flow curve, which provides information about the power flowing through the whole system.

It is known that the power supplied to the loads has to be exactly the same than the demand stablished by them at any time. It can be observed that there exists a difference between these two curves: the active power flow of the network is higher than the load consumption. This fact is produced because of the power losses generated by means of the distribution lines and other losses produced at some components, such as the transformers.

Therefore, the network has to provide more power than consumed, since part of it is lost in the process of transport from the generating point to the consumption point. This difference will be present in all cases.

On this graph, it can be seen that no PV generation curve has been included yet. Notice that the load demand curve will be the same for the three cases, since the PV-systems have no influence on this parameter, it just depends on the evaluating zone.

- Case 2:

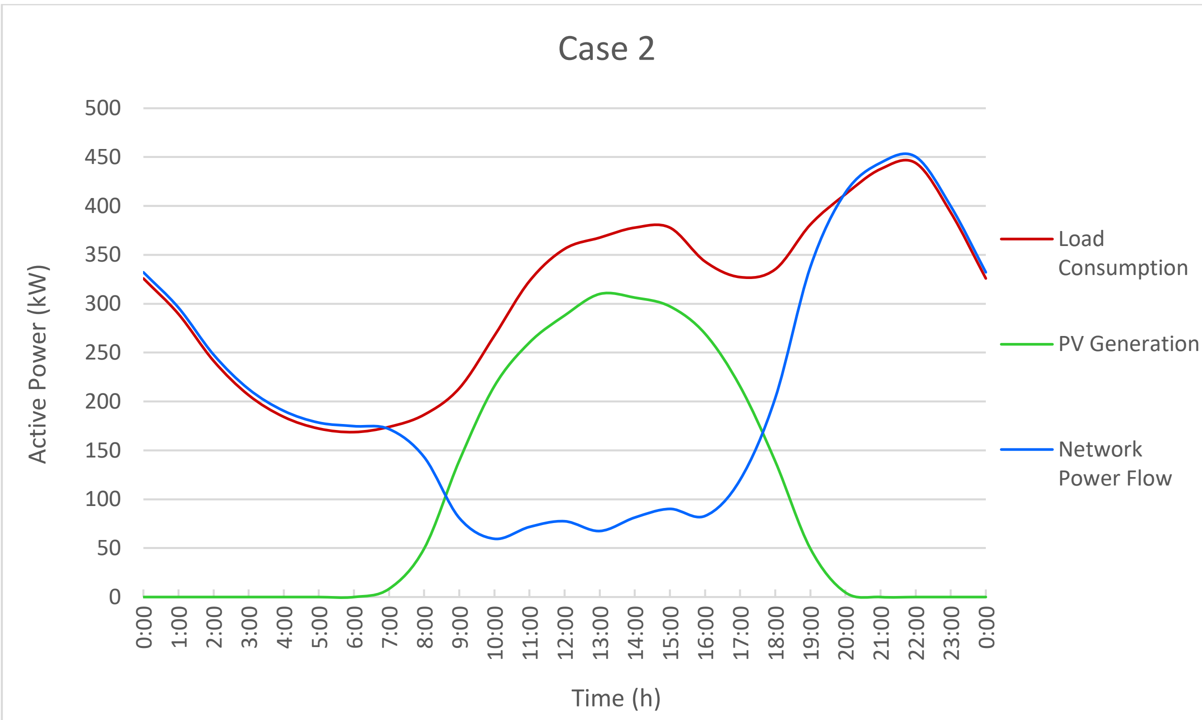

Figure 5.2.- Load consumption and network active power of the whole system during a complete day, with a medium level of PV generation.

In this case, a medium level of PV generation has been included. This curve represents the total generation produced by the PV-systems, which directly supplies energy to their corresponding LV load. On later analyses, it would be determined if some zones generate more PV than consumed. If this occurs, the excess of power will be used to feed other zones of this system with deficit, since, as the network power flow curve shows, the whole system is not exporting energy (it does not take negative values).

In other words, it can be observed that the PV curve does not exceed at any time the load consumption curve. Therefore, the network power flow never works under negative values, as is to say, the grid always has to supply energy to the loads.

Even so, it can be determined that, as the PV sources supply an important amount of energy during their operating period, the grid power transportation has to be significantly reduced.

- Case 3:

Figure 5.3.- Load consumption and network active power of the whole system during a complete day, with a high level of PV generation.

As it can be observed, this case represents the most extreme operating conditions of the network, since the PV generation curve widely exceeds the load consumption values in an important time period of the day. Since the PV-systems are interconnected with the LV network, the energy which is not consumed by the users is directly injected (without control) into the grid.

This fact produces that the network power flow curve takes negative values, as it represents the difference between the load consumption and the PV generation (considering, of course, the line losses). The negative values mean that this LV network is exporting power to the external network (MV network).

This scenario leads to several problems, which will be evaluated later.

5.3.1.2.- Analyses of the transformation centres.

In order to perform a complete analysis of the grid, it is interesting to make studies of the different defined zones of the LV network. As it has been defined five different zones (one for each TC), several analyses will be carried out now.

Since not all zones have the same number of loads, neither the same number of PV installations, it will be interesting to evaluate the differences produced in such different scenarios.

The graphs will follow the same disposition than those used to the evaluation of the whole system, but this time, comments will be made after the representation of the three cases of each TC.

- Transformation centre 1 (Zone 1):

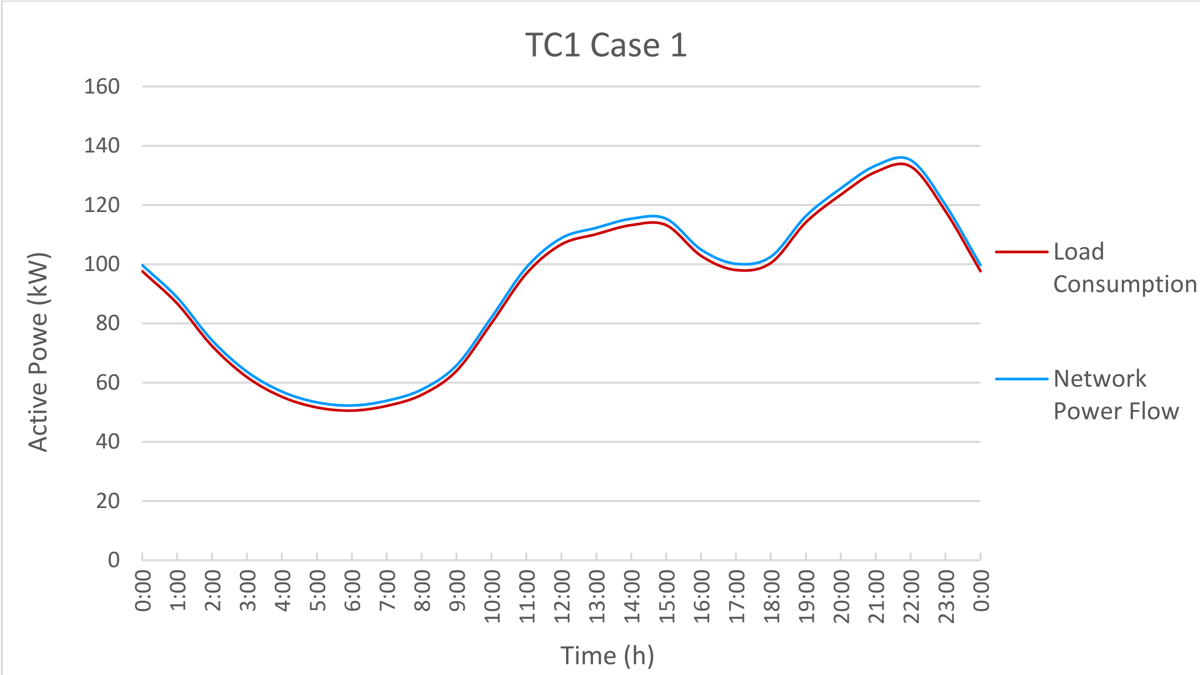

Figure 5.4.- Load consumption and network active power of Zone 1 during a complete day, without PV generation.

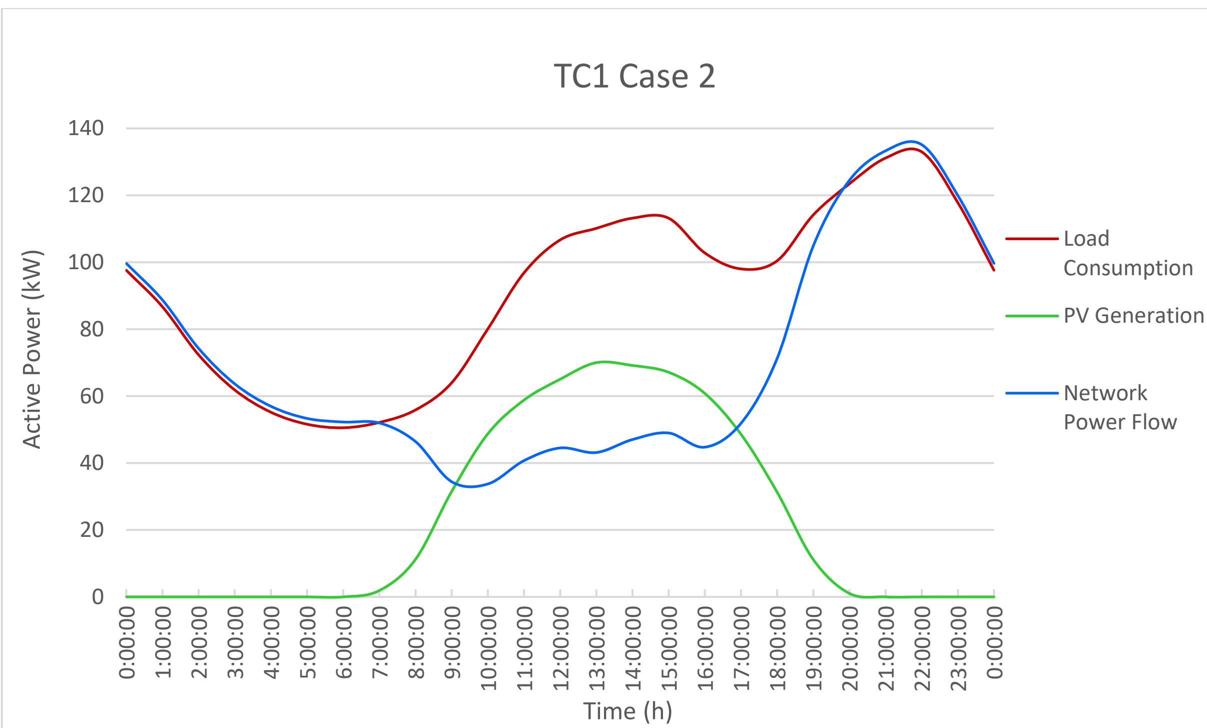

Figure 5. 5.- Load consumption and network active power of Zone 1 during a complete day, with a medium level of PV generation.

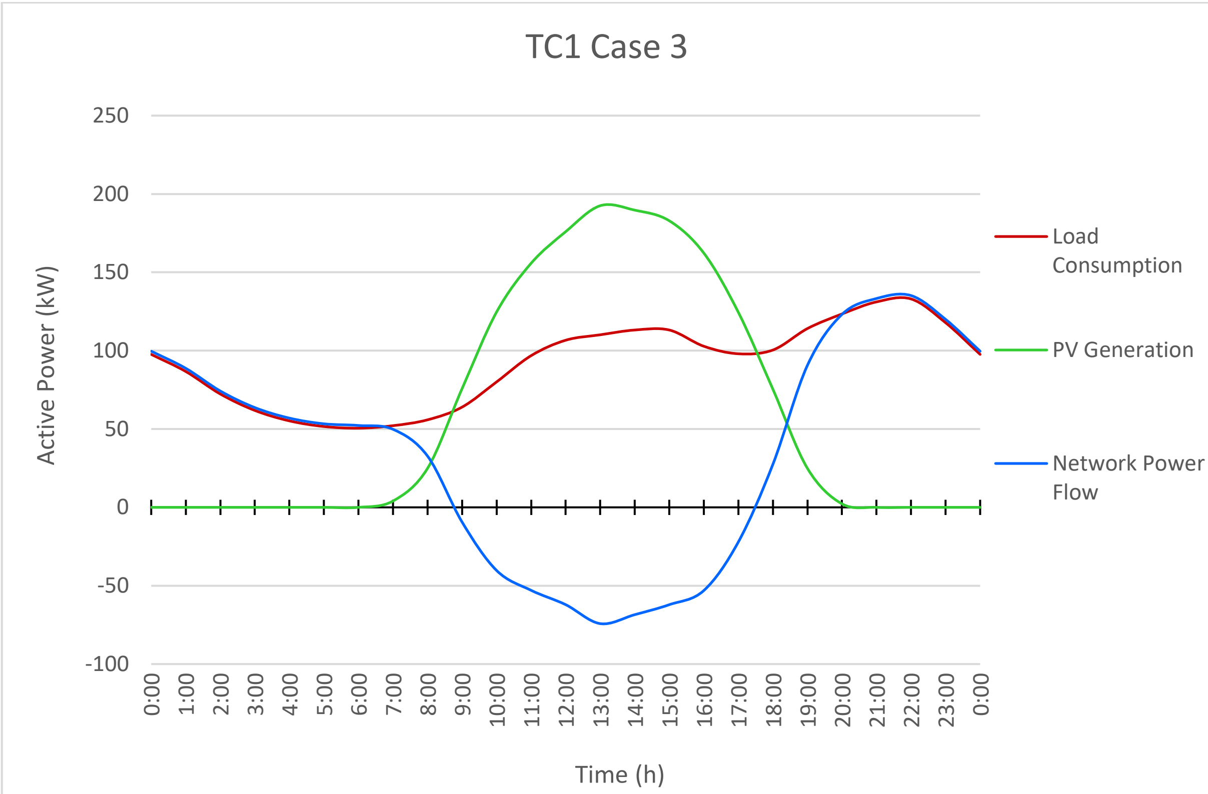

Figure 5.6.- Load consumption and network active power of Zone 1 during a complete day, with a high level of PV generation.

The Transformation Centre 1 is the most overexploited centre of all forming TCs of the analysis system, since it has the highest number of load demands.

As it can be observed, in the first graph the load consumption is quite high, reaching values of almost 140 kW at peak hours, which represents over a 31% of the total demand.

In the next graph, it can be determined that on these zone and for Case 2, there are no a high level of distributed generation with respect to the existing consumption. As is to say, this scenario represents a high power demand and no quite high PV generation.

Therefore, the variation on the network power flow curve is no as high as the one seen at the whole system analysis for Case 2.

Finally, on the third case, a high level of new generating sources is introduced on the network, making the shape of the curves similar to those of the chart which represents the whole system. In his model it can be concluded that, since there is a large amount of PV generation, there exists an important quantity of energy exported to external networks. The highest value is registered at the peak hour of solar generation, and represents a 28% of the total exporting power.

- Transformation centre 2 (Zone 2):

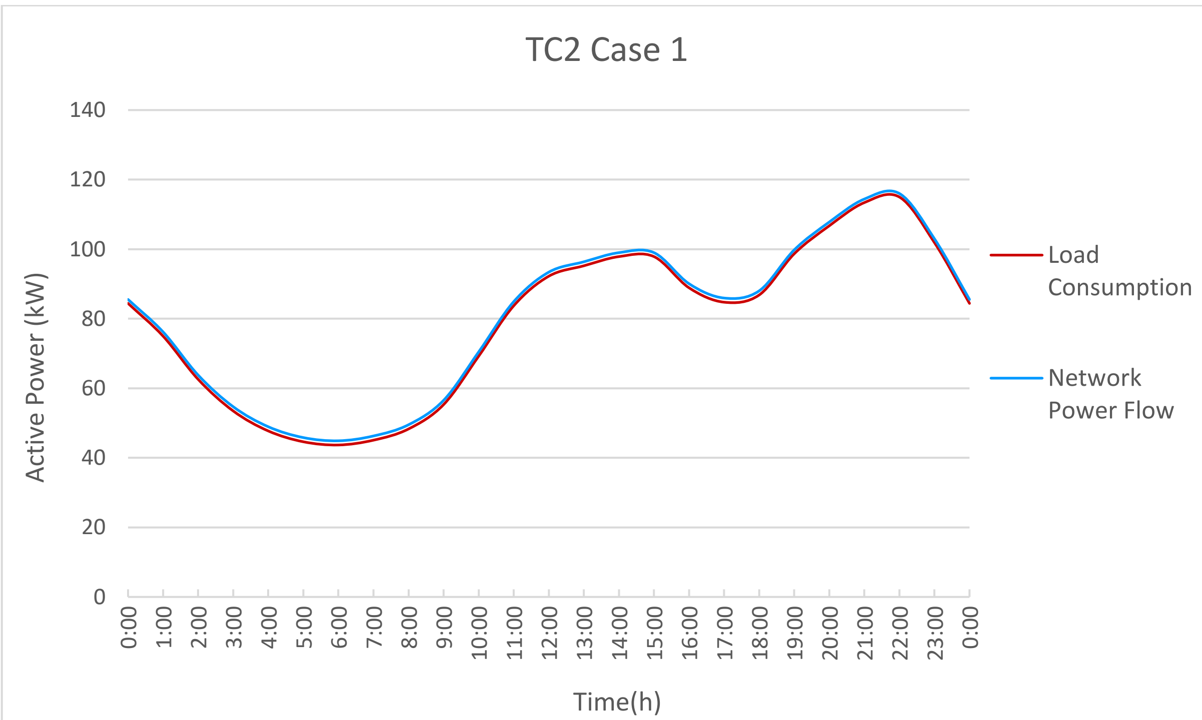

Figure 5.7.- Load consumption and network active power of Zone 2 during a complete day, without PV generation.

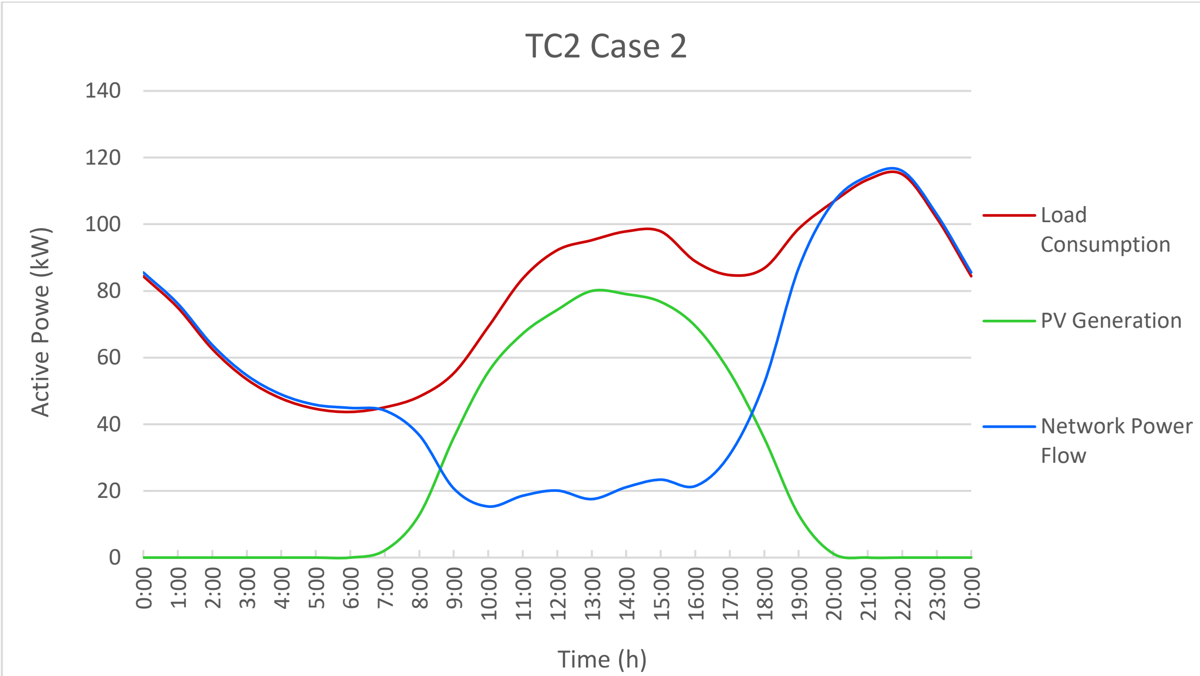

Figure 5.8.- Load consumption and network active power of Zone 2 during a complete day, with a medium level of PV generation.

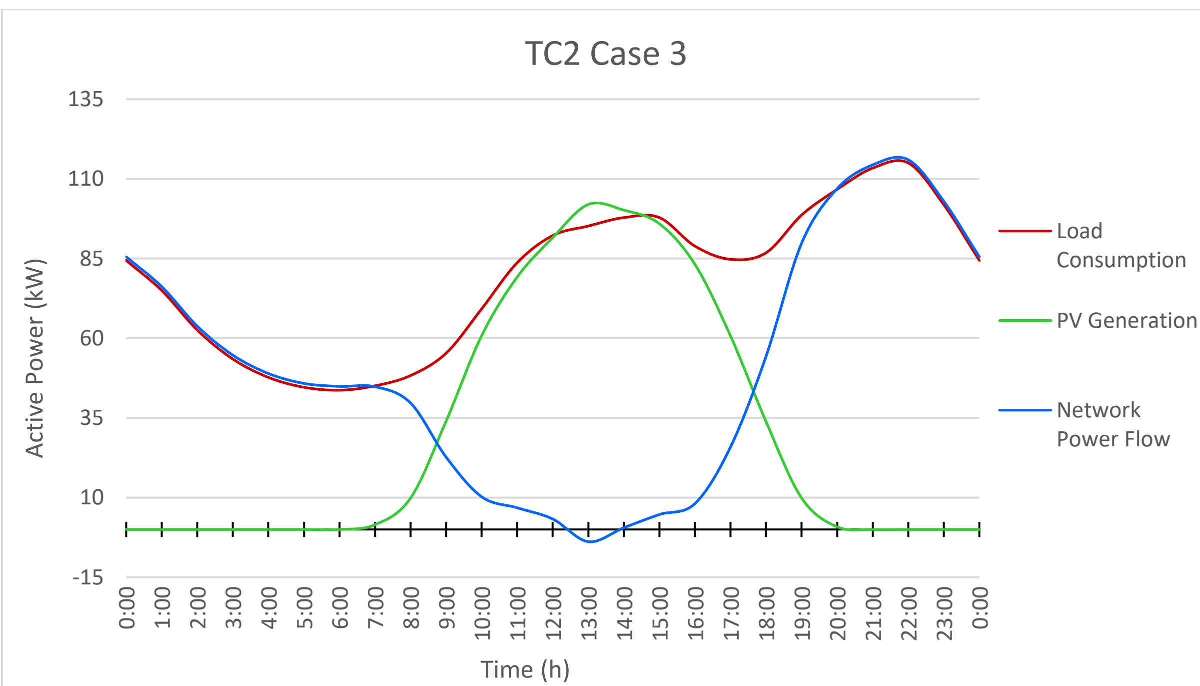

Figure 5.9.- Load consumption and network active power of Zone 2 during a complete day, with a high level of PV generation.

The first plot shows that in this zone there also exists an important power load consumption, reaching values at peak consumption hours close to 120 kW.

The next two charts represent the adverse situations regarding the results obtained in the plots of the TC1:

- In Case 2, it can be seen that the demand is quite high (as said before and as it occurred on TC1), but the PV penetration for this zone is higher than the one produced in TC1, reaching values closer to the demanded.
- In Case 3, it can be determined that the PV generation does not increase so much, since on the previous case, an important amount of this technology were included. So it can be concluded that in this case, the amount of power injected to the network is lower than other cases, principally because of the higher consumption of the zone and the lower number of users (the zone has been programmed with a low number of costumers but each one consumes a large amount of energy, with the aim of get more variety of results). Therefore, the exported energy to other systems is really low.

- Transformation centre 3 (Zone 3):

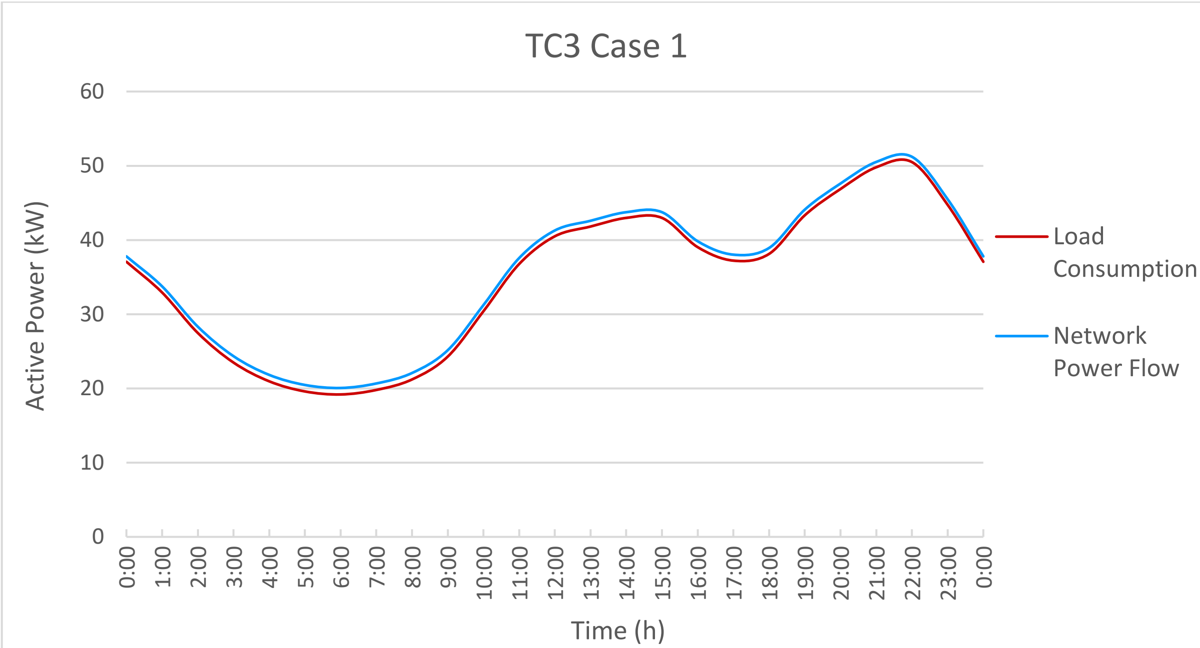

Figure 5.10.- Load consumption and network active power of Zone 3 during a complete day, without PV generation.

