System aspects of large scale implementation of a photovoltaic power plant

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Abstract

In this thesis the static and dynamic behavior of large scale grid connected PV power plants are analyzed. A model of a 15 MW power plant is developed and implemented in DlgSilent Power Factory. The model considers all the panels operating at the MPP of the V-I characteristic with $\cos \phi = 1$.

The static behavior of this PV power plant connected to the grid is analyzed. To perform this analysis, the 15 MW power plant model is connected to a realistic grid. Two different static aspects are studied by using the U-Q curves of the PV power plant: variations of the injected active power of the PV power plant and variations of the short circuit power of the grid. As the injected active power is very dependent on the sun’s irradiation, the first analysis is performed in order to analyze the behavior of the PV power plant when the injected power is reduced. The second analysis is performed to determine the influence of lower short circuit power at the PCC where the PV power plant can be connected in order to maintain a reasonable voltage level.

Spain and Germany have started to develop a grid code which will be applied to these large scale power plants. Spain is one of the European countries which has a better potential of PV solar electricity and the government is giving a lot of subsidies to develop this technology. German government is also giving a lot of subsidies to develop PV technology. An analysis of the requirements of both grid codes is made concerning to the voltage dips and how the developed model of the PV power plant fulfills these requirements.

Finally, as wind power technology is one of the most common renewable energy resources that is being developed in these days, a comparison between the model of the PV power plant and a model of a wind power farm of the same nominal power is made. The differences in steady state condition and dynamic condition of both technologies will be discussed and how both technologies fulfill the grid codes’ requirements mentioned before. During the fault, the behavior of both technologies is very different. The LVRT behavior of both technologies will be compared, when a pure three phase fault at the PCC occurs.
Sammanfatning


Det statiska beteende i denna PV kraftverk som är anslutna till nätet analyseras. För att utföra denna analys, är 15 MW kraftverk modell ansluten till ett realistiska nätet. Två olika statiska aspekter studeras med hjälp av UQ kurvor av PV kraftverket: variationer av den injicerade aktiva effekten av PV makt anläggning och variationer av kortslutningseffekten av nätet.

Eftersom den injicerade aktiv effekt är mycket beroende av solens strålning, är den första analysen utförs för att analysera beteendet av PV kraftverket när den injicerade aktiva effekten minskar. Den andra analysen utförs är att fastställa påverkan av lägre kortslutningseffekten på PCC där PV kraftverk kan anslutas för att upprätthålla en rimlig spänningsnivå.

Spanien och Tyskland har börjat utveckla elnäs som kommer att tillämpas dessa storskaliga kraftverk. Spanien är ett av de europeiska länder som är bäst potential för solel och regeringen ger mycket stöd för att utveckla denna teknik. Den tyska regeringen ger också subventioner för att utveckla PV teknik. En analys av kraven i båda ländernas rester för elnät görs om med hänsyn till och hur de utvecklade modell av PV kraftverket uppfyller dessa krav.

Slutligen, vindkraft är en av de vanligaste förnybar energi resurser som utvecklas nu, en jämförelse mellan modell av PV kraftverk och en modell av en vindkraftpark av samma nominella effekt görs. Skillnaderna i det statiska och dynamiska tillståndet av båda teknikerna kommer att behandlas och hur de båda teknikerna uppfyller elnätsgiv. Under felet, beteende av både tekniker är mycket annorlunda. Den LVRT beteende båda teknikerna kommer att jämfördes, när en ren trefas fel på PCC sker.
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Chapter 1

Introduction

Nowadays the renewable energy production is still very modest compared to the traditional energy production, i.e. fossil fuels and nuclear. The electricity generation can be divided into fossil fuels and nuclear and renewable electricity generation. The renewable electricity generation could be divided depending on the energy source which is used in: hydropower, wind power, solar energy, biomass, biofuel and geothermal energy. Analyzing the electricity generation during year 2009 for the OECD region, it can be concluded that 61% of the energy was produced using fuels, 22% of the energy using nuclear and a 17% using some renewable energy. As it can be seen in figure 1.1, the scope is to reduce the production with the combustible fuels and replace it with nuclear and renewable energies.[1] The main renewable used is the hydropower. Now, some new renewable sources are becoming more interesting.