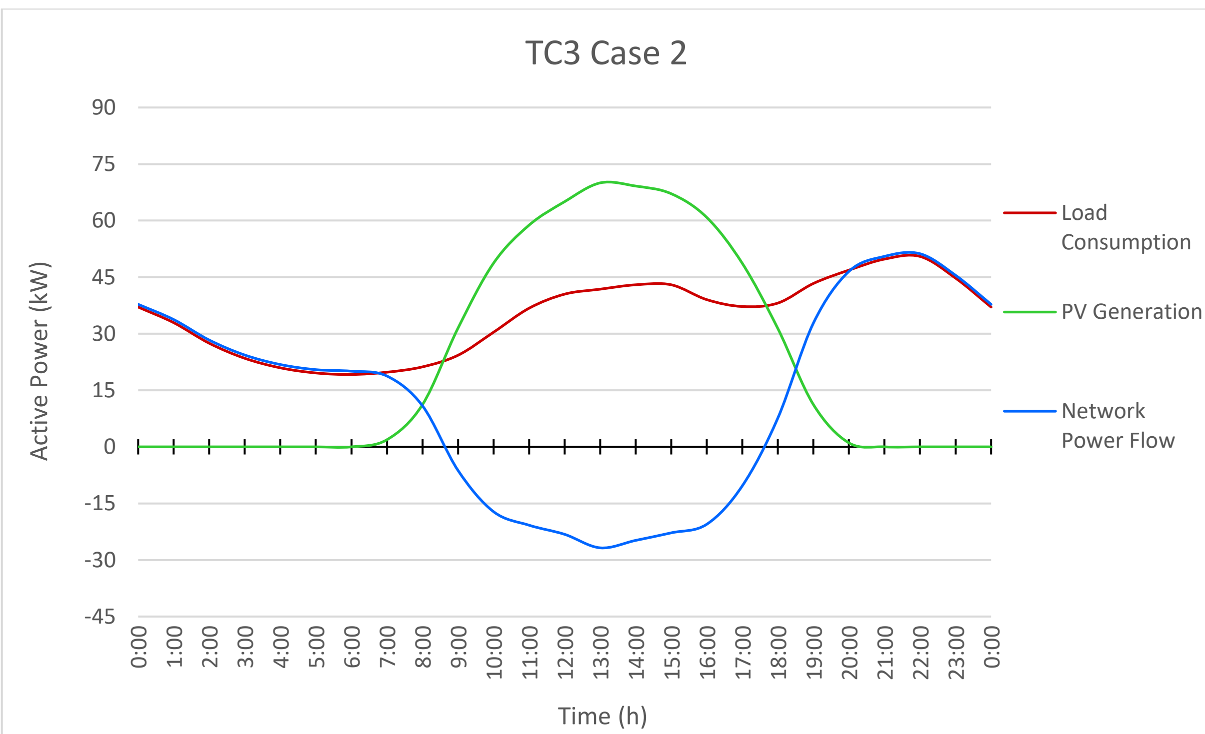

Figure 5.11.- Load consumption and network active power of Zone 3 during a complete day, with a medium level of PV generation.

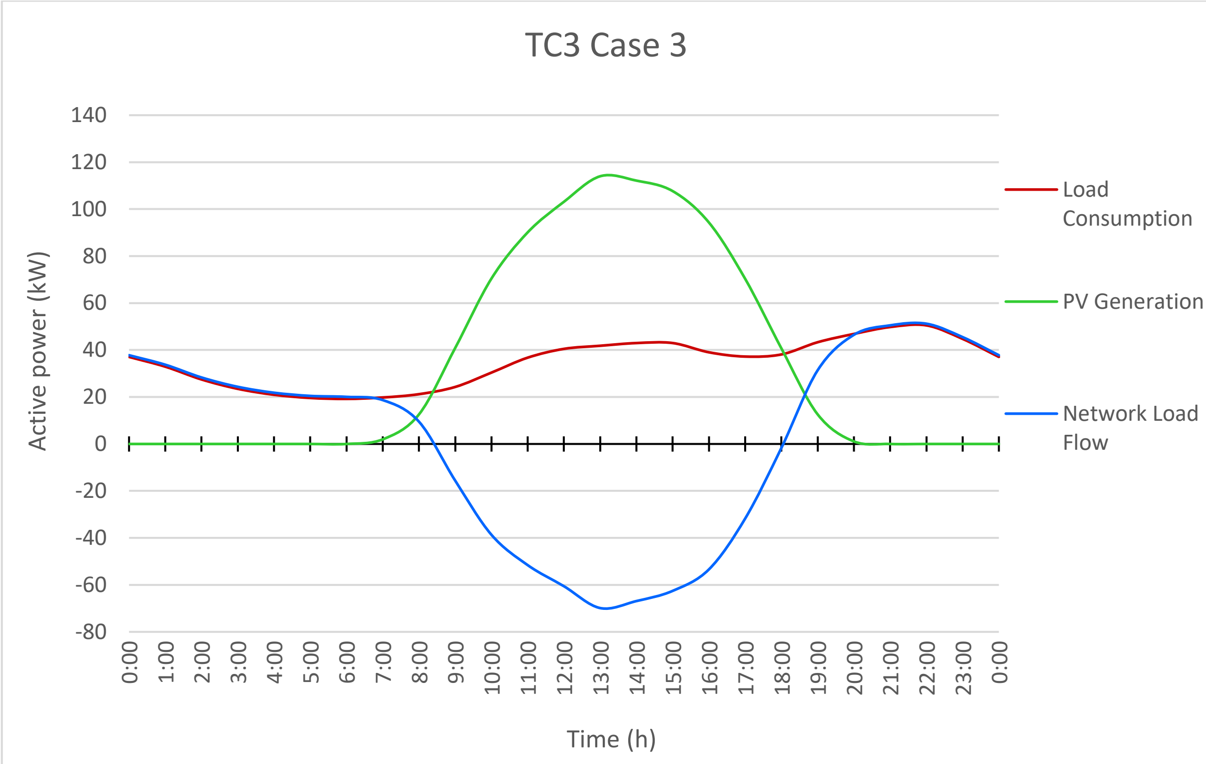

Figure 5.12.- Load consumption and network active power of Zone 3 during a complete day, with a high level of PV generation.

In this scenario, the lowest consumption levels are produced. The highest power consumption values are close to 50 kW and the lowest just reach 20 kW.

This fact leads to the situation produced in Case 2, on which the PV generation exceeds the load consumption. This is because a higher penetration level of DG is incorporated by the users with respect to other zones of Case 2. Therefore, this zone would behave as an exporting energy site, with the aim of supply energy to other regions of the system, in case of having a medium level of DG.

In Case 3, it can be seen that the PV generation increases significantly. The new generated power reaches values of 115 kW at 13:00, which are quite far from the consumption level at that moment, over 40 kW. Therefore, the exported power is about 75 kW, which represents a 29% of the total exported power.

- Transformation centre 4 (Zone 4):

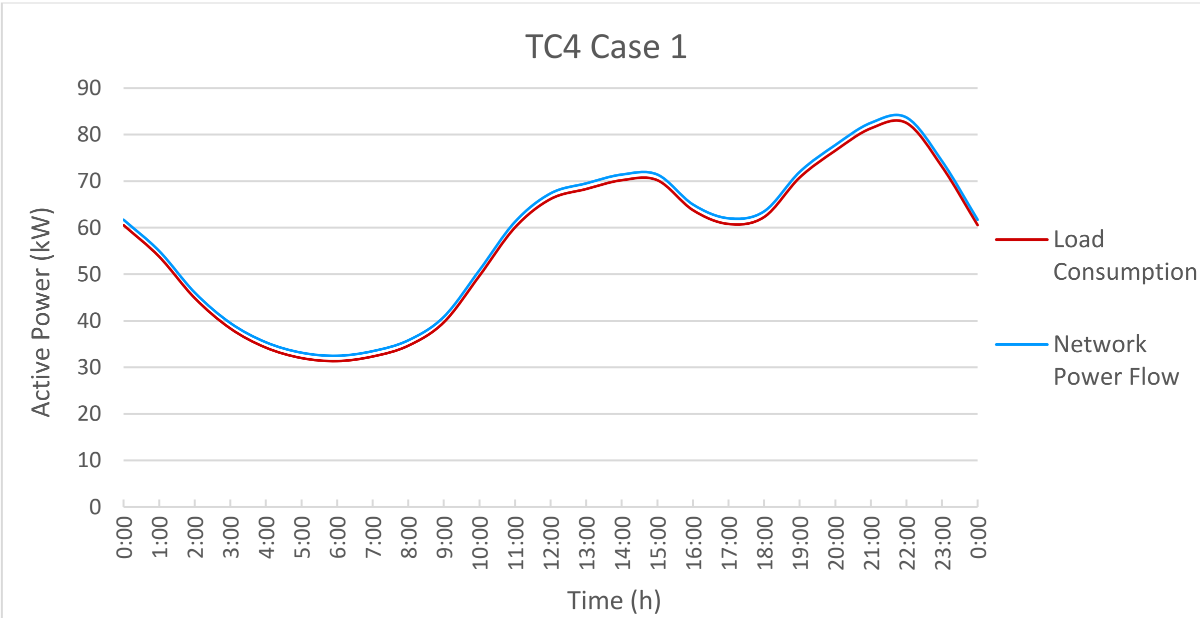

Figure 5.13.- Load consumption and network active power of Zone 4 during a complete day, without PV generation.

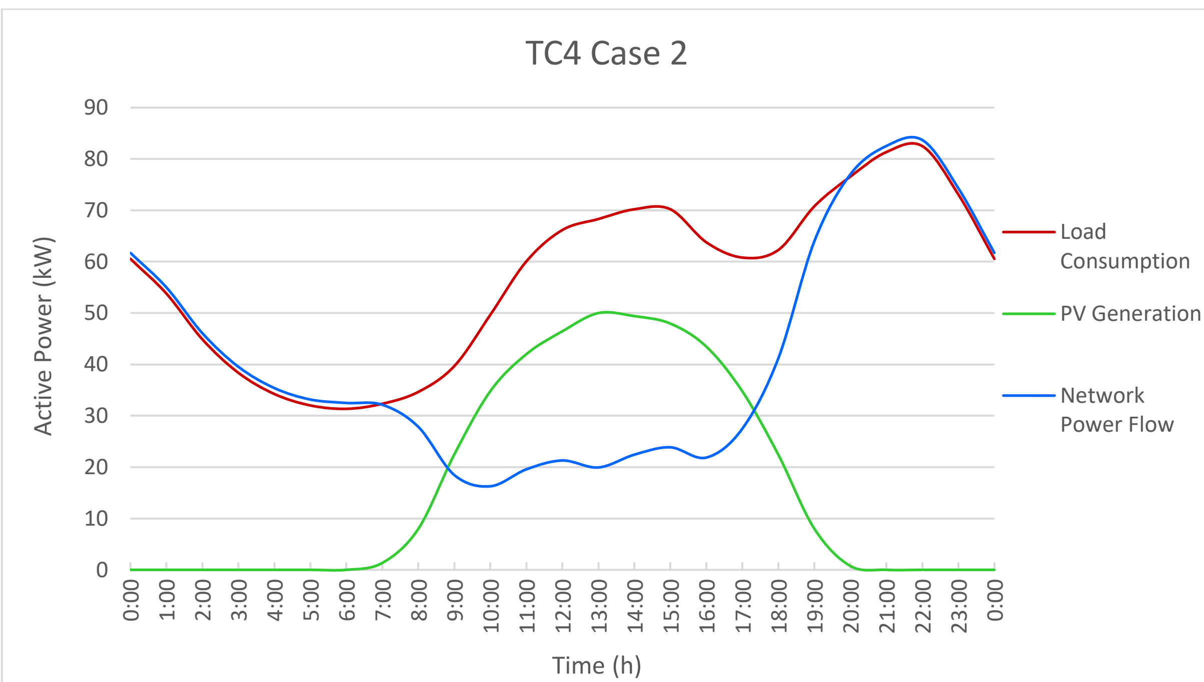

Figure 5.14.- Load consumption and network active power of Zone 4 during a complete day, with a medium level of PV generation.

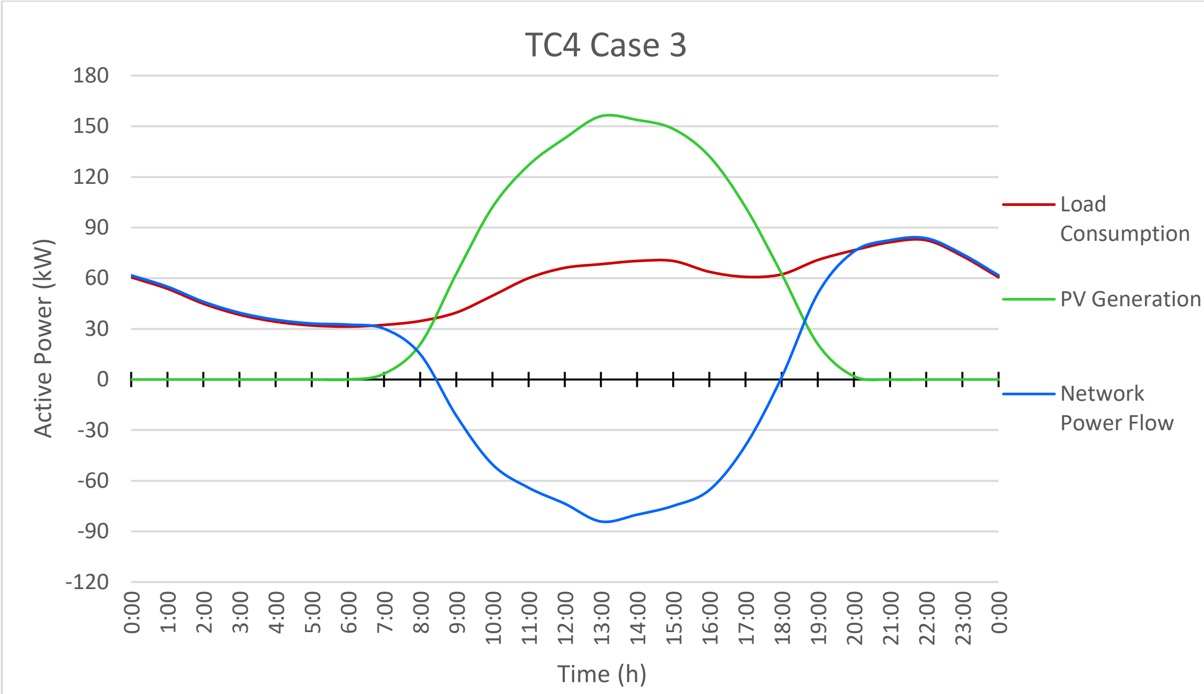

Figure 5.15.- Load consumption and network active power of Zone 4 during a complete day, with a high level of PV generation.

This zone operates with medium-high power consumption levels, which oscillates between 85 kW (at peak demand hours) and 32 kW (at lowest demand moments).

In the second plot, a normal PV generation level is produced, similar to that produced in zone 1 (or as is to say, TC1): the network has to reduce the importing level of energy, but it still has to transport a significant amount of it.

In Case 3, an important incensement of GD is introduced. Therefore, the PV generation exceeds again the load demand. The excess of energy is exported, reaching values at solar peak hours of almost 85 kW, which represents a 32% of the total exported power.

- Transformation centre 5 (Zone 5):

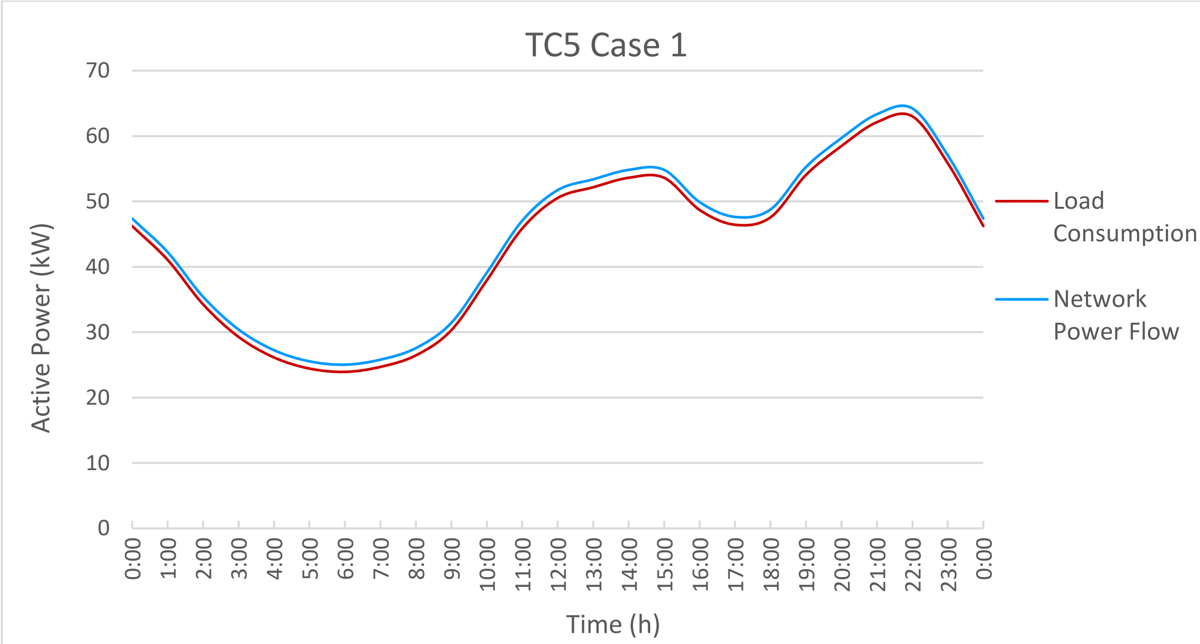

Figure 5. 16.- Load consumption and network active power of Zone 5 during a complete day, without PV generation.

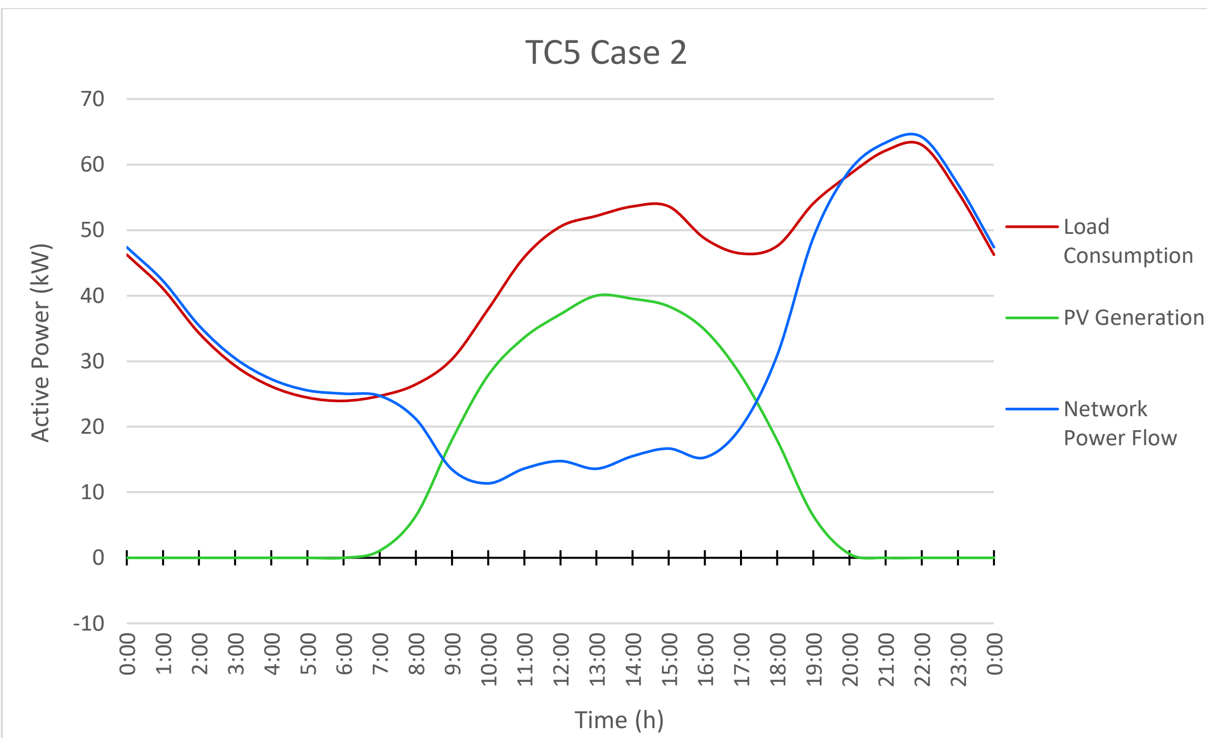

Figure 5.17.- Load consumption and network active power of Zone 5 during a complete day, with a medium level of PV generation.

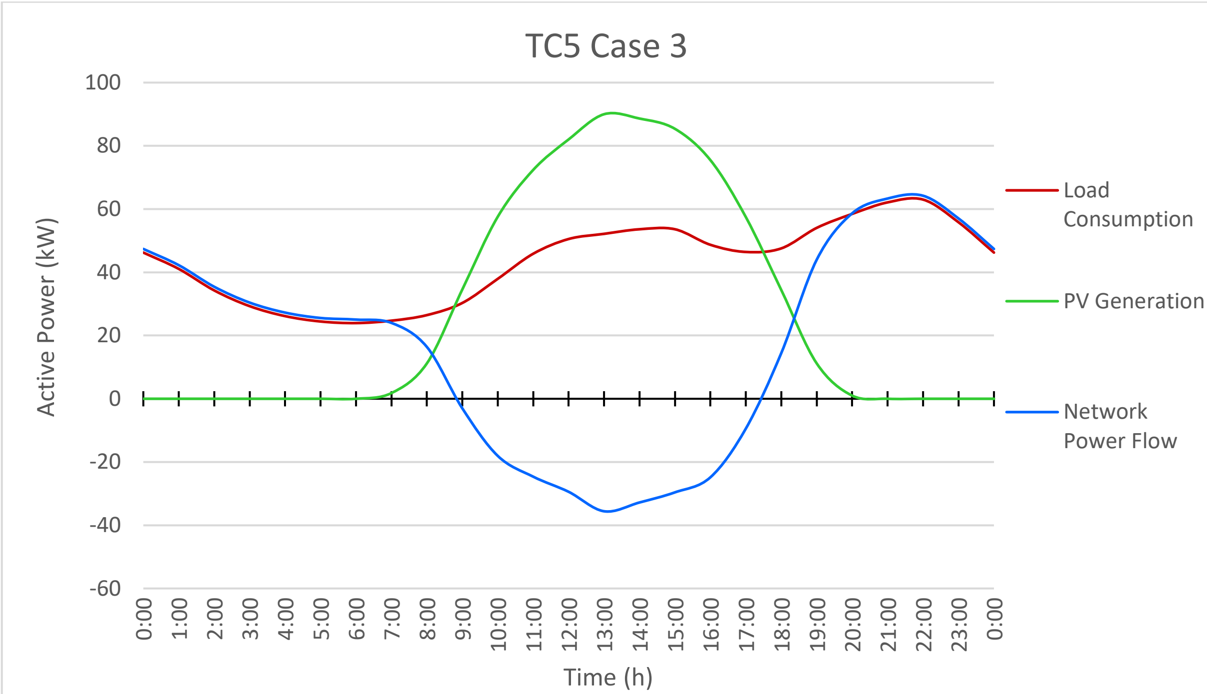

Figure 5.18.- Load consumption and network active power of Zone 5 during a complete day, with a high level of PV generation.

As the first plot shows, in this region there exists a medium-low power consumption, operating with values ranging from 64 kW at peak hours and 26 kW at off-peak hours.

In case 2, similarly than TC4, a normal PV generation level is produced. Therefore, the network has to reduce the importing level of energy, but it still has to transport a significant amount of it.

In the third chart, it can be observed that the PV generation increases reaching values of 90 kW at solar peak hours. The power transfer to external networks in this case is 35.6 kW.

5.3.2.- Transformer loading studies.

One of the major drawbacks that DG introduces to the systems is the modification of the current levels flowing through the different branches of each feeder. This fact defines the loading state of the transformers of the system.

It is necessary to remember that every transformation centre is formed by several feeders, each of them having different levels of consumption and generation. Because of this fact, some branches can export power to other branches with less generation and more consumption.
Therefore, the current flowing through a determined feeder can be widely increased due to the excess of generated power, but if there exist other feeders belonging to the same TC with deficit of power, the previous mentioned feeder can cover such deficit. This situation would reduce the current flowing through the transformer of the TC, since the new PV sources cover a determined amount of the demand (depending on the case of study).

There exist other situations on which all feeders of a TC generate excess of energy. In this case, the current of the transformer could be increased, since energy exported through this TC to external networks can be higher than the current needed to cover the demand in case of having no PV-systems.

In this section, a study of the loading of the transformer of each TC will be made. This study will also allow us to understand what happens on each system according with the power transfer. Notice that, when a TC is exporting power to other networks, the current sign would be negative (as it flows upstream). Because of this fact, it is important to mention that, from the point of view of the transformer loading, the plots will represent the absolute value of the current. Even so, the sign of the current can be easily determined just by looking at the previous power network flow plots.

In this section, a graph including the three different cases for each zone will be used.

- Transformer 1:

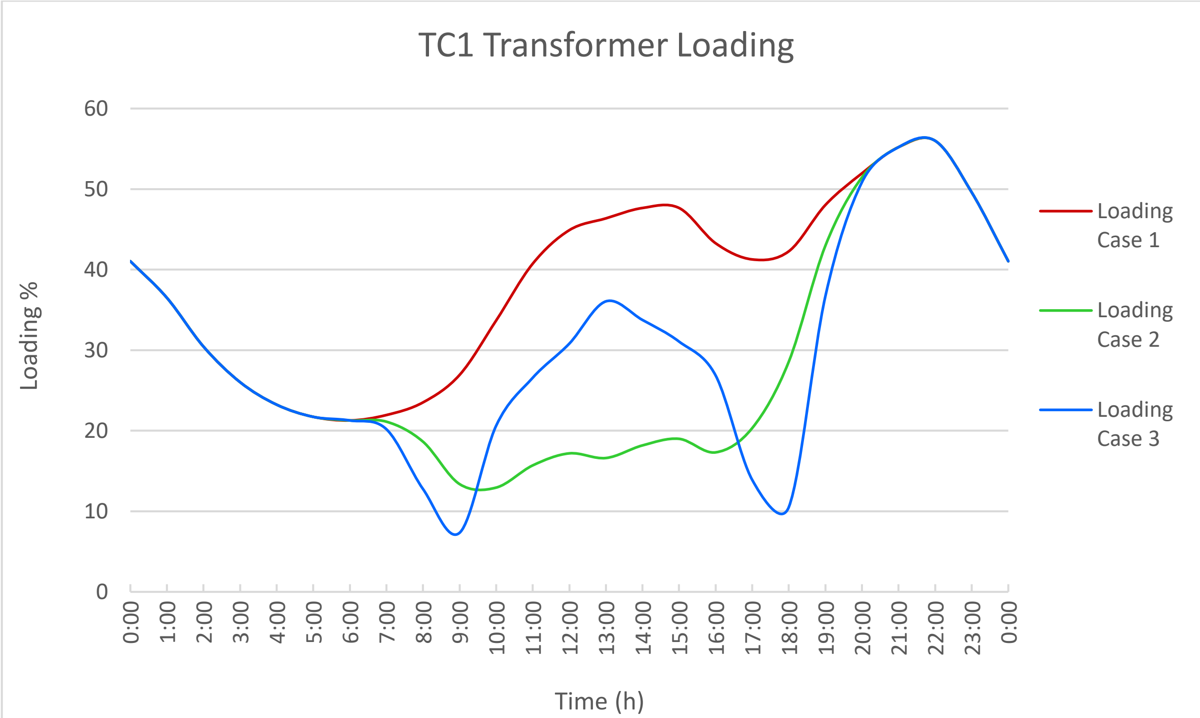

Figure 5.19.- Loading of transformer 1 during a complete day.

From the output window, it can be observed that, after implementing a 'Quasi-Dynamic Report', the transformer which is more affected during the three different cases, is the transformer which belongs to the TC1. This is because, as mentioned on previous section, the zone supplied by this TC is the most overexploited. Therefore, it is the one which is going to be subjected to the worst operating conditions.

As it can be observed in the graph, in case of having a medium level of DG, the energy that the system needs to transmit to the consumers is highly covered by the new sources when they are operating. This situation leads to a decrement of the loading of the transformer, since the PV panels 'help' to feed a portion of the needed current, reducing the transformer circulating current.

In case of having a large level of PV-systems interconnected within the network, the loading of the transformer remains lower than in case of having no DG. As seen on previous section, the PV generated power in Case 3 was used to supply the load consumption of that zone and the excess was transmitted to external networks. That explains why the current in this case is lower than in the first case: the exported current in Case 3 is lower than the imported to supply the load demand when no PV is introduced.

Notice that, as explained below, in Case 3, the current flowing through this transformer would be negative.

- Transformer 2:

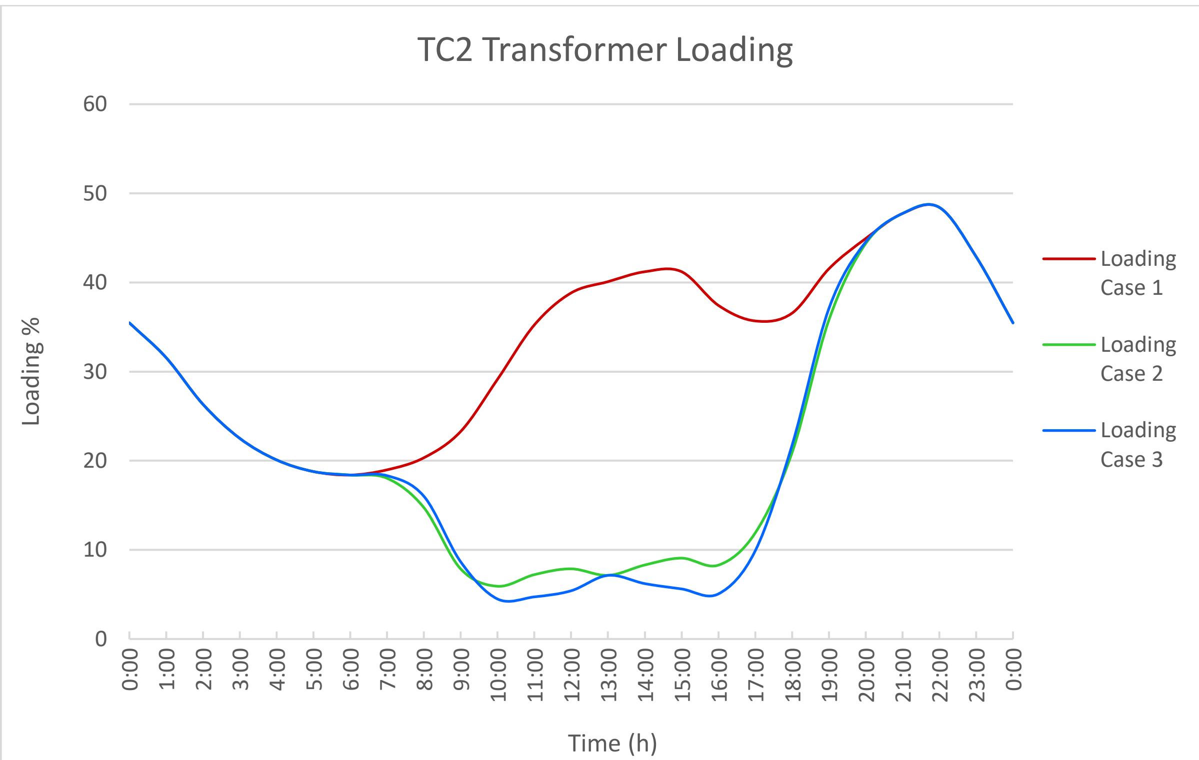

Figure 5.20.- Loading of transformer 2 during a complete day.

First of all, it is interesting to take a look at Figure 5.8 and remember that in this zone, for Case 2, a high level of DG was included. For this reason, the current flowing through the transformer in this case is quite low: as it can be observed, the network supplies a small amount of power which, ultimately, reduces the current flowing through the transformer.

In Case 3, a really small increment of PV generation was stablished, and therefore, this zone just exports power in a brief moment of the solar peak hours. Because of this fact, the current flowing through the transformer around 13:00 increases just a bit (remember that when the zone is exporting power the current would be negative, but in these plots absolute values are represented).

The reason why the current in Case 3 remains lower than in Case 2 in certain moments, is because the network needs to supply less energy to the loads, since more PV generation is produced in Case 3.

- Transformer 3:

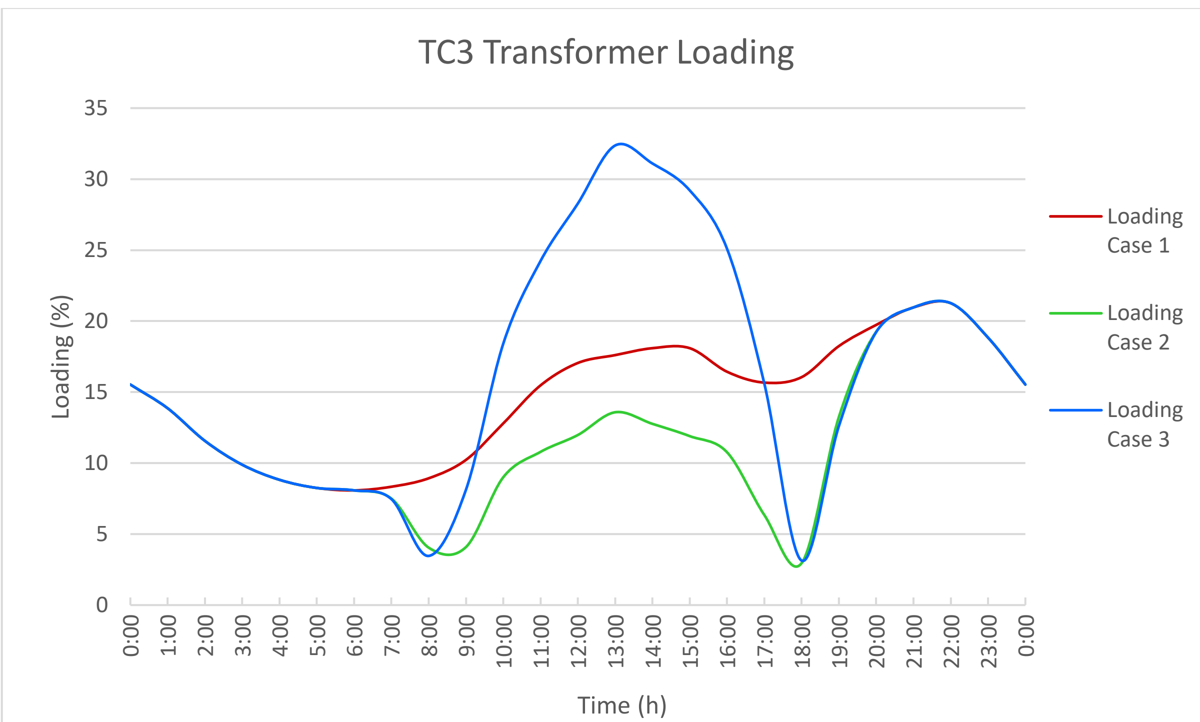

Figure 5.21.- Loading of transformer 3 during a complete day.

It is interesting to remember that this zone behaves as an exporting region (see Figure 5.11 and Figure 5.12): low load consumptions and, when including the PV-systems, high levels of PV generation.

In Case 2, this zone exports power to external networks in a wide time period, so the curve which defines the transformer loading of this case, would be representing negative currents flowing through the transformer. Even so, the current exported in this case, which of course is the difference between the generated and the consumed by this region, is lower than the current needed in case of having no solar installations. So the loading of the transformer is lower than in Case 1.

In Case of having a high level of DG, this region exports a high quantity of power to external regions. As it can be seen in the chart, the loading of the transformer increases significantly due to the increased exported power, which in turn, increases the current flowing through this transformer.

- Transformer 4:

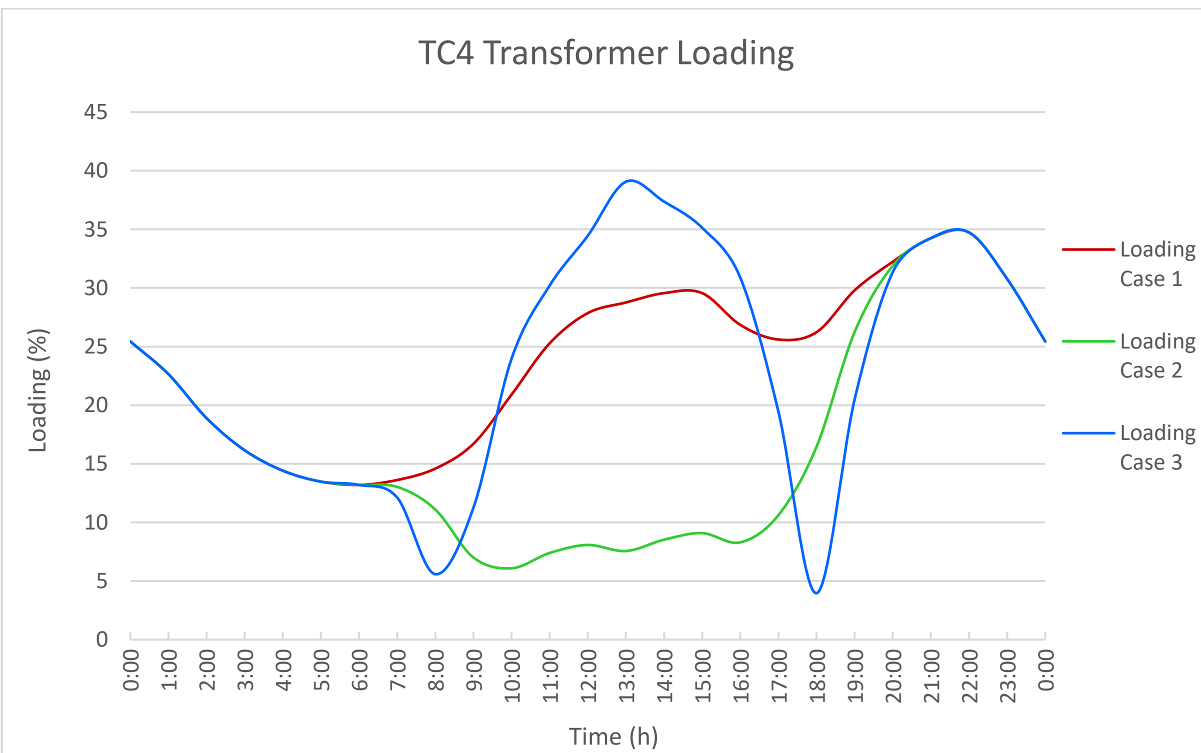

Figure 5. 22.- Loading of transformer 4 during a complete day.

In Case 2, it can be seen that the network reduces significantly the imported power. This fact makes the transformer loading to be reduced, since the new generating sources cover an important part of the load demand and this new generation never exceeds such demand (no exports take place).

In Case 3, the PV generation is highly increased. It is interesting to remember that this zone reaches the highest power exporting values. Because of that, the transformer loading in this case raises even more than in Case 1.

- Transformer 5:

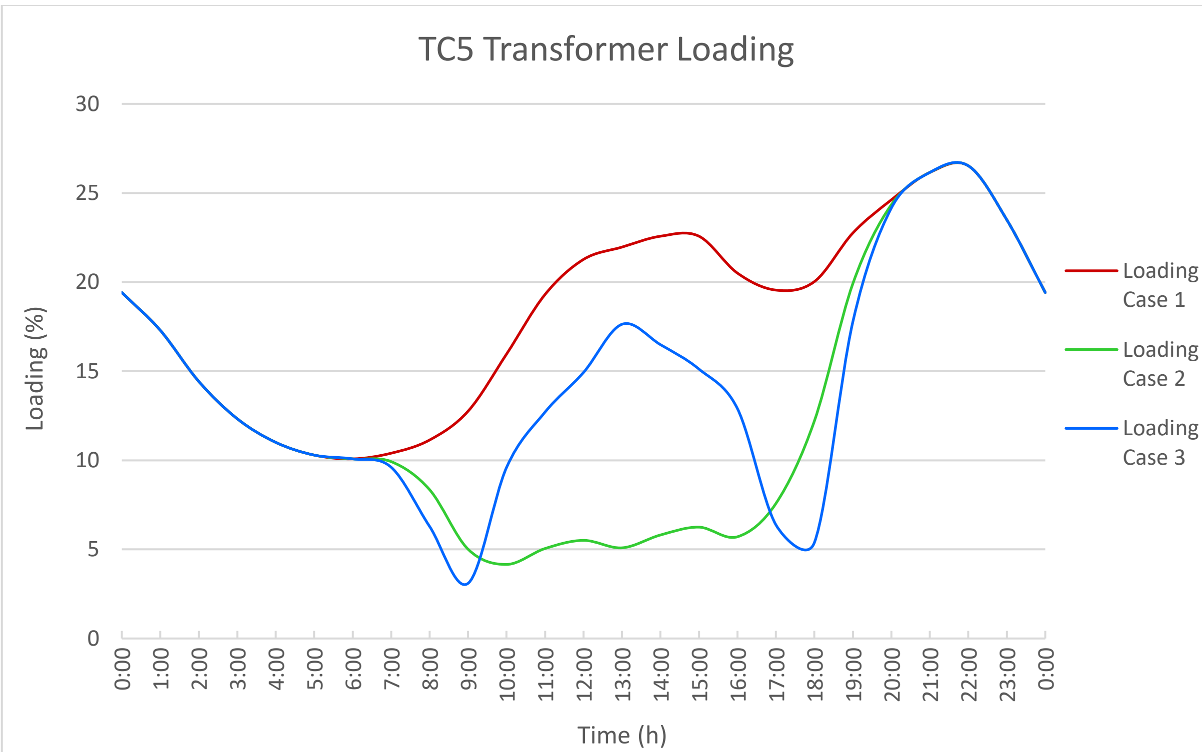

Figure 5.23.- Loading of transformer 5 during a complete day.

In this plot, it can be observed that in Case 2, a similar situation (or curve shape) than in Zone 4 is obtained. The network reduces its power import, reducing therefore the current flowing through the transformer and in turn the transformer loading.

In Case 3, it is seen that an increment of the PV generation is produced, which exceeds the load demand and generating an excess which is exported to other networks. In this case, the current exported is not higher than the one needed in case of having no PV installations, so the loading of the transformer remains always lower than in Case 1.

5.3.3.- Voltage studies.

Voltage-reactive control is one of the most important complementary services carried out by the system operator, the distribution system operator and generation. The objective of this supplementary service is to keep the voltage near nominal values and optimization of reactive flows through the network.

The voltage control in electric networks is essential because an adequate level of voltage depends on the proper functioning of all electrical equipment connected to the network. Therefore, the voltage is a fundamental parameter that serves as a reference for measuring the quality of the product delivered to customers by the distribution companies.

Voltage regulation is usually done in LV networks, by changing the tap position of the transformer of the corresponding TC, typically in the low voltage output (400V), having around ± 5 taps, with a margin of 2.5% or 5%. Another common method is by using voltage regulators and capacitors on the feeders.

Since the control of voltage regulation is usually based on radial power flows, the excess of DG can cause low or over-voltages in the network. On the other hand, the installation of DG can have positive impacts in the distribution system by enabling reactive compensation for voltage control, reducing the losses, contributing for frequency regulation and acting as spinning reserve in main system fault cases.

In this part, a study of the voltages at most important nodes will be made, including the three different cases of analysis. In order to perform a proper evaluation, the selected nodes will be: those of the low side of the transformer of each transformation centre and those at the end of the most significant feeders, which in turn, will suffer most extremely voltage variations.

This section is divided in three different subsections with the purpose of making a complete study by using different tools. Such tools were explained in detail on previous chapter.

5.3.3.1.- Analyses of the voltages at the transformation centres busbars.

In this subsection, the variations in the voltage levels of the principal nodes of the TCs (called busbars), will be analysed. In order to visualise clearly the behaviour of this parameter, time-voltage charts will be used for each TC. The three different cases will be represented simultaneously in the same graph.

It will be necessary to check if the voltage levels exceed the upper and lower voltage drop limits, stablished by the distribution company following the legislation. For this project, these limits are set at: 0.95 pu and 1.04 pu.

Notice that all voltages are exposed in per unit values.

- Busbar 1:

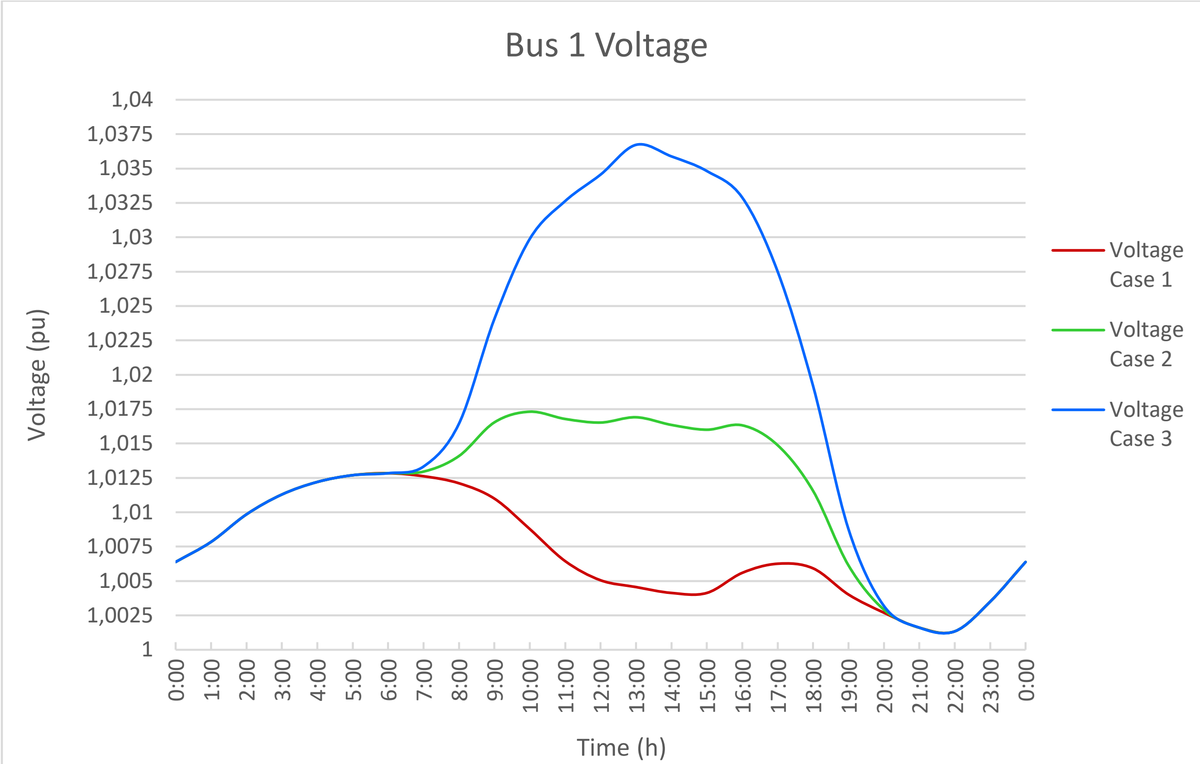

Figure 5.24.- Voltage variation of Busbar 1 during a complete day.

In this plot, it can be observed that, in Case 1, the voltage level at the busbar of the TC1 follows the opposite curve shape that the load consumption has. This fact is produced because the voltage decreases when there is more consumption and therefore more current demand (the higher the current the lower the voltage at the node is).

It can also be observed that the voltage values in Case 1 are always close to 1 pu, with some variations due to such changes in consumption along the day. These values are a bit high in order to compensate the significant voltage drop (due to line losses) produced at the latest nodes of the feeders. The characteristics of Case 1, will be similar in all defined zones.

In Case 2, a medium level of DG is inserted in the network like on previous sections. In the graph, it can be seen that voltage level at this node is increased due to the upstream power flow and to the increment of the generated reactive power. It can be determined that no high voltage values are reached in this case.

As mentioned on previous sections, Zone 1 represents the most overexploited region which, ultimately, major drawbacks can be produced there. As the chart shows, the voltage level in Case 3 reaches values at solar peak hours of almost 1.0375 pu (which are 415 V of line-line voltage). Therefore, this operating conditions would not be suitable, since this value is really close to the upper voltage limit (1.04 pu).