![OECD Electricity Production by Fuel Type Year-to-Date Comparison](image)

**Figure 1.1.** OECD electricity production by fuel type year 2008-2009, International energy agency 2009 IEA

and they are being studied more intensely. This is the case for wind power and
solar photovoltaic. Figure 1.2 shows how the PV production has increased between the 1990 and 2008 and shows the tendency of this technology.

There will be a change in the present power system and the system operator will have to deal with them and include Distributed Generation (DG). The advantages of DG are: they are more flexible in operation because of their small sizes and the short construction lead times compared to most types of larger central power plants, size and expandability. For example, making use of distributed generation allows to react in a flexible way to electricity price evolutions. Distributed generation then serves as a hedge against these price fluctuations. Other advantages are the potential for improving grid operation, an enhanced voltage stability and the quality of the power.\cite{2} One of the major remaining issues is the relatively high capital costs per kW installed power compared to large central plants.

Wind energy has had strong developments during the last years in Germany and Spain and solar technology will have a high deployment in the future. Solar energy technology can be used in two ways to produce electricity:

1. Solar photovoltaic systems: They convert solar irradiation directly to electricity with a solar panel.

2. Solar thermal systems: They usually heat water to produce steam and electricity indirectly in large power plants.

Solar energy has a great energy potential from 1000 to 2000 $\text{kWh/m}^2\text{-year}$. In figure 1.3, the photovoltaic solar electricity potential in Europe is shown. A big increase in PV systems is seen as public subsidies are used to promote environmental issues and reduce of the carbon dioxide emissions.

PV systems are composed by PV modules and PV inverters. PV modules are composed by solar cells which are divided in monocrystalline silicon, polycrystalline
silicon, amorphous silicon and thin film. Approximately the 90% if the market is divided between mono and poly-cristaline silicon cells.[1]
For the development of renewable energy, power electronics plays the important role, to obtain a better utilization of the sources. Energy storage can play another important role because it can increase the penetration level of renewable energy in the market.[3]
The amount of grid connected PV power plants is increasing nowadays as many subsides are given to develop such technology. The scope is that in the future large scale PV power plants will be connected to the grid. The aim of the thesis is to analyze the impact of a large scale PV power plant in the grid. In chapter 2, the solar technology will be discussed in greater detail.
Two different analysis have been performed in the thesis. On one hand, the static behavior of the PV power plant is analyzed by using the U-Q curves of the PV power plant. The theoretical background concerning the U-Q curves will be described in
chapter 3. The active and reactive power injection and the voltage profile are analyzed when the PV power plant is connected to a strong grid for different levels of injected active power. This is important as the injected active power is very dependent on the level of sun. This will be discussed in greater detail in chapter 5. As it not always possible to connect a power plant in parts of the grid where it is very strong, the impact of connecting them in areas where the grid is weak is also analyzed, specially the voltage profile. The scope is to obtain a minimum value of short circuit power which the PV power plant can be connected to. This will be discussed in greater detail in chapter 5.

On the other hand, according to the grid codes, it is important to analyze the impact of the voltage dips. Spanish and German grid codes will be described in detail in chapter 2. To perform this analysis, some voltage dips are simulated and the response of the voltage, the injected active power and reactive power are analyzed. The idea is to check whether the PV power fulfills the grid codes’ requirements. The analysis of the voltage dips will be performed in chapter 6.

Finally, a comparison between a 15 MW PV power plant and a 15 MW wind farm is performed, a wind technology is one of the renewable energies that is being developed most nowadays. In chapter 7 both technologies will be compared in greater detail.

In chapter 3 LVRT capability is analyzed, and deals with the capability to inject reactive power in the grid in case of grid faults, with the purpose of giving a voltage support during fault conditions. Regarding photovoltaics, there are two important grid codes that determine how the PV power plants must behave in order to connect them to the grid.