- Busbar 2:

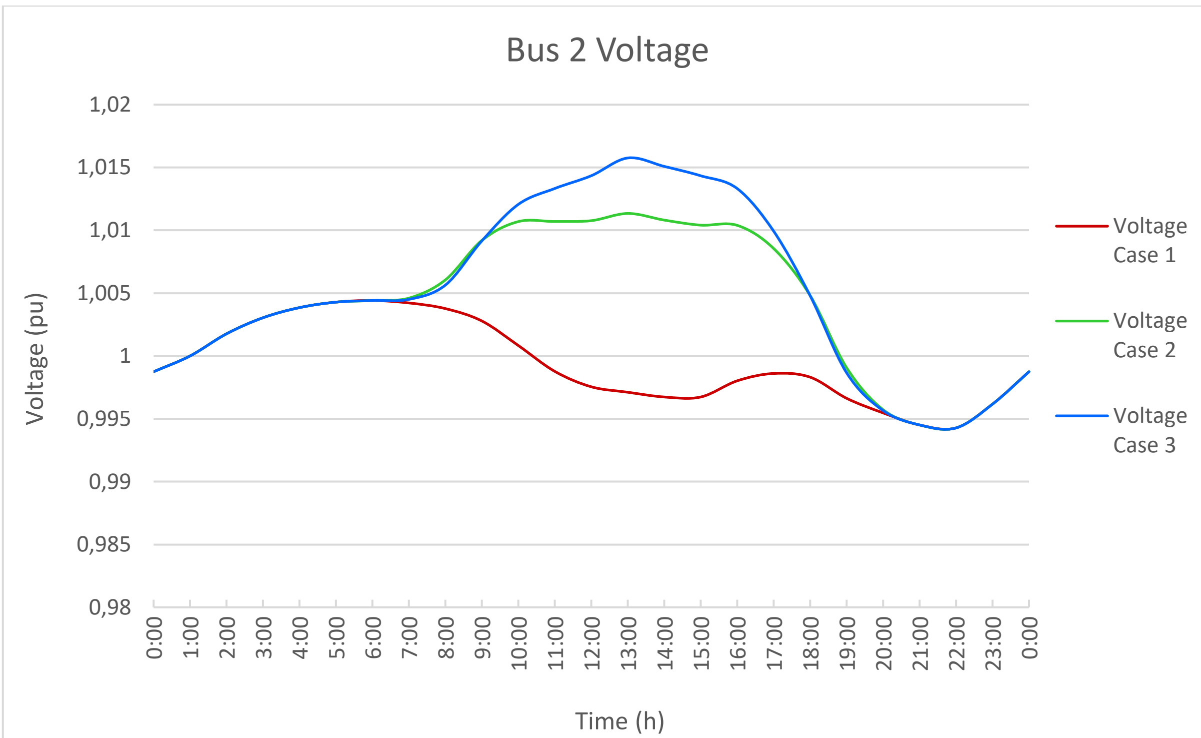

Figure 5.25.- Voltage variation of Busbar 2 during a complete day.

The voltage levels in the Busbar 2 when having no PV installations, are again close to 1 pu, but this time decreasing a bit at peak consumption hours, since the voltage drop is lower in this zone due to the smaller feeders' length.

In the following two cases, medium and high penetration level of DG, it can be observed that the voltage values raise in comparison with Case 1. The differences between these two cases is really small since the PV-systems existing in Case 2 is quite high in this Zone.

The operating voltage values for these three cases of Busbar 2, are inside the allowable range of values stablished by the distribution company.

- Busbar 3:

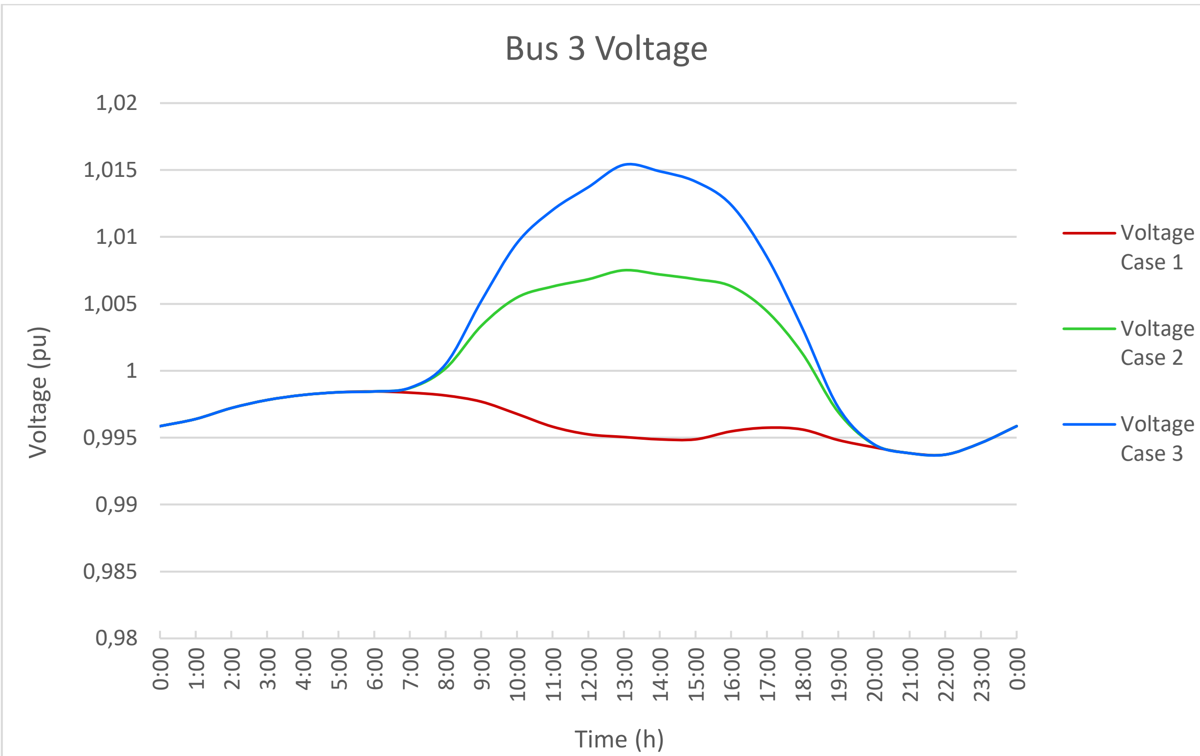

Figure 5.26.- Voltage variation of Busbar 3 during a complete day.

In Case 1, it can be seen again how the voltage remains closer to 1 pu. The operating voltage values are a bit lower than 1, but this is because the voltage drop is not significantly high at the latest nodes of this zone. The voltage could be increased in this busbar by changing the transformer tap position, but in this case, the voltage will increase too much.

In Case 2 and Case 3, it can be seen that the voltage levels are higher than in Case 1, due to the reactive power injected by the new generating sources and the reverse power flows. In this region, the voltage that are reached in these cases are low enough to be inside the allowable limits. Therefore, the PV sources provide an increment of voltage in determined moments where the voltage descends in Bus 3, actuating like a voltage regulating element.

- Busbar 4:

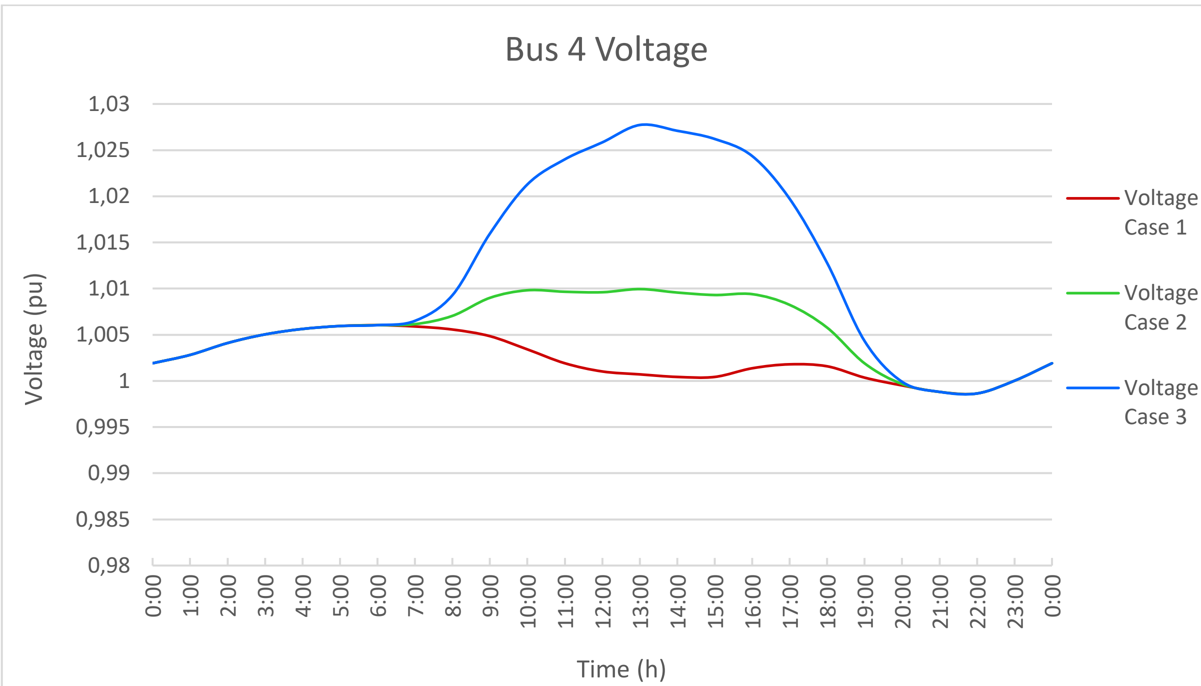

Figure 5.27.- Voltage variation of Busbar 4 during a complete day.

In the 4th busbar, belonging to the TC4, it can be observed that the voltage level in Case 1 is always really close to 1 pu.

When adding the first DG sources, the operating voltage is raised up to 1.01 pu during a period on which the voltage would decrease in case of having no PV installations. Therefore, the voltage is well compensated.

In case of having a high level of DG interconnected with the system, it can be determined that the voltage increases significantly with respect to other cases, since a high value of reactive power is being generated. Even so, the operating values in this case are correct, since they no exceed the limits.

- Busbar 5:

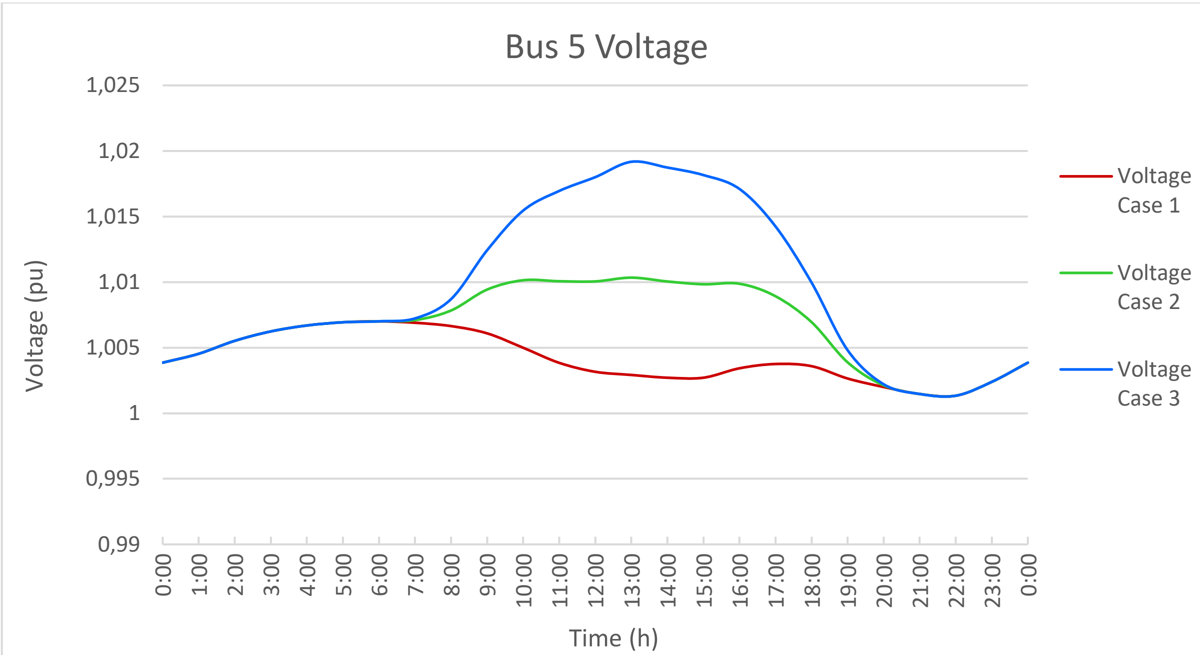

Figure 5.28.- Voltage variation of Busbar 5 during a complete day.

Similarly, in Case 1 voltage levels remain close to 1 pu, this time a bit higher since the feeders have larger lengths and therefore, voltage drops are more significant.

Again, in Cases 2 and 3 the decrease of voltage which takes place in Case 1 at peak consumption hours, is compensated by the new generation sources. The operating values for both cases are inside the allowable values.

Although the voltage is compensated in some important moments, as the technology used consists on PV-systems which directly depends on the sun radiation, it can be observed that when these sources stop generating power, the voltage curve becomes the same as the one of Case 1. Hence, more fluctuations are observed in the curve belonging to Case 3.

In order to obtained a constant time-voltage curve, which maintains the operating voltage value at any hour at the same level, it would be interesting to incorporate a battery, which stores energy in high generating moments and supplies the stored energy in deficit energy moments.

5.3.3.2.- Voltage profiles analyses:

Since voltage profiles cannot be calculated with respect to time, but with respect to feeder length, it is necessary to know which are the most interesting operating conditions (moments of the day) and cases to analyse.

Once the time-voltages studies of the principal bursars of the TCs haven been completed, quasi-dynamic reports must be executed. This tool provides more information about most interesting feeders to analyse, since it shows most extreme voltage cases of the nodes of the system and when they occur.

After performing these analyses, it can be determined that the feeders which are summited to worst operational conditions are: Feeder 2, from TC1; Feeder 13, from TC4; Feeder 3, from TC2; Feeder 17, from TC5; and Feeder 12, from TC3. The moment of the day at which these scenarios take place coincides with the maximum PV generation moment, which is between 13:00-14:00, according with the data introduced when modelling the PV-systems.

In order to make a complete study of the voltage profile of such nodes, the three different cases will be evaluated. Since the voltage profiles obtained in the program cannot be exported to excel files, just one feeder per case can be shown in the plot. Therefore, three plots for each feeder have to be executed in order to analyse the three cases. Comments will be included after the three plots of each feeder.

- Feeder 2:

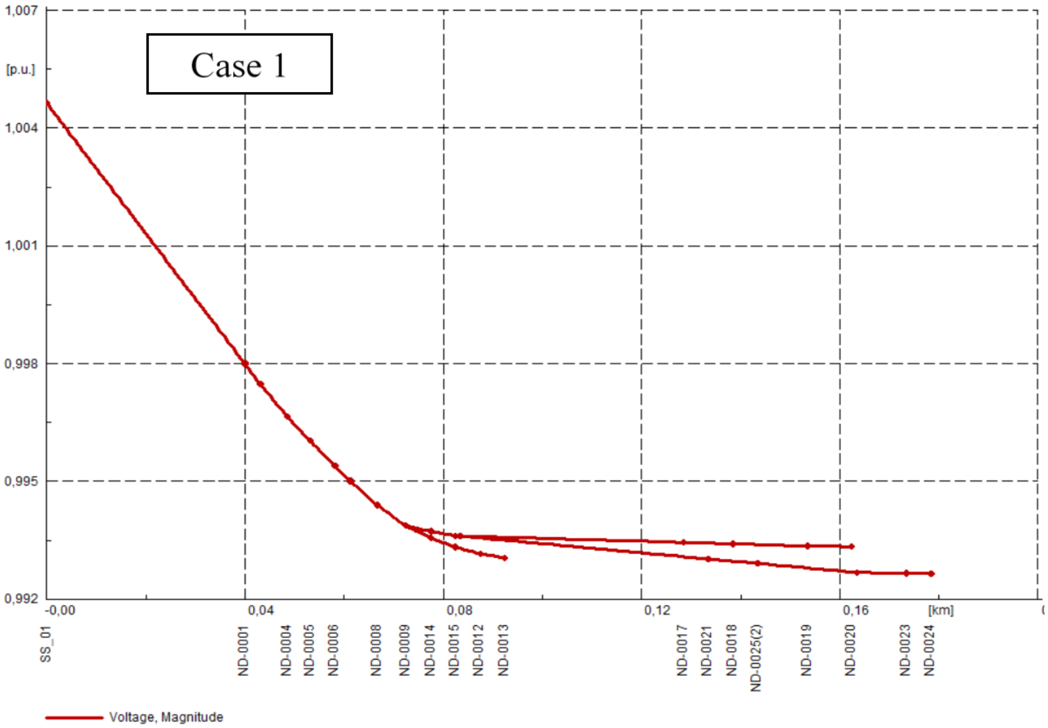

Figure 5.29.- Voltage profile of Feeder 2 without PV generation.

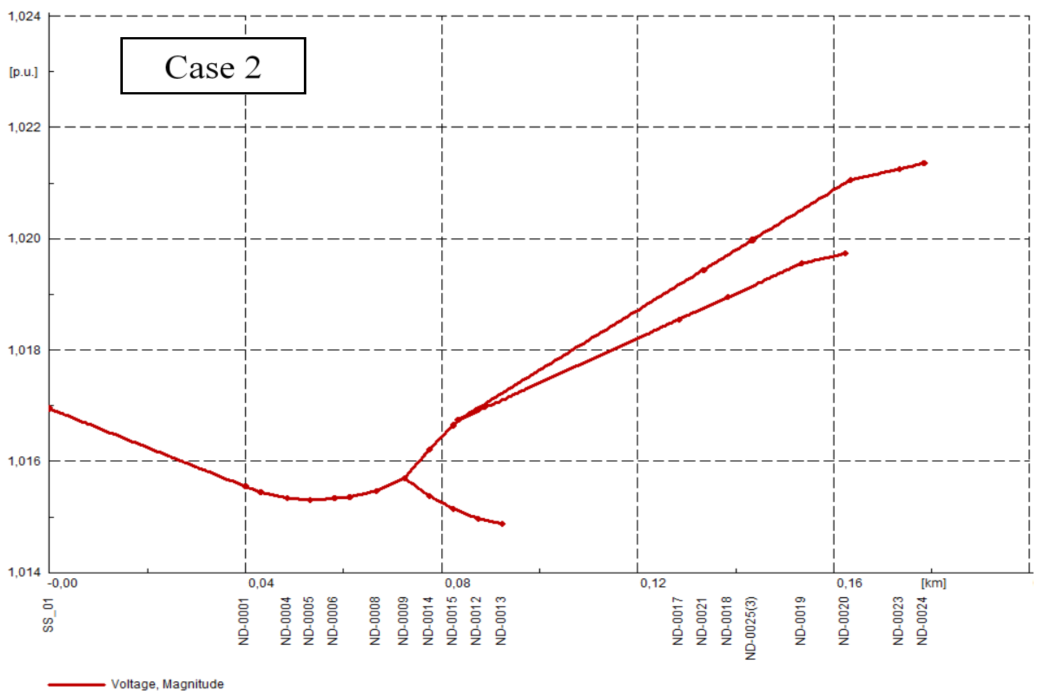

Figure 5.30.- Voltage profile of Feeder 2 with a medium level of PV generation.

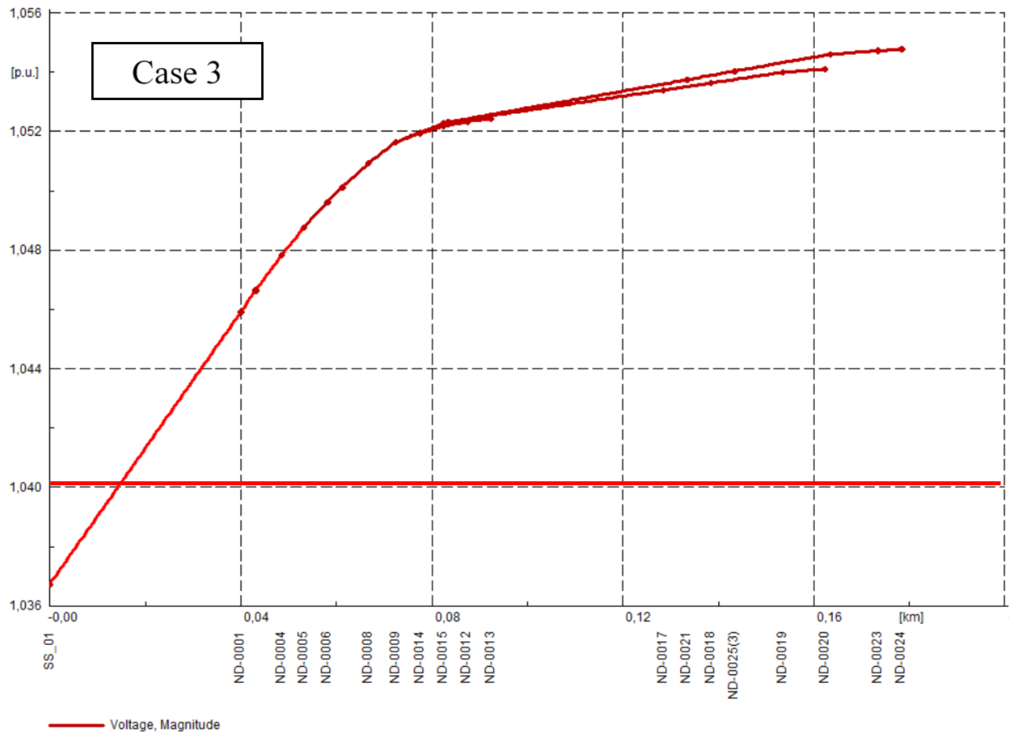

Figure 5.31.- Voltage profile of Feeder 2 with a high level of PV generation.

Feeder 2 belongs to the TC1, which supplies energy to the most overexploited zone. As it can be observed in this graph, largest distances are covered by this feeder, supplying along it a great number of customers.

The first plot represents this feeder in case of having no PV installations at any part of the system. As the graphic shows, there exists a significant voltage drop, mainly caused by line losses. Along the first 40 m there are no nodes (no consumers), and the voltage drop is high (line losses).

When introducing the first level of PV-systems (2nd graph), it can be observed a clearly compensation of the voltage, which is produced by the nodes which have PV-systems interconnected to the network and therefore inject reactive power to the system. This feeder, at a certain point, is divided in three different branches. The plot shows which of them have more

PV penetration, since it can be easily seen how the voltage raises on each branch. In this case, the DG sources have been included at the ending nodes, in order to produce this effects of voltage compensation at most affected parts.

In Case 3, a high level of PV-systems is interconnected within the LV network. It can be clearly observed that just the opposite phenomenon than in Case 1 takes place: the voltage increases along the feeder, since all nodes have at least one PV installation injecting the excess of energy produced upstream, losing its radial behaviour. In this situation, it can be determined that an over-voltage is produced at final nodes of the feeder. It can be seen that at certain points, the system operates at 1,055 pu (422 V), which exceeds the maximum allowable voltage values.

- Feeder 13:

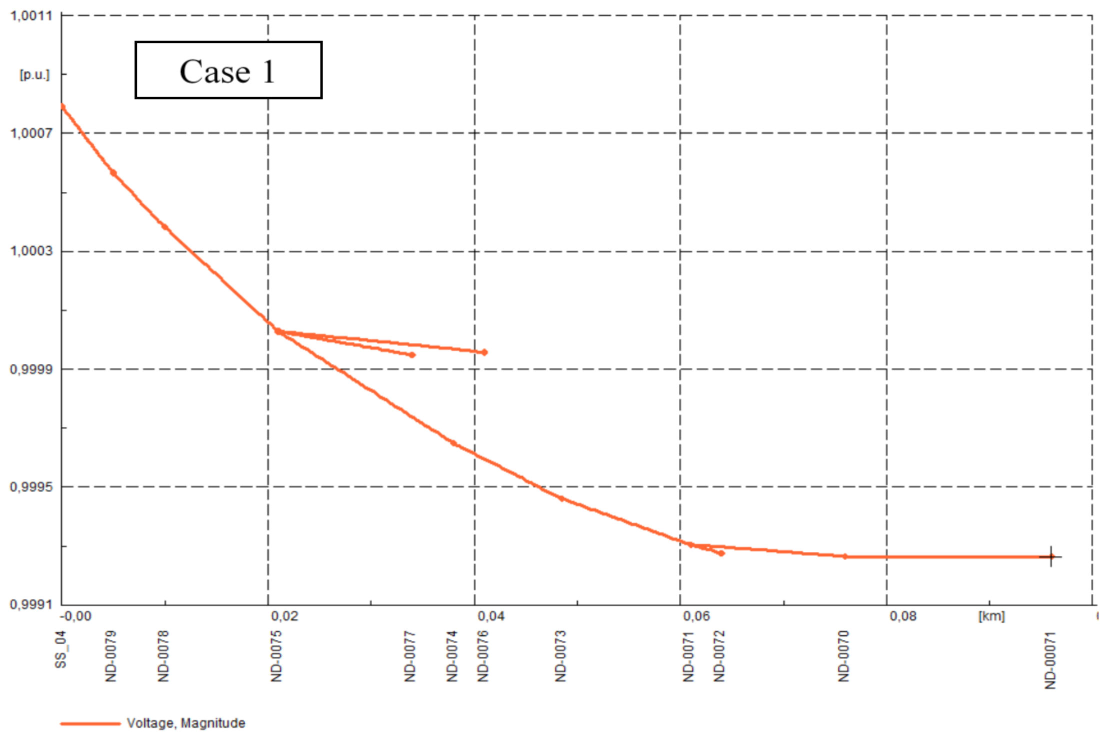

Figure 5.32.- Voltage profile of Feeder 13 without PV generation.

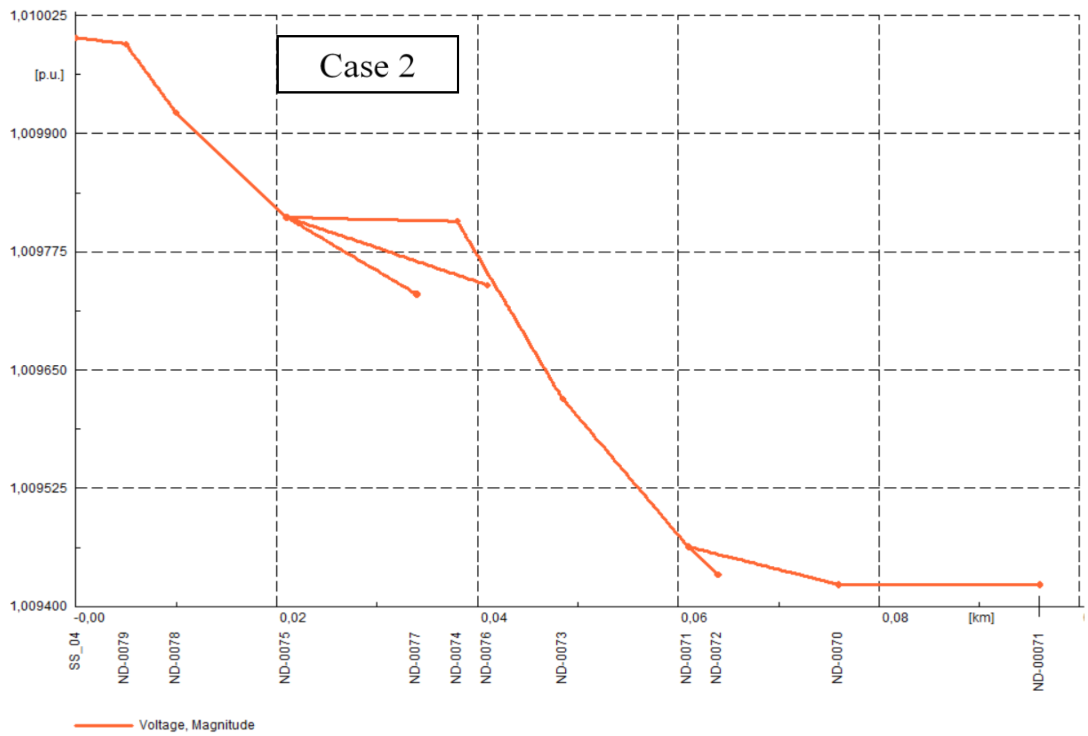

Figure 5. 33.- Voltage profile of Feeder 13 with a medium level of PV generation.

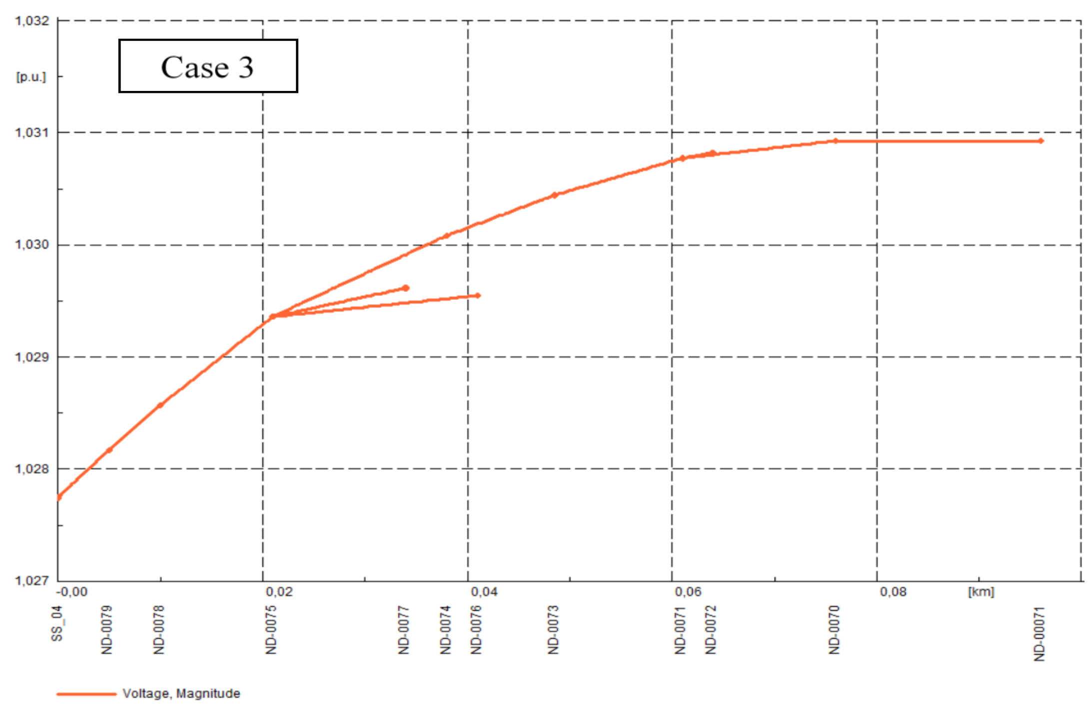

Figure 5. 34.- Voltage profile of Feeder 13 with a high level of PV generation.

Feeder 13 belongs to TC4, which supplies energy to Zone 4. In the first plot, it can be observed how the voltage decreases with length of the feeder. Notice that there exist two branches which separate from the mean branch to supply energy to two different nodes. Since the consumption is not as high as the one of the mean branch (which cover more users), the voltage drop is not so high.

In the second graph, it can be observed how the voltage profile changes depending on the site where the new generating sources are place. In this case, some PV installations have been incorporated at the middle part of the feeder, compensating in that part the voltage drop. Then, the voltage level decreases until reach the final nodes, on which some PV installations have been included also (less than on the middle part), compensating a bit the voltage drop.

On the 3rd case, similar to Feeder 2, the voltage drop is totally compensated by the PV-systems, since they are located at every node. In this case, the maximum voltage levels are around 1.03 pu (412 V), which are inside the voltage margins stablished by the distribution company and the Legislation.

- Feeder 3:

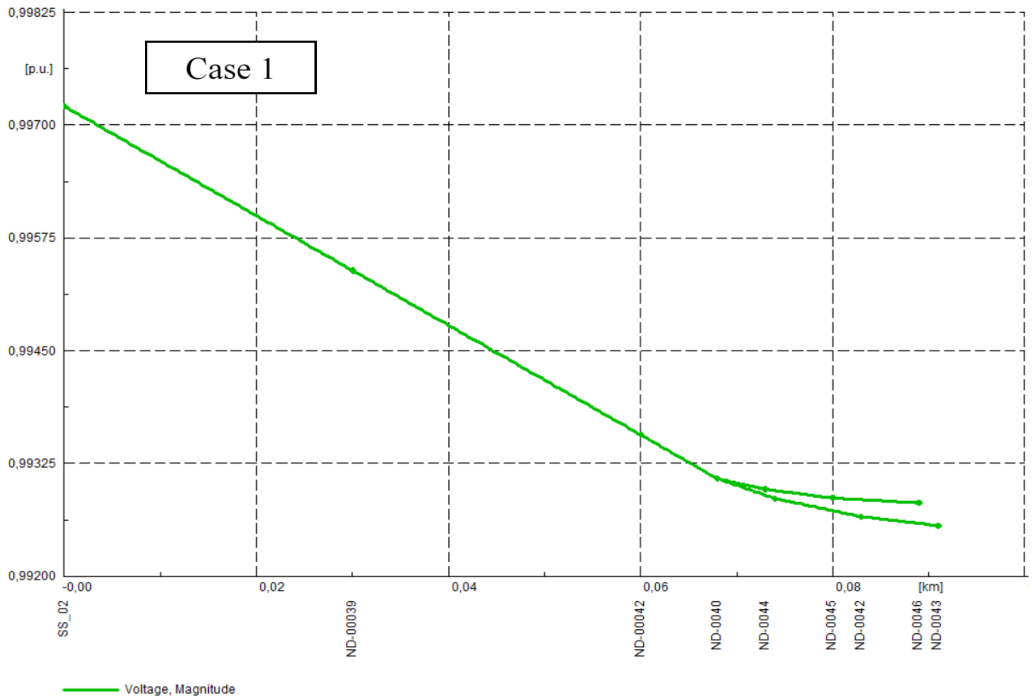

Figure 5.35.- Voltage profile of Feeder 3 without PV generation.

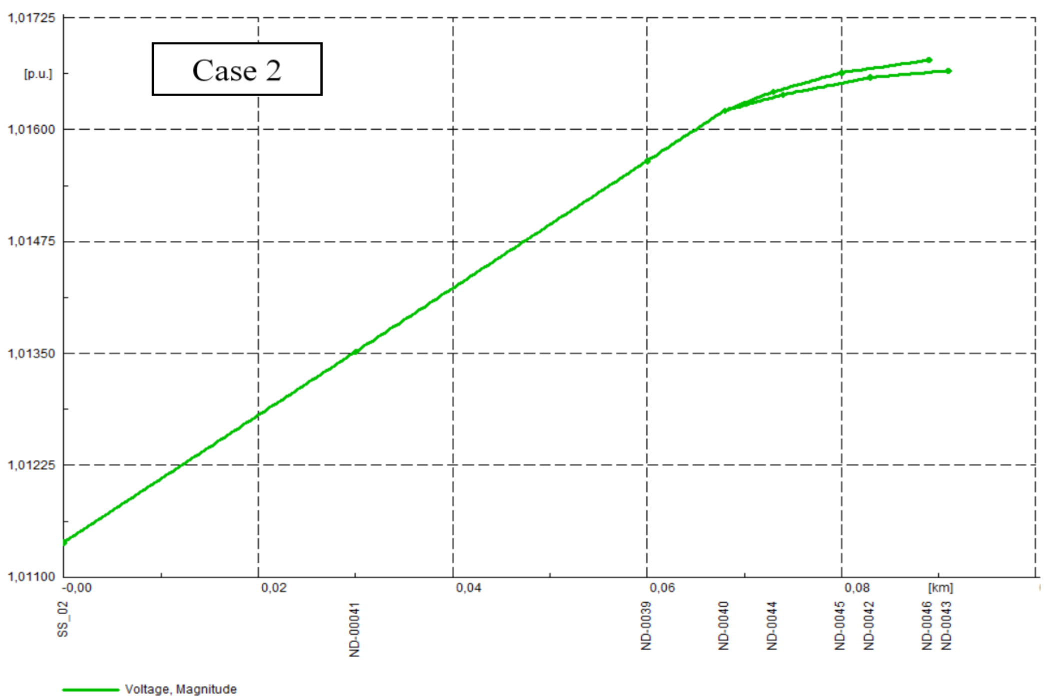

Figure 5.36.- Voltage profile of Feeder 3 with a medium level of PV generation.

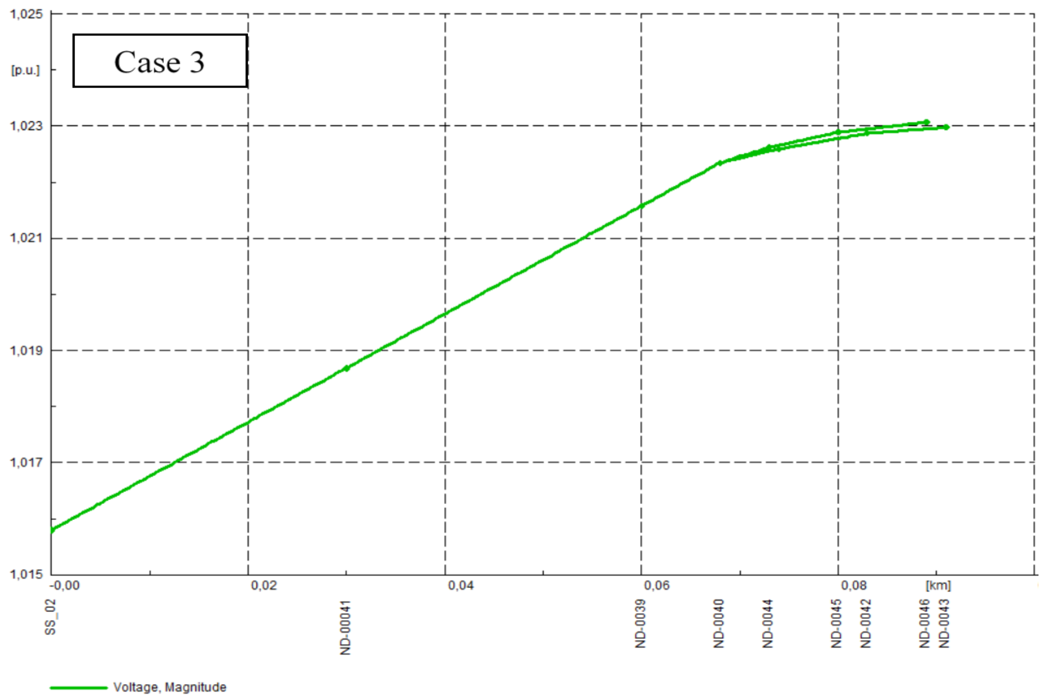

Figure 5.37.- Voltage profile of Feeder 3 with a high level of PV generation.

Feeder 3 belongs to TC2, which supplies energy to Zone 2. In the first plot, it can be seen how the voltage descends without any compensation, since no solar installations have been included on the system yet. It can also be mentioned that most consumers are located at final nodes, divided in two branches. The one with more consumption has more voltage drop.

Since most users are located at the ending nodes, the PV-systems for Cases 2 and 3 are also concentrated at such regions. As it has been seen on previous sections, in Case 2 of Zone 2, a high penetration level of DG was already included. Therefore, the differences between voltages in Cases 2 and 3 are small.

It can be seen that in both cases the voltage drop is clearly compensated (of course in the 3rd case with more intensity). It can be commented that, the previous mentioned branch with more consumers and therefore more voltage drop, is now closer to the other branch, as it has been compensated with more PV generation.

- Feeder 17:

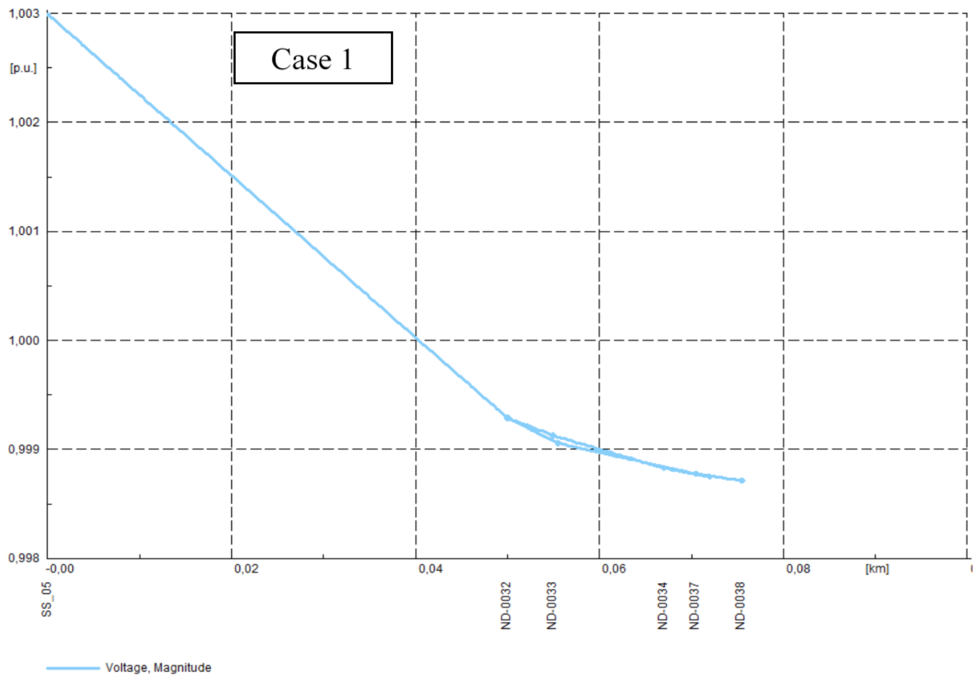

Figure 5.38.- Voltage profile of Feeder 17 without PV generation.

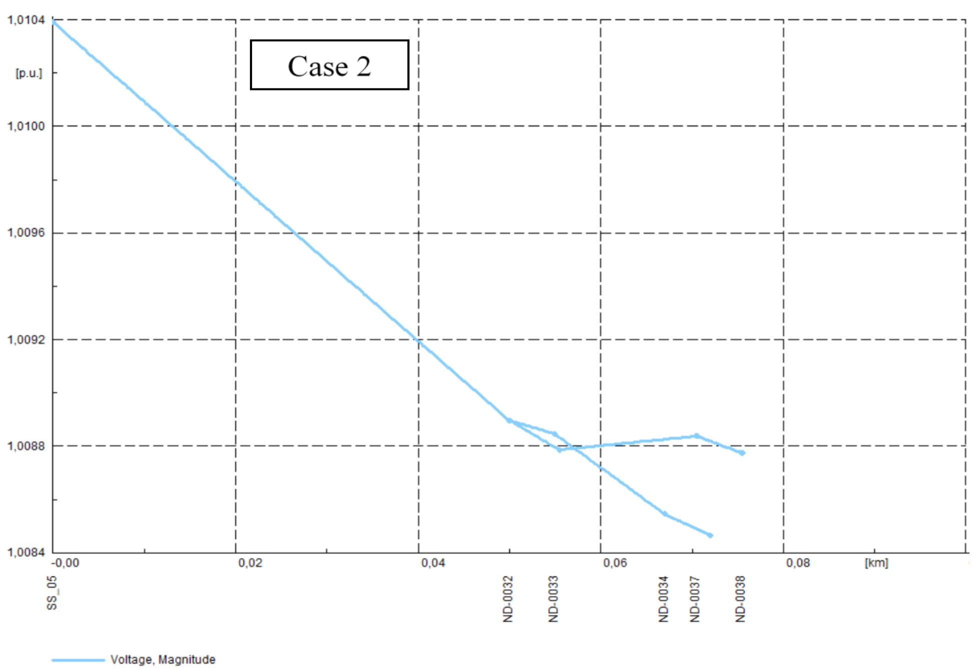

Figure 5. 39.- Voltage profile of Feeder 17 with a medium level of PV generation.

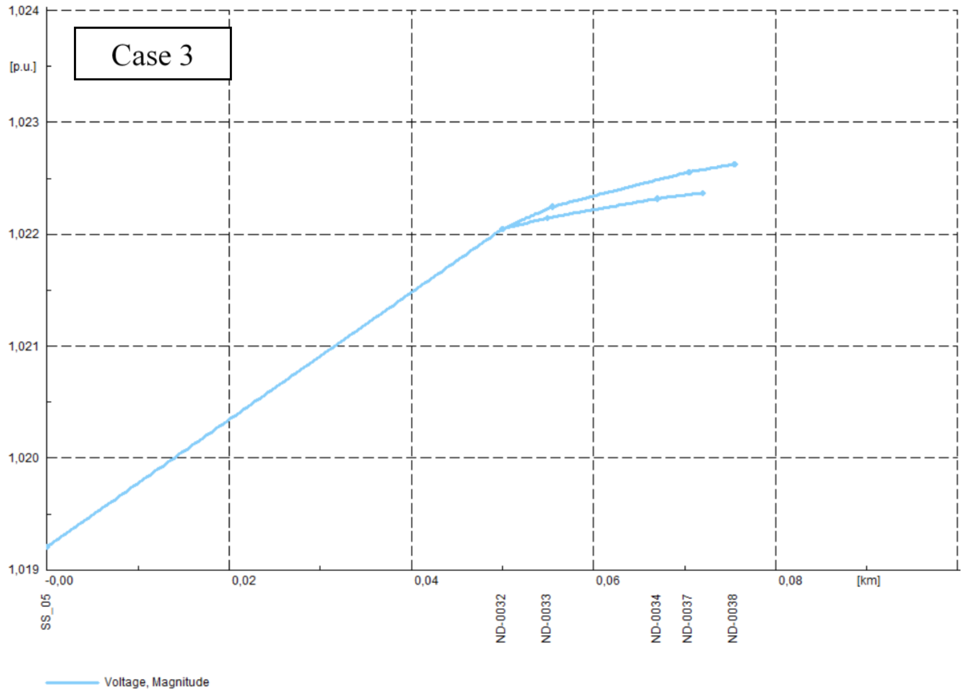

Figure 5.40.- Voltage profile of Feeder 17 with a high level of PV generation.

Feeder 17 belongs to TC5, which supplies energy to Zone 5. In this case, it can be seen that at the end of the feeder, it is divided into two different branches, where all consumers all located. The first plot shows the voltage drop that takes place along the feeder, and how the two ending branches have a similar behaviour, since the voltage drop in both is almost the same.

In the 2nd graph, when a medium level of DG is incorporated by some users, it can be observed that voltage is compensated better at the branch which includes the PV-system first. It is important to know that the penetration level of DG is the same in both branches, the difference lies in the distance from the beginning of the feeder, at which are located. Therefore, it can be concluded that in case of having a medium level of DG, is better to incorporate these new sources as closer as possible to the beginning of the feeder, in order to get a smoother voltage drop at the end of the branch.

In Case 3, it can be seen that one of the branches increases more its PV generation level than the other. Because of that, the voltage increases a little bit more, but this difference is not really significant. Both branches operate at correct voltage levels.

- Feeder 12:

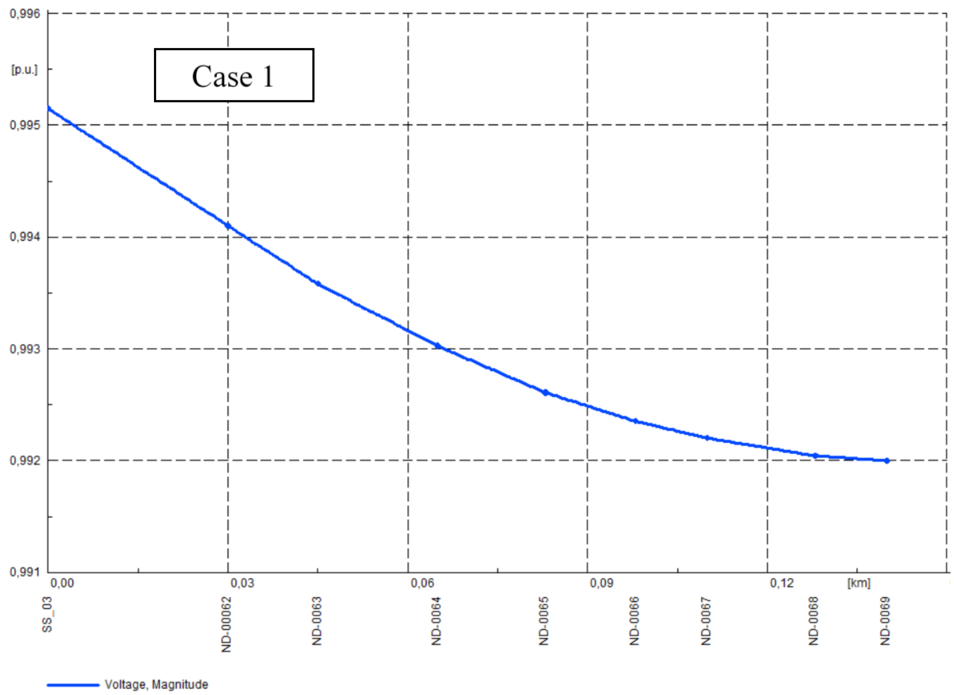

Figure 5.41.- Voltage profile of Feeder 12 without PV generation.

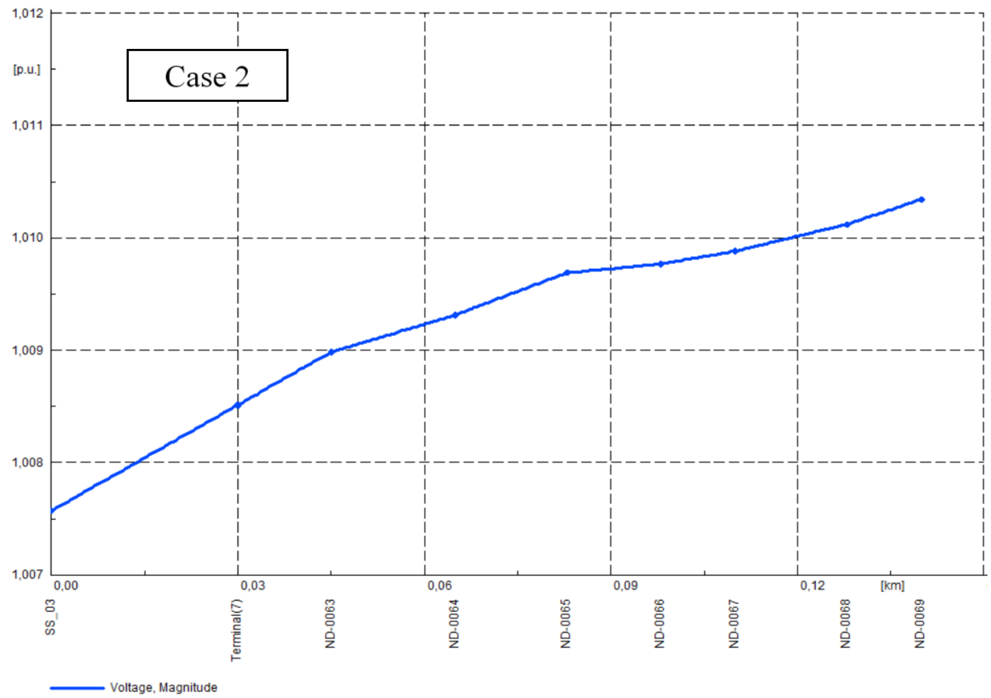

Figure 5.42.- Voltage profile of Feeder 12 with a medium level of PV generation.