All the models used in the simulations will be described in chapter 4: the PV power plant model, the grid where the solar power plant is connected and the wind farm.
Chapter 2

Introduction to photovoltaics

2.1 Basis of photovoltaics

The average power density radiated from the sun through the atmosphere is 1373 kWh/m²·year. One part of this energy is absorbed and scattered by the earth’s atmosphere. The final incident power on earth’s surface is around 1 kWh/m² in the tropics during noon. Photovoltaic’s technology converts this energy into electrical energy.

The basic element of photovoltaic’s technology is the solar cell. During this chapter some of the basics of generation of electricity using photovoltaics are explained.

A solar cell uses the photovoltaic effect, which is a quantum-mechanical process, in order to produce electricity. A solar cell is a p-n junction formed in a semiconductor similar to a diode. Figure 2.1 shows a scheme of a photovoltaic silicon cell. The electric field is formed at the junction by doping it with impurities, usually boron and phosphorous. This electric field is established from the negative part which is doped by phosphorous to the positive part which is doped by boron. When light hits on the solar cell, the energy of the light composed by photons creates some charge carriers, which are separated by the electrical field. Because of that, a voltage is then generated at the external contacts, so if a load is connected current can flow through this load. The photocurrent, i.e. the current generated in the solar cell, is proportional to the radiation intensity.[3] Many semiconductor materials are suitable to create solar cells. The most commonly used material is silicon. This kind of silicon is known as solar grade silicon. Bulk silicon is separated into different categories according to crystallinity and crystal size in the resulting ingot, ribbon or wafer. Three types of silicon solar cells can be distinguished: monocrystalline, polycrystalline and amorphous silicon cells. Other materials, such as cadmium telluride, copper-indium selenide, gallium arsenide multi-junction, organics or polymers, are used to produce solar PV cells. But they are less common.

Solar cells can be operated at any point along its current-voltage characteristic, as can be seen in figure 2.2. The most important points of the current-voltage characteristic are:
1. Open-circuit voltage ($U_{oc}$): the voltage that provides the solar PV cell when no load is connected. Its value is around 0.6-0.7 V for silicon and is proportional to the logarithm of the illumination level.

2. Short-circuit current ($I_{sc}$): the current that flows when the terminals of the solar PV cell are short-circuited. Its value is around 20-40 mA and proportional to the illumination level.
3. **Maximum power voltage** ($U_{mmp}$): the voltage where the solar PV cell provides maximum power.

4. **Maximum power current** ($I_{mmp}$): the current where the solar PV cell provides maximum power.

The goal is to operate a solar PV cell is that it works near its maximum power point.

Another parameter is the fill factor (FF) which is defined as the ratio of the actual maximum obtainable power to the theoretical maximum, which is given by the product of the open-circuit voltage and the short-circuit current. This parameter is very important to evaluate the performance of solar cells. The equation of the fill factor is:

$$ FF = \frac{U_{mmp} \cdot I_{mmp}}{U_{oc} \cdot I_{sc}} $$

(2.1)

The typical value of the fill factor for a solar cell is between 0.6 and 0.8.[4]

Finally it should be said that a silicon solar cell produces approximately 0.5 V, so many cells will be connected in series to provide a higher output voltage. A solar panel can be defined as a collection of modules which are physically and electrically connected on a support structure. [3]

### 2.2 Types of photovoltaic power systems

Photovoltaic power systems can be classified into three different groups:

1. **Stand-alone PV systems**: These PV systems are usually located in remote areas where there is no access to the grid.

2. **Hybrid**: The hybrid PV systems are used as well in remote areas. They combine a diesel generator or storage with PV panels. The PV-systems are added to provide 24-hour power in a more economical and efficient way. The aim of these hybrid systems is to save diesel and reduce the maintenance and operation costs.