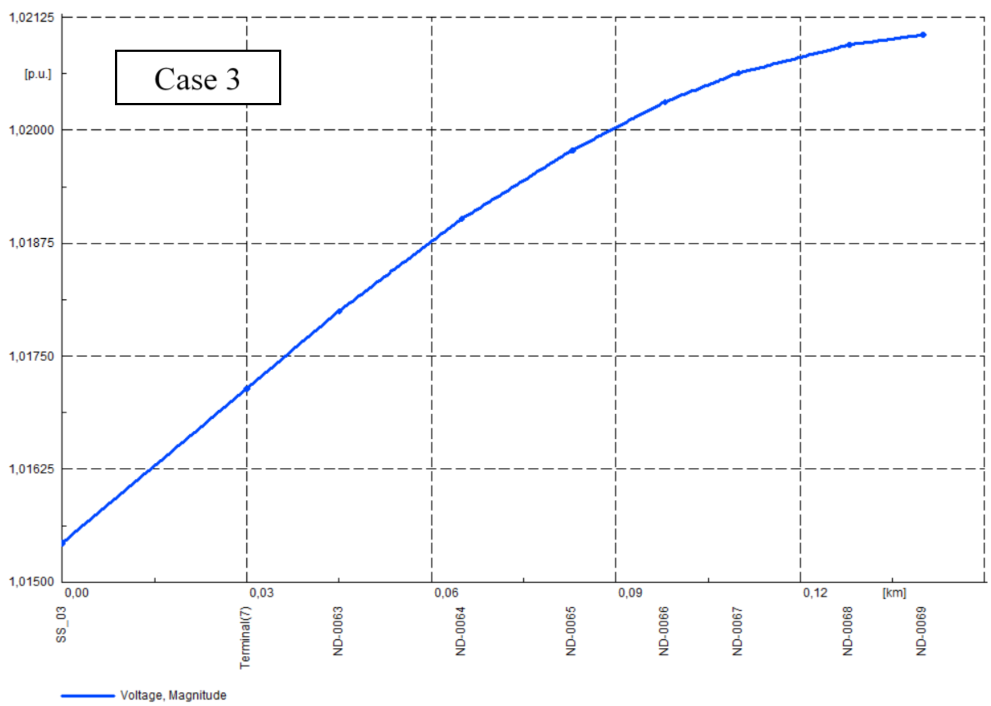

Figure 5.43.- Voltage profile of Feeder 12 with a high level of PV generation.

Feeder 12 belongs to TC3, which supplies energy to Zone 3. In this case, the feeder is not divided into several branches at any point. It behaves like a single line with various loads (consumers) located along its length. In Case 1, it can be observed a clear voltage drop through the line, as occurs in the rest of feeders in the first case.

In Case 2, it is interesting to know that some PV installations have been introduced into the system at different locations (at the beginning, at the middle part and at the end). This disposition compensates the voltage drop of the feeder, even increasing its level slightly.

Finally, the 3rd graph shows how the voltage of this feeder would behave when introducing a large amount of PV-systems. As it can be observed, the situation produced is just the opposite than in Case 1, since the power flows upstream. Even so, the operating voltages are inside the allowable values.

5.3.3.3.- Analyses of the final node voltage.

After the performance of the voltage profiles of the feeders which work under most critical operating conditions, from the point of view of most extreme voltage cases, it can be concluded that the final nodes are those which suffer more voltage variations.

Therefore, it results interesting to make a time-voltage study of the most exploited node, with the purpose of observe the voltage oscillations during a complete day and compare them with those produced at the busbars of the transformation centres. The evaluation mode will be similar to the 'Bus Voltage Analyses': the three cases will be represented simultaneously for each node.

Therefore, the evaluation node will be: ND-0024, from Feeder 2, which will provide information about the worst operational conditions.

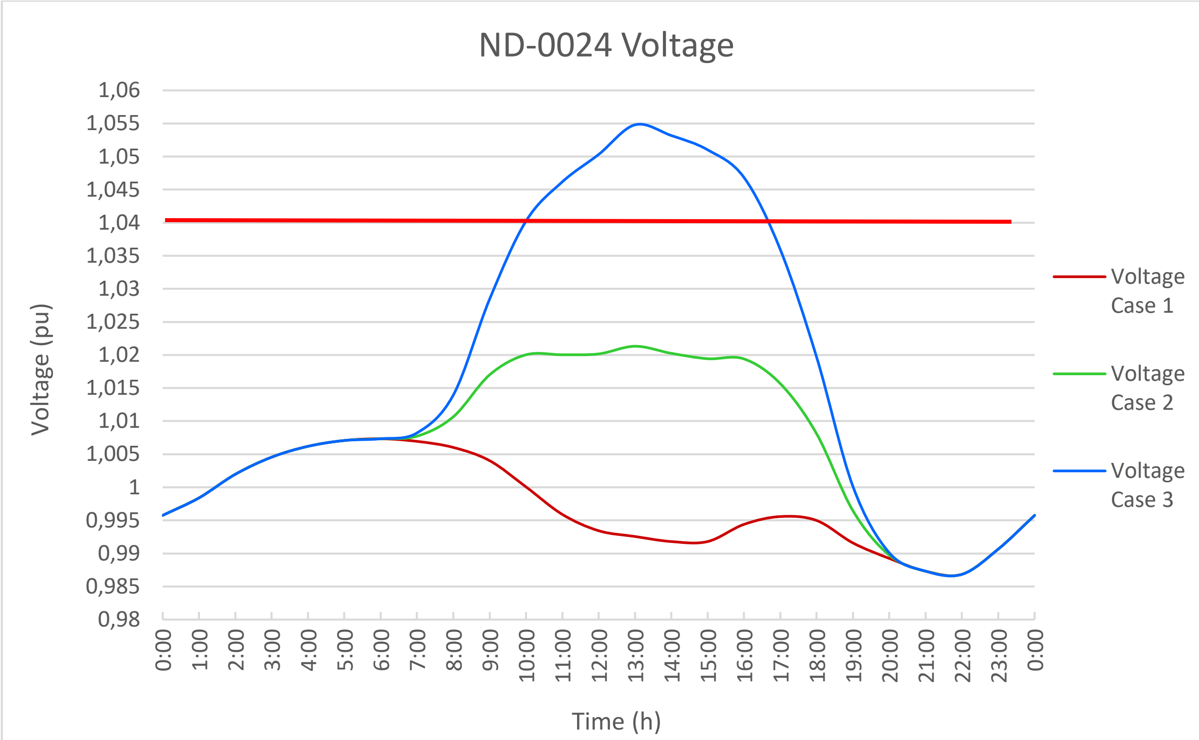

Figure 5.44.- Voltage variation of ND-0024 during a complete day.

ND-0024 belongs to TC1, which supplies energy to Zone 1.

As it can be seen, in case of having no PV installations on the system, the voltage levels are lower than those of their corresponding transformation centre busbar. This fact is produced principally, as seen on previous section, because of line losses along the feeder.

The most extreme operating conditions are produced in node ND-0024. As the first plot shows, in Case 3, at peak solar hours, the voltage reaches values which exceed the maximum allowable values by the distribution company. The curve oscillates significantly during the whole day. This behaviour, although not as severe as in ND-0024, is also produced in the rest of nodes. Therefore, it would be necessary to include some regulating system such as a battery, capable of store the excess of energy produced and then, inject such energy in case of network deficit. This solution will allow the system to operate under a more constant voltage level during all day.

In case 2, it can be seen that these oscillations are not as large as in Case 3. The PV-systems provides increments of voltage when more demand is produced, a is to say, when some important voltage drops take place. However, around 22:00-23:00, the load consumption is highly increased, and no solar generation is produced at that moment.

5.4.- PROTECTION ELEMENTS ANALYSES.

The analyses performed in this section are intended to ensure a proper working of the protection devices of the system under the new operating conditions. Therefore, it will be necessary to make studies of the relay of the substation and the currents flowing through the feeders which exit the TCs, protected with fuses.

The analyses will be made at worst operational conditions, when current levels are more significant. This means that the study time will be set at peak PV generating hours. As on previous sections, this will be around 14:00.

5.4.1.- Substation Relay Analyses.

The studies performed in this section will be made by causing short-circuits in strategic points, and observing whether the relay fulfil its function properly or not.
It will also be evaluated the behaviour of this device in normal operating conditions (without failures), as is to say, by implementing a simple load flow and checking if the increment of current affects to this device.

To make a suitable analyse of the relay of the substation, the short-circuits will take place in two critical points of the system: the principal node of the substation and the farthest node from the substation of the model (ND-0024). Three phase short-circuits, as well as single phase to ground short-circuits will be evaluated.

In this section, time current plots will be used, as explained on chapter 'XX'. In this case, is not possible to draw the data obtained to create graphs in excel files. Hence, the plots used will be those provided by the software.

5.4.1.1.- Analyses in normal operating conditions.

In this sub-section, the plots corresponding to the three different study scenarios, will be represented consecutively; comments will be included after them.

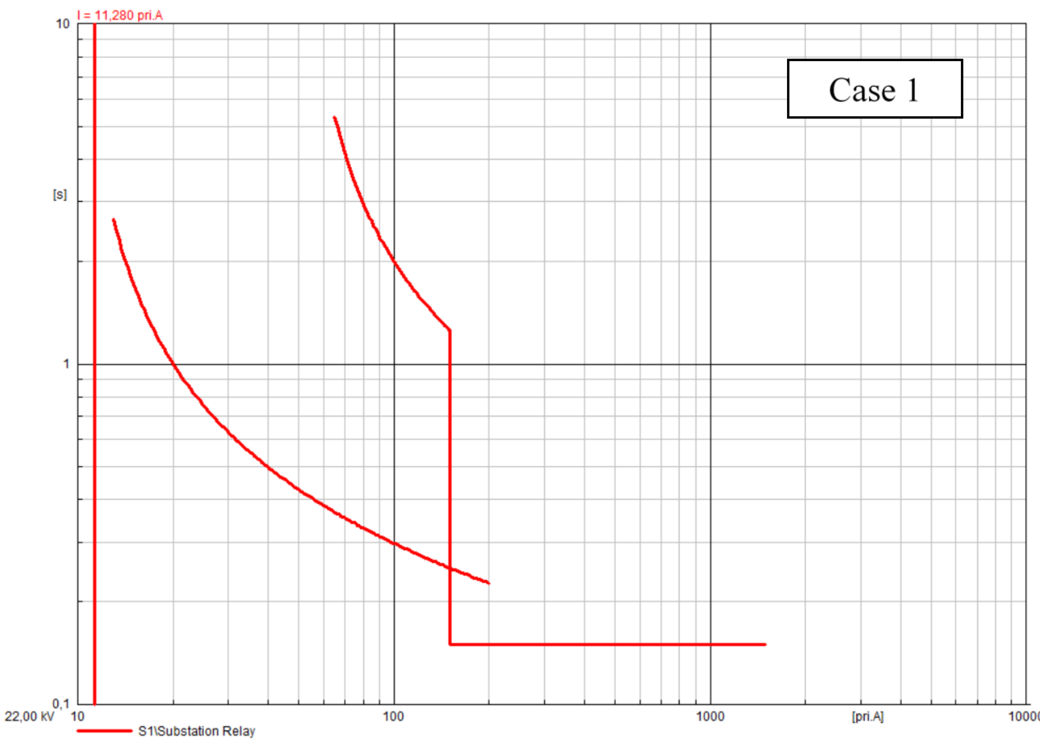

Figure 5.45.- Relay behaviour during a load flow without PV generation.

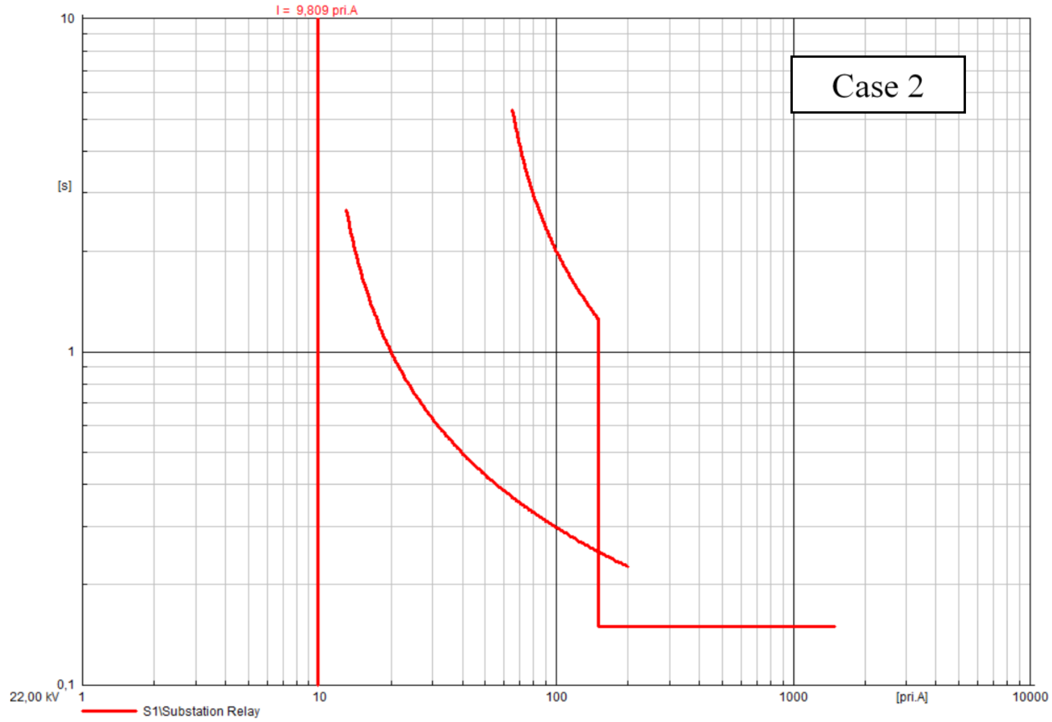

Figure 5.46.- Relay behaviour during a load flow with a medium level of PV generation.

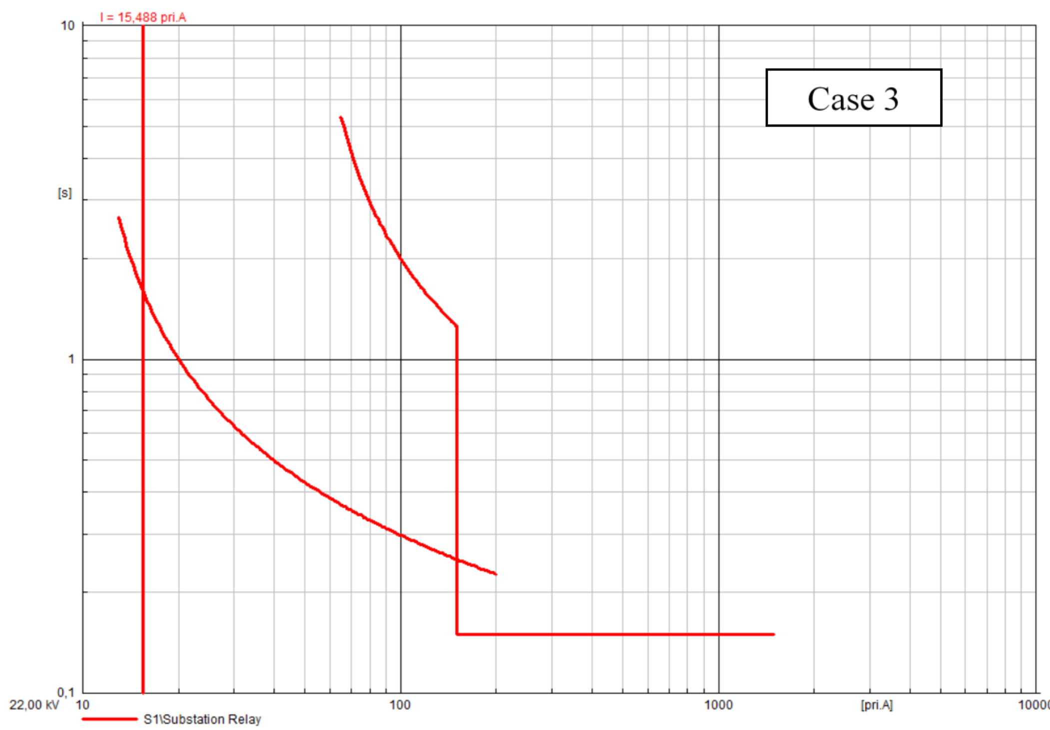

Figure 5.47.- Relay behaviour during a load flow with a high level of PV generation.

The plots represent the current flowing through the relay at the same time but varying the level of penetration of DG sources existing on the system.

In the first and second plot (Case 1 and Case 2), there is no problem with the circulating current, since it is no high enough to cause the relay to trip. It can be seen how the current is lower in Case 2. This is because the needed current to supply the load demand is lower since the PV-systems are covering part of such demand.

In Case 3, it can be clearly observed that the circulating current crosses the inverse earth curve of the relay. This situation will cause the associated circuit-breaker to trip when operating in non-failure conditions.

This behaviour is not desirable at all. Therefore, it would be necessary to regulate the generating current or substitute the existing relay for another one.

5.4.1.2.- Three phase short-circuit analyses.

- Substation Node.

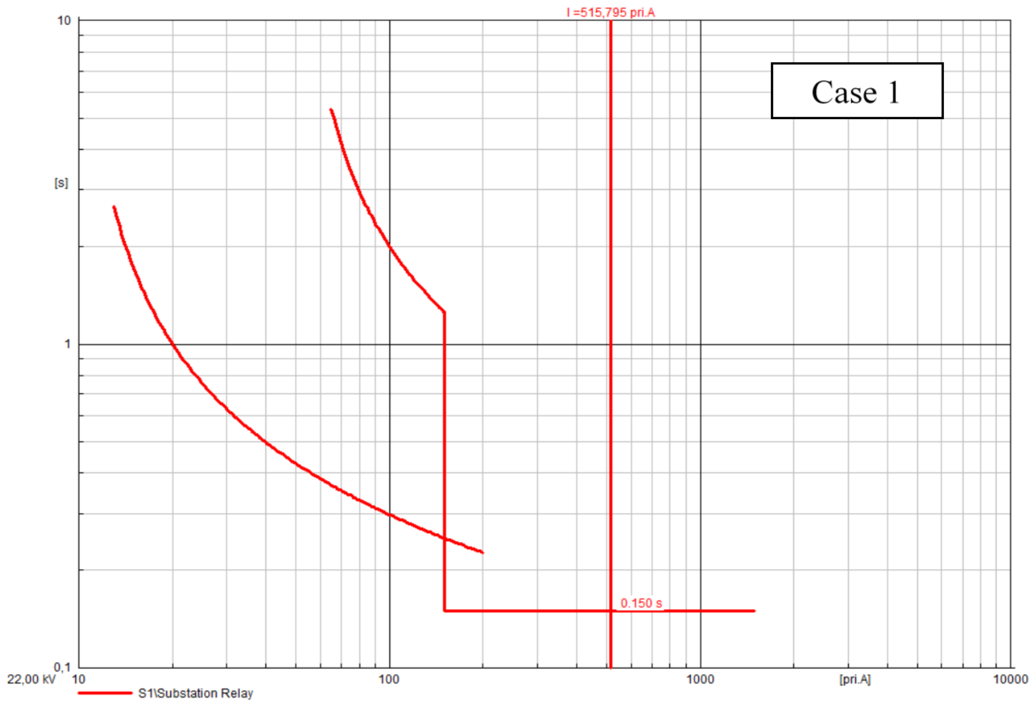

Figure 5.48.- Relay behaviour during a 3-phase short-circuit at the substation node without PV generation.

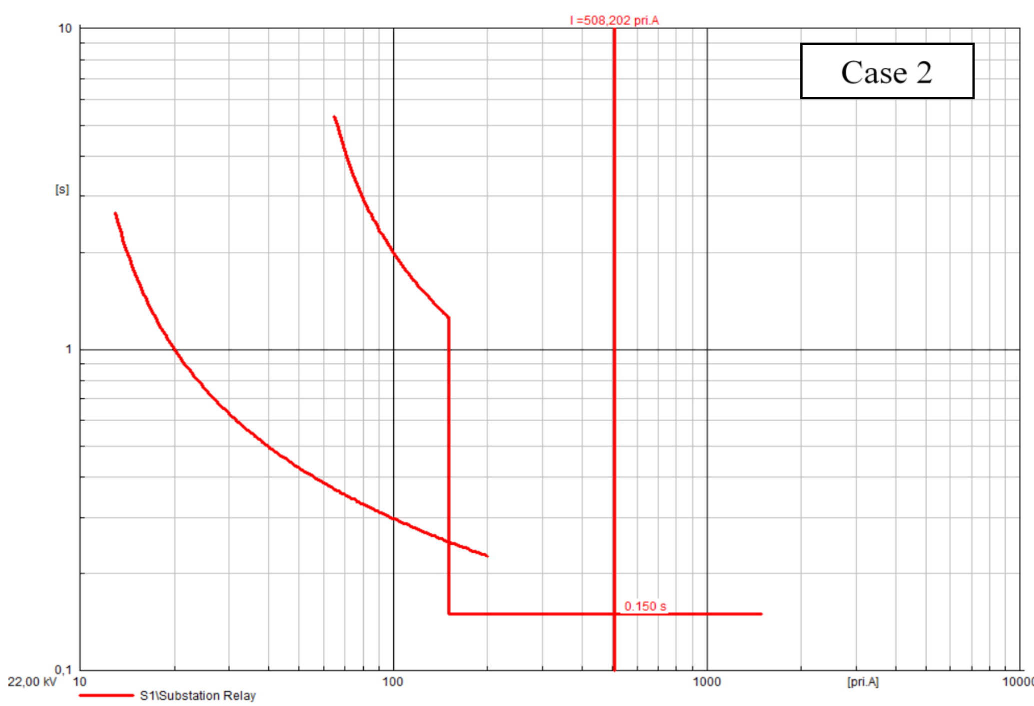

Figure 5.49.- Relay behaviour during a 3-phase short-circuit at the substation node, with a medium level of PV generation.

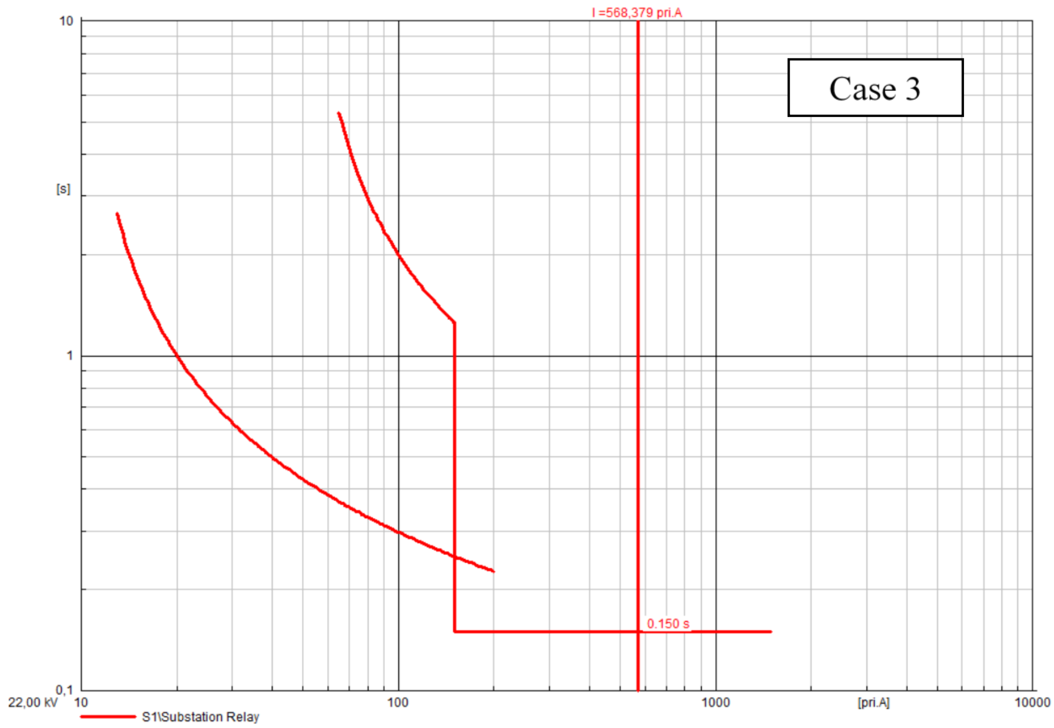

Figure 5.50.- Relay behaviour during a 3-phase short-circuit at the substation node, with a high level of PV generation.

Regarding with the three phase short-circuits at the substation node, it can be concluded that the relay behaviour does not suffer important variations, since this component performs its task correctly in all cases.

- ND-0024.

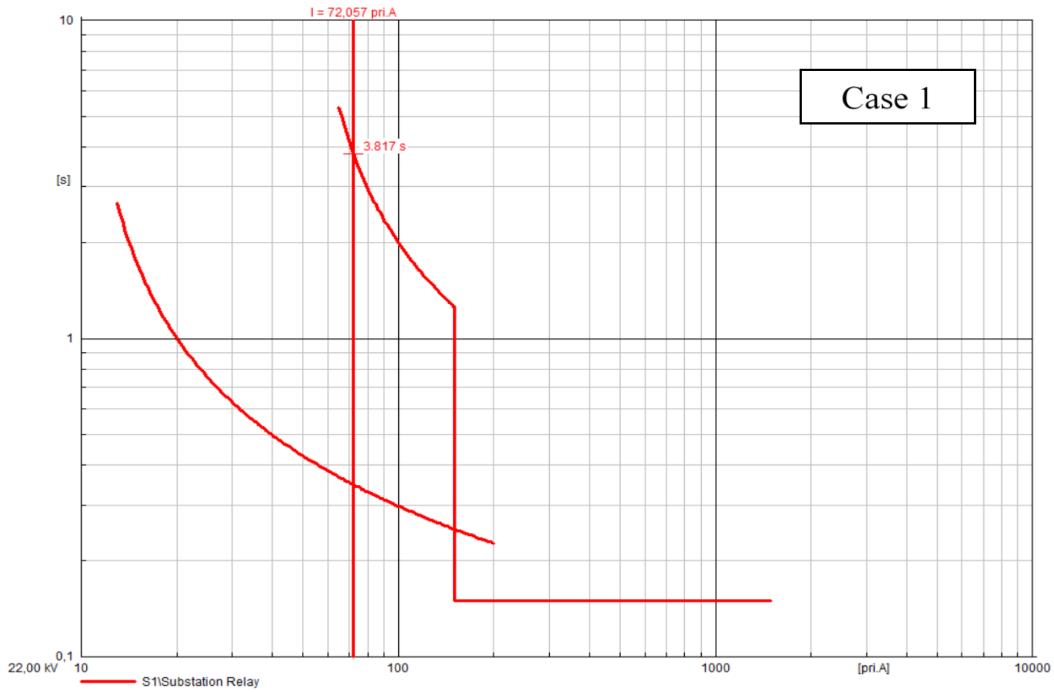

Figure 5.51.- Relay behaviour during a 3-phase short-circuit at ND-0024, without PV generation.

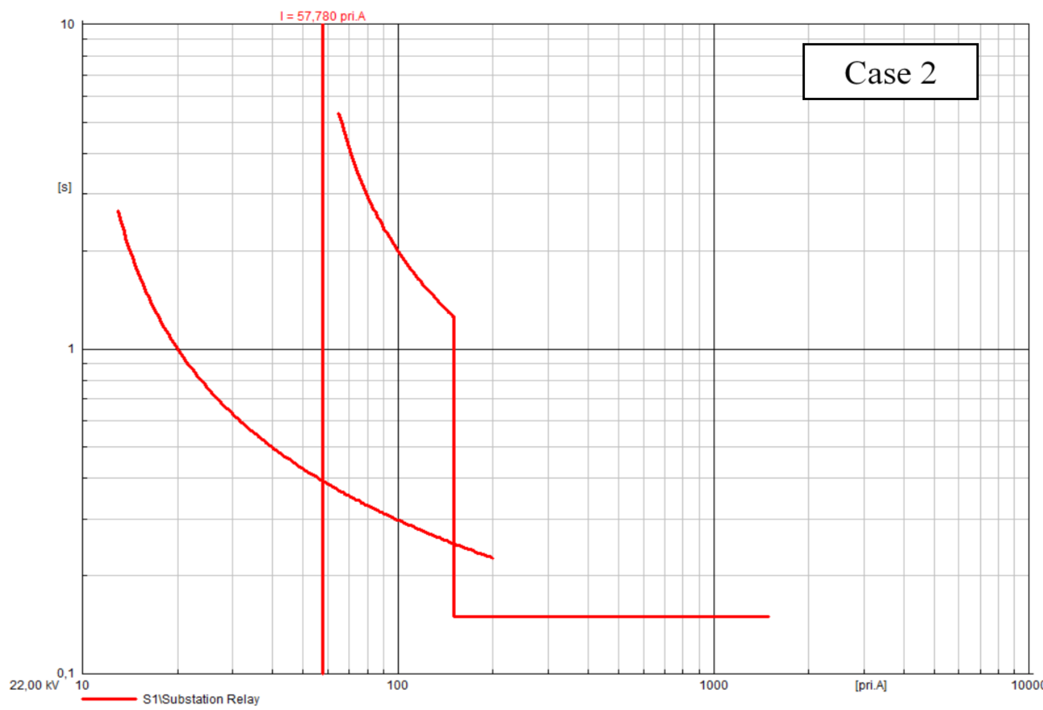

Figure 5.52.- Relay behaviour during a 3-phase short-circuit at ND-0024, with a medium level of PV generation.

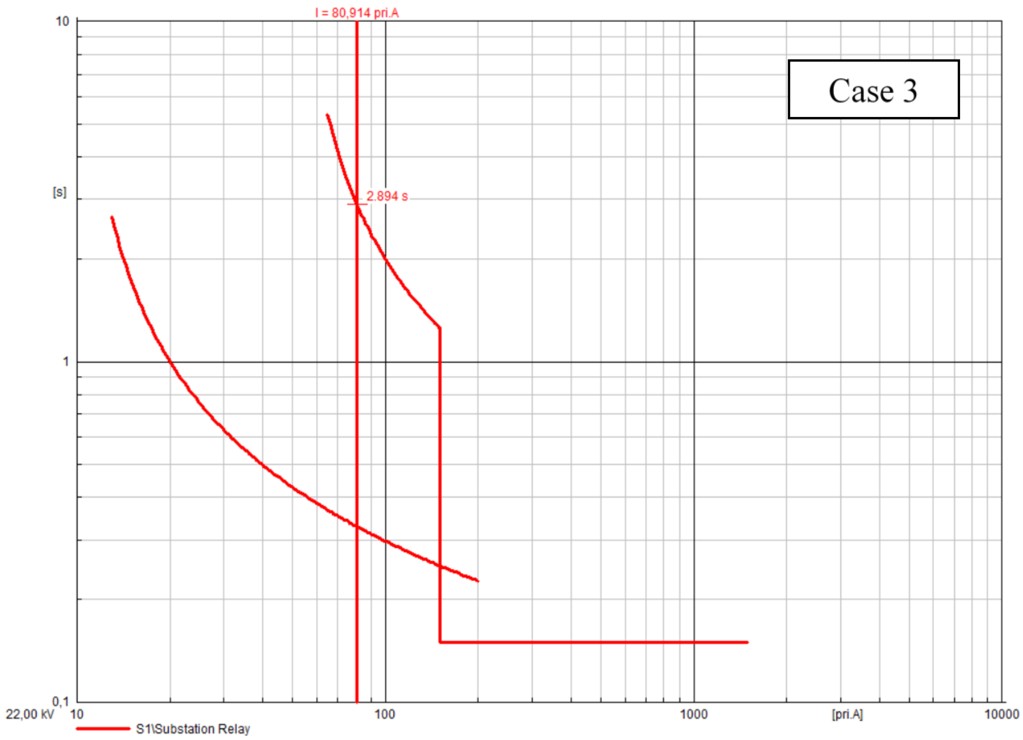

Figure 5.53.- Relay behaviour during a 3-phase short-circuit at ND-0024, with a high level of PV generation.

The relay performs again properly its function in all cases if a short-circuit would take place on the farthest node of the system from the substation. It can be observed some variations in the current levels, but not large enough to cause significantly changes which lead to inapropated behaviours of the relay.

5.4.1.3.- Single phase to ground short-circuit analyses.

- Substation Node

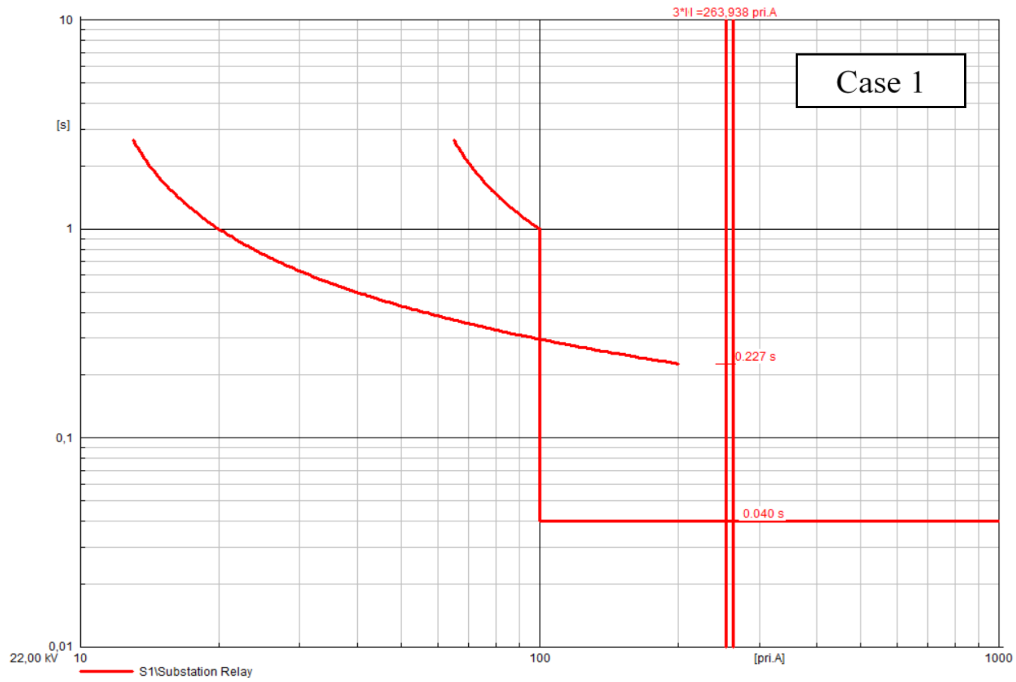

Figure 5.54.- Relay behaviour during a single phase to ground short-circuit at the substation node, without PV generation.

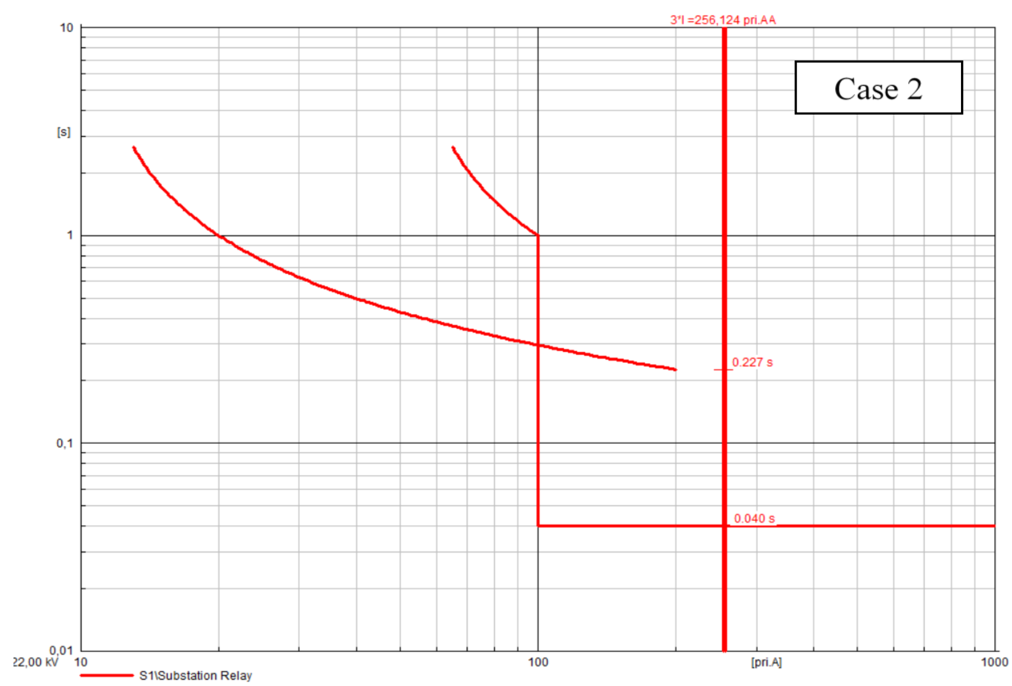

Figure 5.55.- Relay behaviour during a single phase to ground short-circuit at the substation node, with a medium level of PV generation.

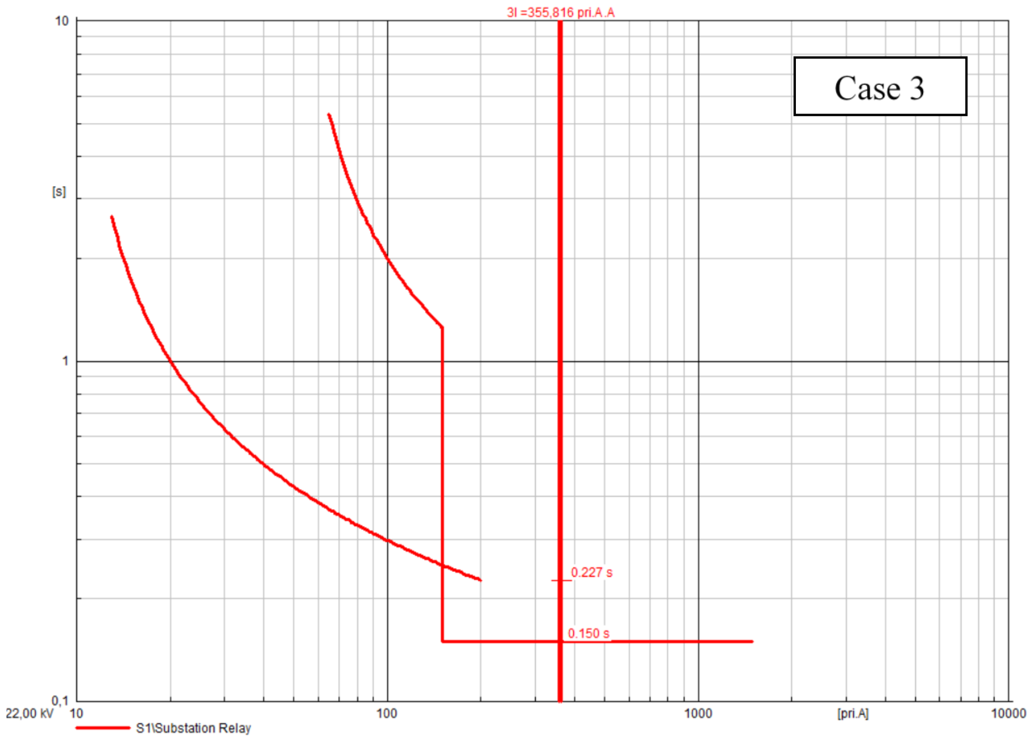

Figure 5.56.- Relay behaviour during a single phase to ground short-circuit at the substation node, with a high level of PV generation.

The same occurs in case of having a single phase to ground short-circuit at the substation node. The relay performs correctly its role.

5.4.2.- Analyses of the feeders' currents: Fuses evaluation.

During the section of 'Load Flow Analyses' it have been studied power flows of the total evaluating network, as well as in all defined zones; voltages levels at several parts of the system, looking for the most interesting operating conditions; and some studies about the load of the transformers.

The latter is directly related with the currents of the system, but they are not enough to provide the needed information in order to check that all feeders satisfy the stablished rated voltage of the fuses which belong to the transformation centres (160 A as maximum value). It will also be tested the loading capacity of the existing lines, since these elements cannot exceed a determined value of current.

In order to make a proper evaluation of this issues, it will be necessary to use again the 'Quasi-Dynamic Simulations' tool. This time, the currents flowing through the feeders (at the very beginning of them, just when they exit the TC) will be selected to be represented on a graph. In this way, the highest current values of the system will be registered and showed with respect to time, in order to know when this events take place.

In this case, three charts (one for each different study case) will be used to represent the current levels of each feeder.

- Case 1:

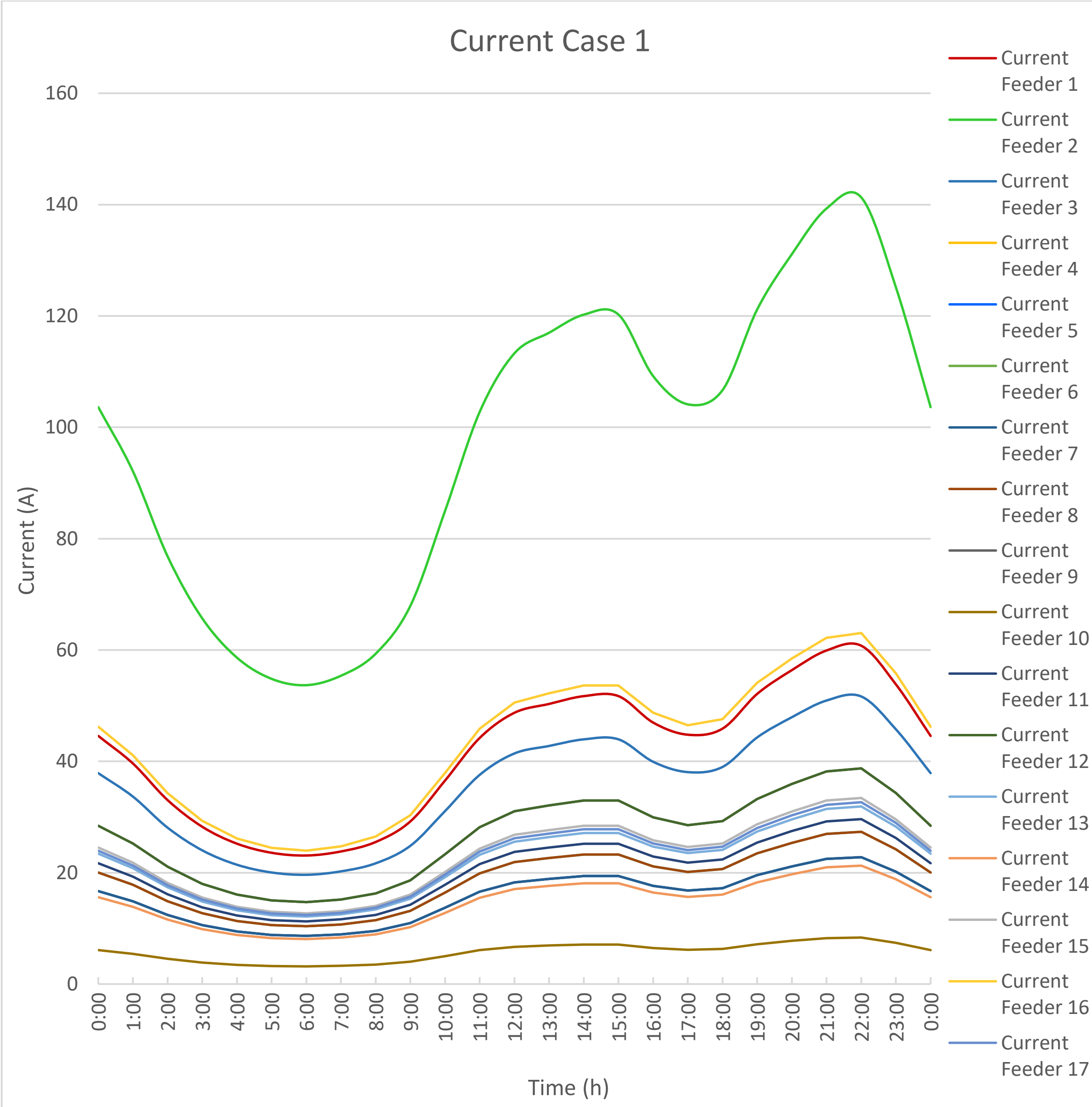

Figure 5.57.- Currents of feeders during a complete day, without PV generation.

In Case 1, no PV installations have been introduced yet on the system. Therefore, the current levels plotted in the chart above show the values corresponding to normal operating conditions.

As it can be observed, the Feeder 2 (light green), which belongs to TC1, represents the most overexploited feeder. This fact is due to the high density of consumers and the high length of its branches. The rest of feeders operate with more adequate current values.

The current curve follows the same path than the consumption curve does, since in this case, the current is being supplied radially to costumers downstream, without any additional generation source. It can be seen how the current consumption decreases significantly at peak-off hours, taking its lowest value at 6:00, and how the current reaches its maximum value at peak consumption hours, around 22:00.

In this chart, it can be seen that all feeders follow this curve shape, of course with different current levels which depend on the consumption of each feeder zone.

- Case 2:

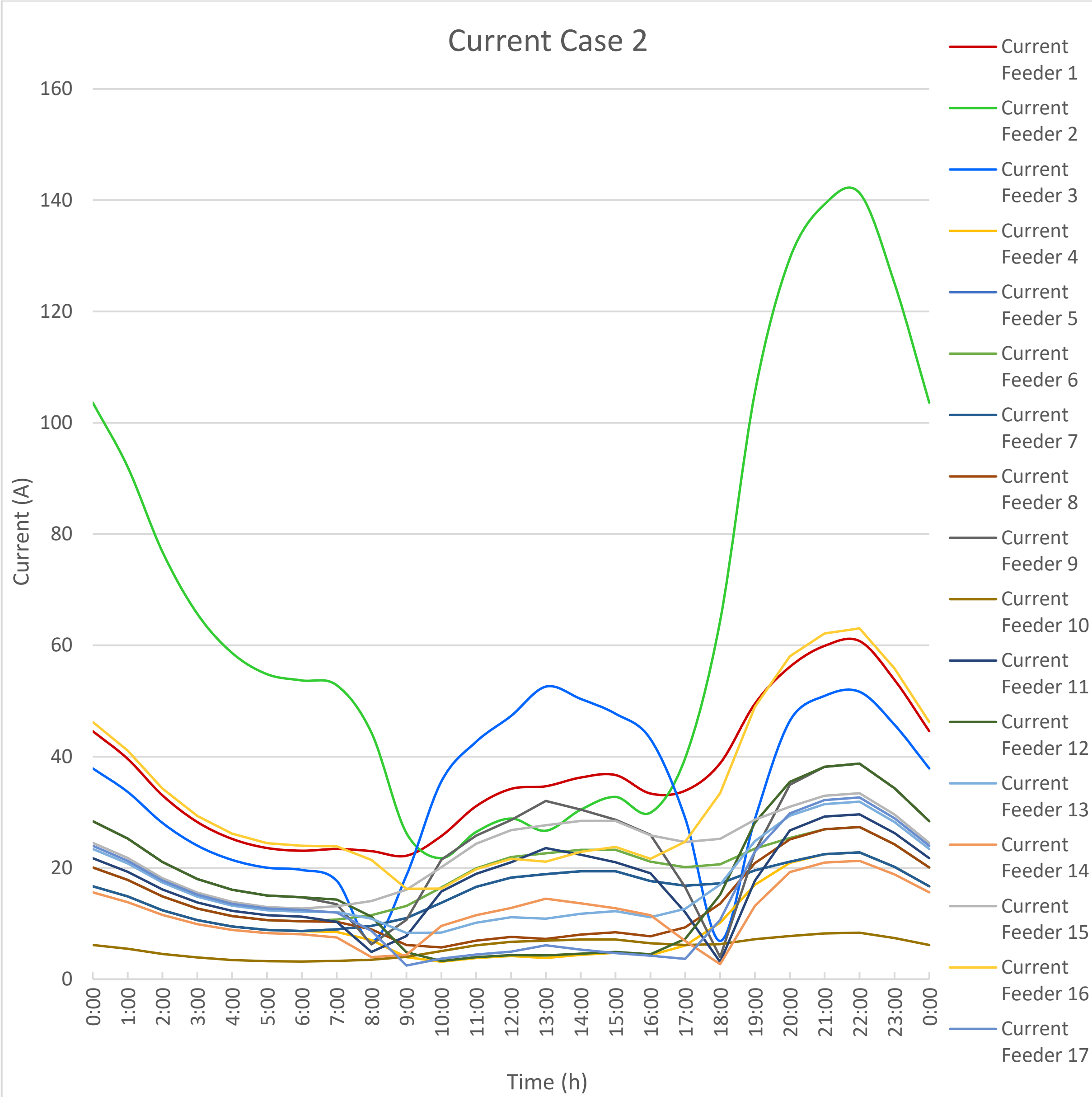

Figure 5.58.- Currents of feeders during a complete day, with a medium level of PV generation.

The chart now shows the current levels of all feeders of the system during a complete day in case of having a medium level of DG interconnected on the system. It can clearly be observed that several changes are produced during the operating hours of the PV-systems on the current curves

As viewed on Figure 5.12, the TC3 in Case 2 exports energy to external networks or zones. In this plot, it can be observed how Feeder 3, which belongs to TC3, increase its current level while in the rest of them decreases. First it is needed to explain that the current in Feeder 3 is being exported, since the generation exceeds the consumption in such feeder. Therefore, this current is flowing upstream, which means negative currents, although absolute values of currents are used in this plot. The reason why in the rest of cases the current decreases is because of the fact that, the PV generation is lower than the load consumption, and the demand is partially covered by these new sources. Therefore, the TCs needs to supply less current to consumers.

It can be concluded that, in case of having a medium level of PV generation on the system, the current levels are generally reduced when such sources operate. A clear case of this behaviour is produced in Feeder 2, where feeder currents are highly reduced, changing significantly its current curve. In other feeders, it can be observed that the current curve is more linear during operating PV periods than in Case 1, since PV generation compensates very well the current demand.

It can be determined that in this hypothetical case, current values do not exceed the maximum allowable values of the system at any moment, which are stablished by the fuse of the TCs at 160 A.

- Case 3:

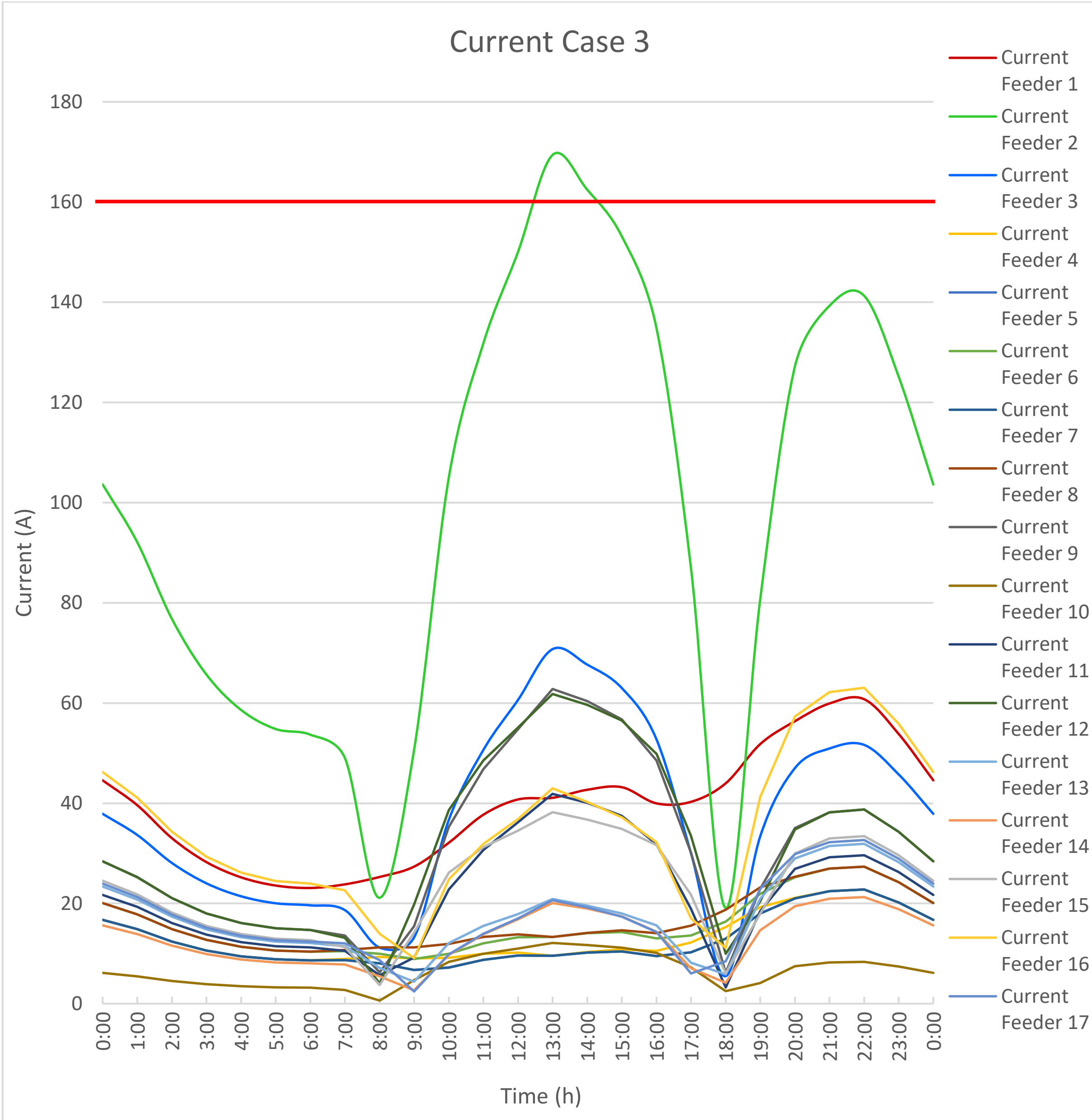

Figure 5.59.- Currents of feeders during a complete day, with a high level of PV generation.

In case of having a large level of PV-systems interconnected within the LV network, the results regarding with the circulating currents trough the different feeders are exposed on the plot above.

First of all, it is important to remember that in this case, in all feeders the generation produced by the PV sources at peak hours is higher than the load consumption. Therefore, in some moments the current flows upstream in all feeders, acquiring negative values, although absolute values are used in these graphs (magnitude representation).

Due to the increment of PV generation, most feeders increase their flowing currents with respect to Case 1. It is interesting to indicate that the current flowing through the feeder is the generated minus the consumed. Therefore, in other cases, the flowing current (after covering the demand) is not as high as the one needed when no PV generators are used.

The most significant case is the Feeder 2 current. In this feeder, an extreme case of penetration of DG is produced. The current reaches values at solar peak hours that exceed the maximum allowable ones. This situation will cause the fuse of the TC1 to actuate in normal operating conditions, as is to say, without failure conditions. The loading of the line, which is set to 190 A will also be at risk, since very close circulating current values are achieved.

Therefore, it can be concluded that this feeder would have to reduce its PV generation in order to satisfy the required operating conditions.

In feeders which are at lowest current ranges, it can be appreciated how the currents are well compensated, stabilizing the current curve in PV generating moments. This will be the ideal situation for all cases. As it is very difficult to be produced without control, some control system will have to be incorporated in order compensate correctly the current curve.

5.5.- HARMONIC ANALYSES.

The total harmonic distortion voltage wave generated by the inverter, is a measure of the quality of the power generated by the inverter, which has to satisfy the legislation existing on the international standards. Inside such standards, it is indicated that the THD has to be lower than

5% when the total harmonic distortion of the voltage wave of the power grid on which it is connected is less than 2%.

Since several PV installations are connected with their respective power inverter (specially in Case 3), several harmonic contents will be introduced to the power network, increasing the total harmonic distortion of the voltage wave of the LV grid.

Additionally, the legislation indicates that the individual harmonic distortion of each harmonic component, has to be lower than 3 %.

In order to check that this statements are accomplished, harmonic distortion analyses will be carried out at the busbars of the TCs. This will allow to know whether the HD for each component, as well as the THD of the voltage wave, are operating under suitable conditions.

In order to make these analyses, the 'Harmonic Distortion Analyses' tool will be used for Cases 2 and 3. Of course, in Case 1 the harmonic content at the transformation centres is '0', since there are no other elements programmed on the software which modify this characteristic.

Since these analyses are not represented in graphs with respect to time, a first analyse has been previously made, which provide information about the moments on which the harmonic distortion injections are higher. The output results showed that critical moments coincide with solar peak hours, as is to say, when the PV generation is maximal.

Therefore, the setting time for this studies has been selected in order for the system to operate with the most adverse conditions, in other words, when the harmonic injection is maximal.

5.5.1.- Analysis of the Harmonic Distortion of the harmonic components:

In this section, an analysis of the harmonic distortion of the individual harmonic components injected in LV network by the power converters of the defined zone, will be made at the busbar of each substation.

As in Case 1 there are no elements which affect to these evaluations, it just will be necessary to plot Case 2 and Case 3. The five different busbars, belonging a determined TC, will be represented on the same plot together for each case.

- Case 2;

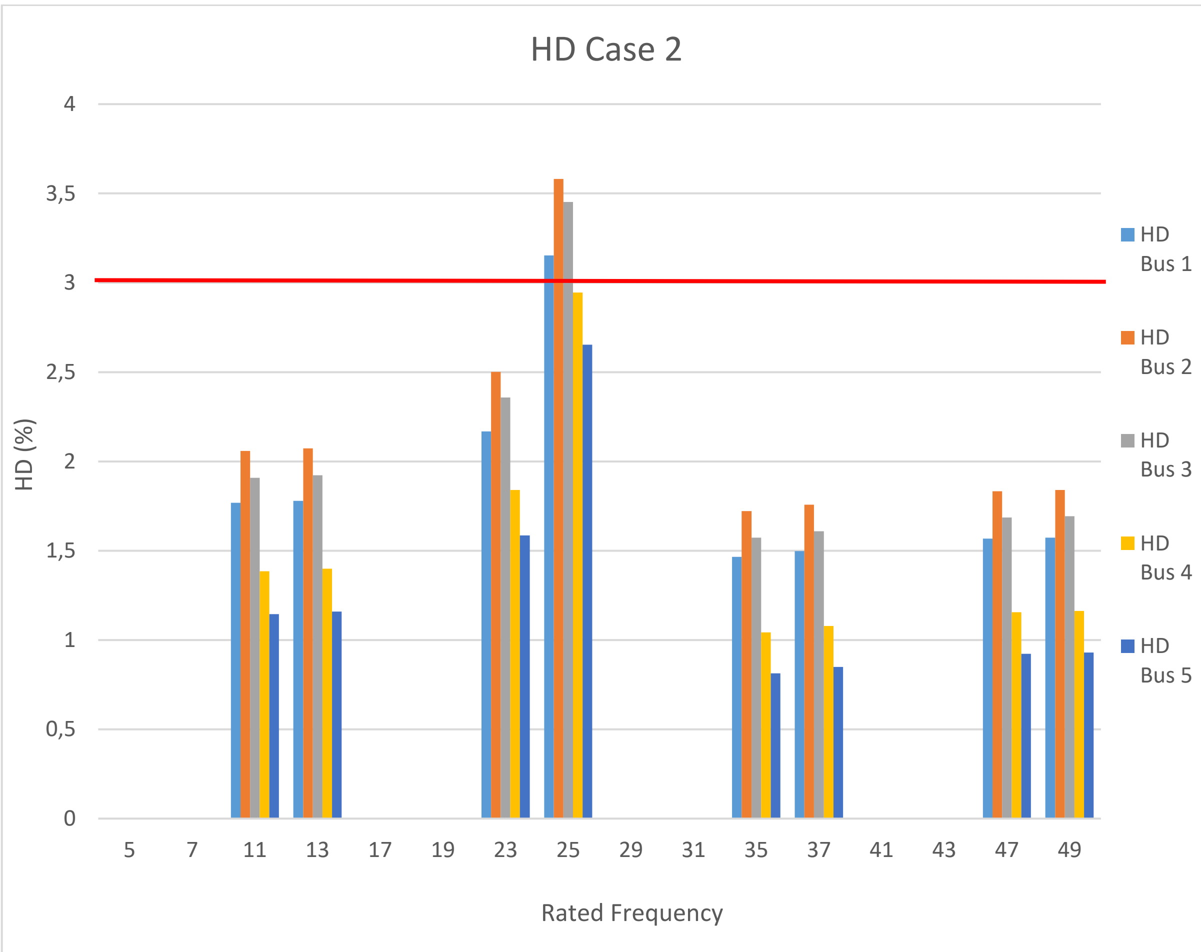

Figure 5.60.- Harmonic distortion of the harmonic components of the voltage waveform at the different busbars of the TCs, with a medium level of PV generation.

The graph above shows the HD content for each significant harmonic components of the voltage wave which is obtained at the busbars of the TCs in case of having a medium level of PV installations interconnected to the LV network.

First, it is necessary to comment, that: in the situation produced on previous analyses of Case 2, the load consumption did not exceed the PV generation in the evaluated zones (except in Zone 2). However, the inserted PV sources inject the excess of energy produced to the LV network in order to supply energy to other consumers of their same region. Therefore, harmonic contents are introduced into the network.

In this case, it can be observed that the HD of the individual components exceed the maximum allowable value (3%) in Bus 1, Bus 2 and Bus 3. It can be seen how Bus 2, which is the one which exports energy in Case 2, reaches the highest value of HD at a frequency of 25x50 Hz.

- Case 3:

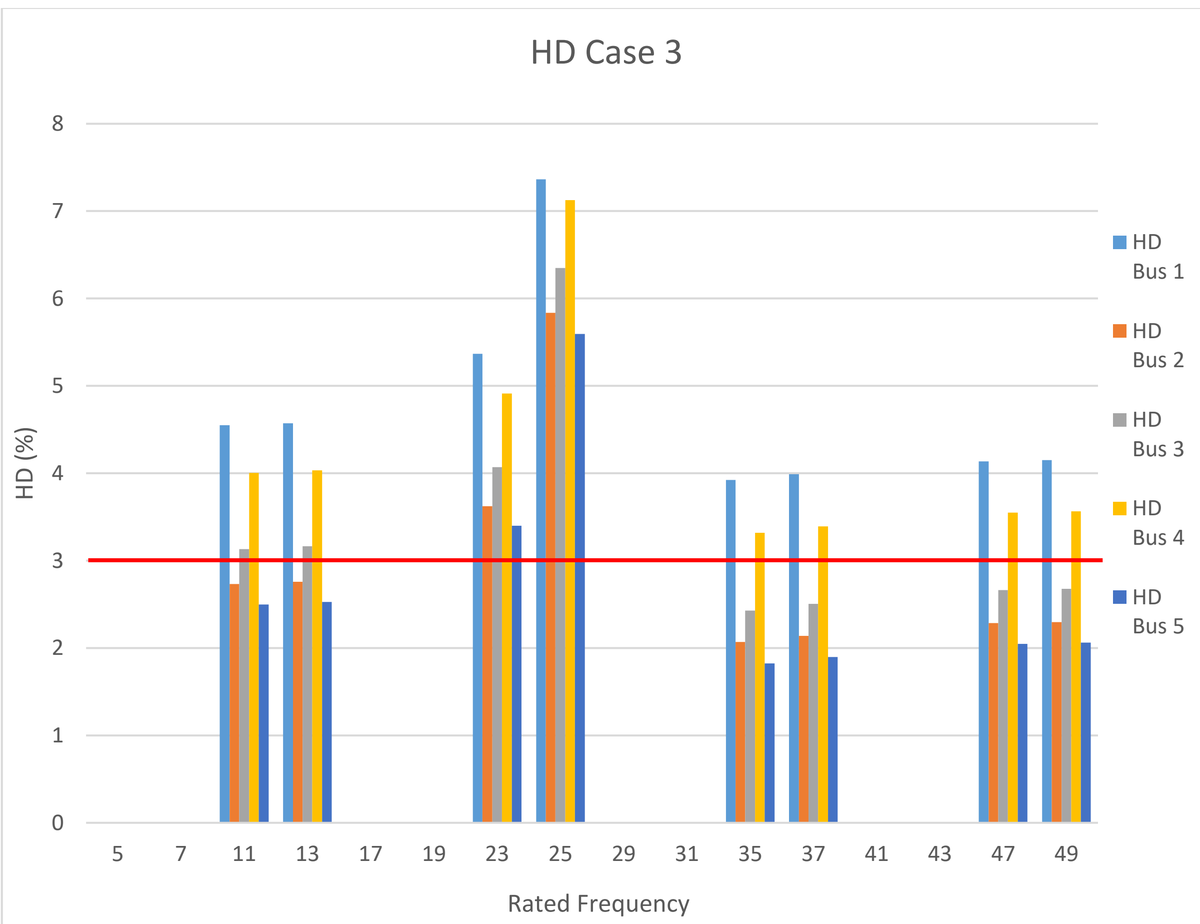

Figure 5.61.- Harmonic distortion of the harmonic components of the voltage waveform at the different busbars of the TCs, with a high level of PV generation.

In case of having a large number of PV installations interconnected within the LV network, it can be clearly seen that the HD of the individual components exceed the stablished maximum 3% in several frequencies and in several busbars.

The most adverse conditions, form the point of view of the harmonic distortion, are achieved this time at the busbar of the transformation centre 1. This fact is produced because Zone 1 has the largest number of PV sources of the five defined zones.

5.5.2.- Analysis of the Harmonic Distortion of the Harmonic Components:

In order to calculate the THD of the buses of each transformation centre, it is necessary to use the 'Output Calculation Analysis' tool. This function will show the THD of the bus at the desired moment of the day. The analyses will be made at 14:00, since at this moment the PV production is maximal and the THD will also be at its maximum values.

First, a measurement of this parameter will be made for Case 2 on the five existing TC buses. Then, Case 3 will be evaluated in the same way. Of course, in Case 1 the THD is '0', since no solar installations have been incorporated on the system yet.

The results obtained are exposed on the following table:

		Bus 1	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**
THD (%)	**Case 2**	14.97	17.37	16.20	12.01	10.06
	Case 3	36.06	23.74	26.99	33.90	21.85

Table 5.1.- THD at the different busbars of the TCs.

As it can be clearly seen, the THD limit, stablished at 5%, is exceed at every Busbar of the TCs, violating the stablished legislation existing on the international standards.

The RMS voltage wave form can be obtained from the program, showing the obvious harmonic distortion on the voltage wave, produced by the power converters:

- Case 2: Busbar 2 and Busbar 5.

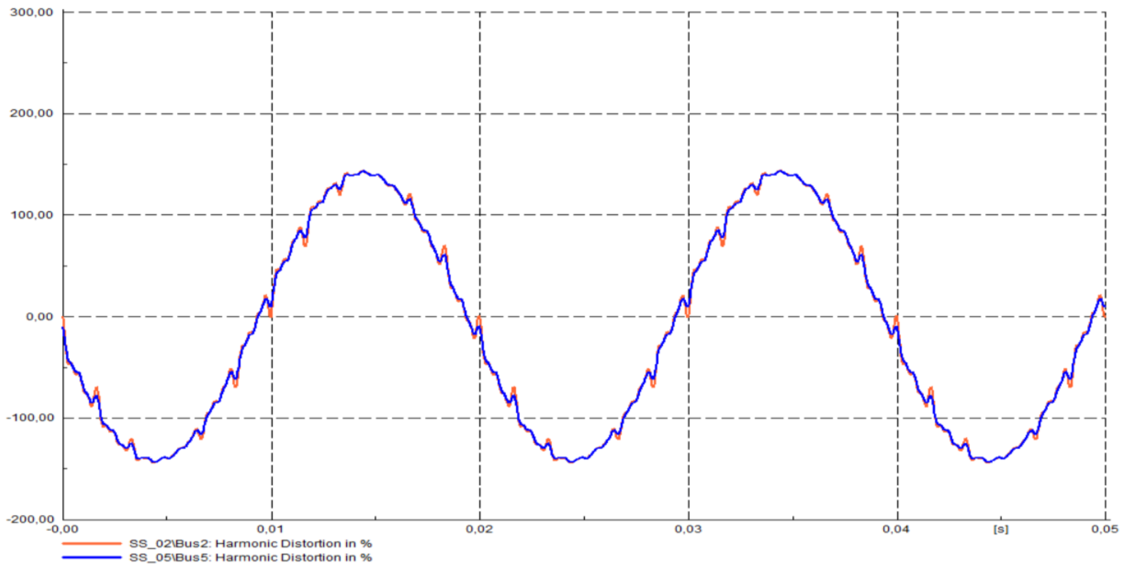

Figure 5.62.- Distortion of the voltage waveform at busbars 2 and 5, with a medium level of PV generation.

- Case 3: Busbar 1 and Busbar 5.

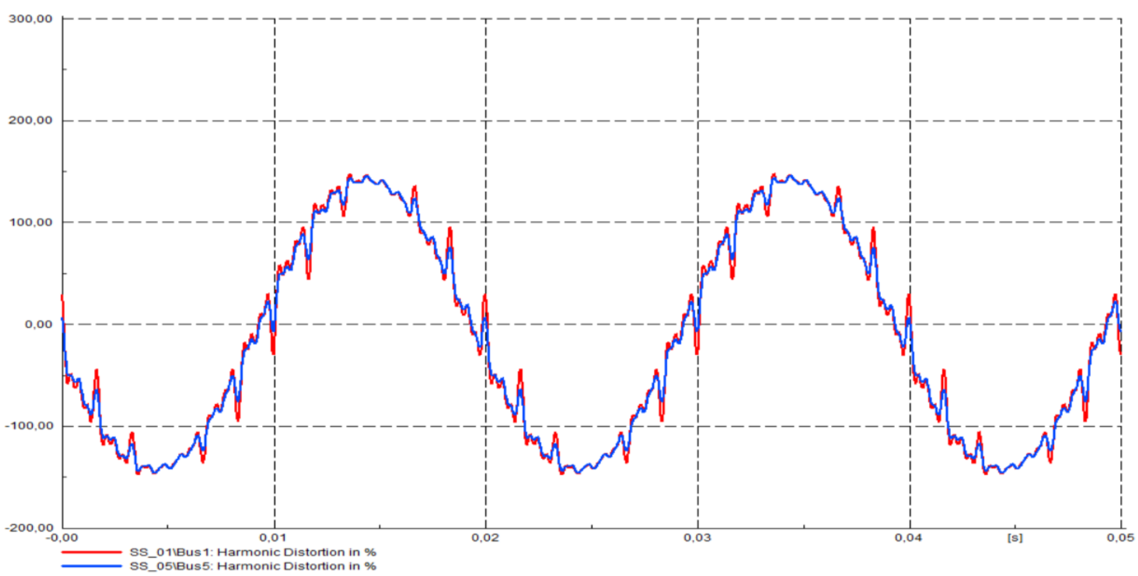

Figure 5.63.- Distortion of the voltage waveform at busbars 1 and 5, with a high level of PV generation.

These two plots show how the harmonic contents introduced by the power converters causes an inadmissible distortion on the voltage waveform.

It can be appreciated that in Case 3, the wave is more distorted, since the level of PV-systems is considerable higher and therefore, the number of inverters too.

6. Conclusions.

It is expected that Distributed Generation will fulfil an important function in the coming years, especially close to the end-use low voltage consumer side. The great advances and improvements in PV technology, and in general in all DG sources, will promote rapidly this field, reducing prices every day and leading to more sustainable economic situations.

There exists an increasing interest of the power costumers for installing their own generating sources which allow to consume directly the generated power in favourable moments, as well as enhance power reliability and quality, or supply heating/cooling needs. Energy storage devices such as batteries, will play an important role in the future, since they are controllable components which provide flexibility of operation, allowing to store the excess of energy produced to consume it when is not possible to use DG sources. However, a new legislation which captures these aims, as well as the possibility to inject the excess of power generated to the grid (if desired), would have to be made. Inside them, it would be also necessary to specify the prices that distributed generators pay and receive for electric power, connection to the grid, and transmission and distribution services.

With respect to the results obtained during the simulations of the model performed with the software, some clear conclusions can be drawn:

- Load flow analyses: When including the DG sources, the system loses its radial power flow characteristics during their generating period. This behaviour, assisted with an increase of the circulating reactive power caused also by the DG sources, makes the voltage to raise in most nodes, exceeding in some cases the maximum allowable voltage levels stablished by the distribution company. It could also be observed a severe variation of the voltage in the system during the whole operation day, which cannot be controlled by varying the transformer taps in all cases.

When analysing the currents flowing through different parts of the system, or in other words, the loading of the components, it could be appreciated that some elements exceed their loading capacity, as for example the fuse of Feeder 2. In relation with the distribution lines and transformers loading, it can be concluded that no problems appeared, since these components are oversized enough to withstand this hypothetical conditions.

Even so, in order to avoid the problems mentioned above, it would be necessary to regulate somehow the power generated by the DG sources, in such a way, that not all the excess of energy produced were injected to the common network at the same time. This approach could be achieved by including storage elements connected with the PV installations, such as batteries. These devices will allow to obtain a more constant time-voltage curve, which maintains the operating voltage value at any hour at a similar level, avoiding the overvoltages observed on the simulations.

- Protection devices studies: The incorporation of DG sources interconnected with the distribution network, causes significantly variations on the operating currents which flow through the protection elements. These variations can cause inadequate behaviours of the relay of the substation, as could be observed during the simulations.

  To avoid this problem, the relay would have to be adapted to the new operating conditions by updating the relay settings. As it could be observed, it directly depends on the penetration level of the PV-systems injecting power to the grid, so several studies would have to be performed to find the proper relay working setting.

- Harmonic distortion analyses: One of the most important issues that the PV installations introduced to the network operating conditions, is the injection of harmonics, which cause harsh distortions on the voltage and current waveforms.

  During the simulations, it could be clearly observed that in many cases, the THD as well as the HD contents of the TCs busbars, did not satisfy the stablished specifications, even when the PV penetration was not the maximum.

Knowing that individually, the PV-installations accomplish such harmonic injections limitations, it would be necessary, from part of the distribution company, to incorporate filters along the distribution lines in order to reduce or eliminate the inadmissible harmonic contents caused by all PV installations together of the system.

The integration of DG into existing distribution networks is a complex issue that requires several and complex analyses. It can be determined that several operating scenarios with significant differences are found depending on the penetration level of the DG sources.

The solutions of the problems, briefly commented on this section, have to be widely studied and evaluated in a simulating program to achieve a proper implementation of a high density level of DG interconnected with the distribution networks.

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