3. **Grid connected**: The PV systems are connected to the grid without battery storage through an inverter. The PV systems must be synchronized with the grid in voltage and frequency. These systems can be divided into small systems, which are located on the roofs of some residential areas, and large grid-connected systems.[3]

#### 2.2.1 Grid-connected PV systems

One of the fields which is being studied more recently in PV is the Grid connected PV systems. In these systems the inverters must ensure the power output and that the PV arrays are fully synchronized with the grid to which they are connected.
Grid connected systems can have a bank of batteries but they can work without batteries as well. The batteries are usually added to the system in order to provide additional power supply reliability, but the costs and the maintenance is higher. In systems with grid connected PV systems, a two-way power flow can occur: the utility grid absorbs the excess of the PV power and also utility grid will feed the load during nights or when the light conditions are no adequate. Grid connected PV systems can be classified in two groups:

1. Rooftop application of grid connected power systems: These systems are used to supply a residential load and they are located on the roof of the houses. The PV modules can be mounted on the roof or integrated into the roof. Some batteries can also be included to improve the grid’s reliability when the insolation level is low, during nights or cloudy days. The main problem of the batteries is that the maintenance must be performed more frequently and that the costs are higher. The main problem of these systems is that the orientation of the PV array is determined and fixed by the roof.

2. Utility-scale large system: The utility-scale large systems are now being developed in Germany, Spain and the U.S.A. These systems can be centralized or distributed systems. In these systems the possibility of islanding when the main supply fails must be considered. In case of islanding they must be disconnected. Most studies are focusing on preventing the disconnection of these systems when a fault occurs. This will be discussed in detail in chapter 3.[3]

The capacity credit of these systems is based on the statistical probability that the grid can reach the peak demand. During peaks the capacity credit of the utility-scale large system is very similar to the conventional plants’ capacity credit, except when the power plants are generating very poor power.

One important element of the grid connected PV system is the inverter. The aim of the inverter is to convert the dc voltage produced by the solar cells into ac voltage. The output must be produced with a good quality and it must be a sine-wave. The inverter must extract the maximum power of the solar cells. The control of this inverter must follow the maximum power point of the solar cells. The inverter input will vary the input voltage in order to reach the maximum power point in the U-I characteristic shown in figure 2.2.

The inverters can be classified in two types:

1. **For grid interfacing:** They are subdivided in:

   a) **Voltage-source inverters (VSI):** the dc source appears as a voltage source to the inverter. They have a capacitor in parallel with the input. In this thesis the voltage-source inverters are going to be implemented.

   b) **Current-source inverters (CSI):** the dc source appears as a current source to the inverter. They have an inductor in series with the dc input.
2. Based on control schemes: They are subdivided in: current-controlled inverters (CCI) and voltage-controlled inverters (VCI).

It is easy to change from one type to another by adding passive components.

Concerning the converter topologies, three kind of topologies are usually used. The three most important topologies are: line-commutated inverters, self-commutated inverters and PV inverter with high frequency transformer. Other topologies which are also used are: multilevel converters, non-insulated voltage source, non-insulated current source, buck converter with half-bridge transformer link, flyback converter and interface using paralleled PV panels.

As mentioned before, the most important thing of the converters is the power control through them. They feed the local load and export the excess of the active and reactive power to the utility grid.

According to the figure 2.3 which represents a simple grid interface system and the phasor-diagram of grid-integrated PV, the equations of the voltage and current controllers can be written.

\[ \overline{S} = P + j \cdot \overline{Q} = U \cdot T^* \]  \hspace{1cm} (2.2)

The power equation in voltage controllers is:

\[ \overline{S} = \frac{U \cdot U_{pwm}}{X_L} \cdot \sin \delta + j \cdot (\frac{U \cdot U_{pwm}}{X_L} \cdot \cos \delta - \frac{U^2}{X_L}) \]  \hspace{1cm} (2.3)
The power equation in current controllers is:

\[ S = U_{pwm} \cdot 1 \cdot \cos \theta + j \cdot U_{pwm} \cdot 1 \cdot \sin \theta \] (2.4)

Sometimes when the voltage controller is implemented, it can present a slight error in the phase when synchronizing the waveform that can overload the inverter.[3] The current controller is less susceptible to voltage phase shifts, but on the other hand the voltage controller is better suited for the control of power export.

The characteristics of the inverter which for grid connected PV systems are [3]:

1. **Response time**: It has to be extremely fast which has to be governed by the bandwidth of the control system.

2. **Power Factor**: It has to be close to the unity according to the grid codes.

3. **Frequency Control**: It has to be locked to the grid.

4. **Harmonic Output**: Traditionally the harmonic output is very poor and can be injected to the grid which will increase the losses and the power might have a very poor quality. By using a PWM of sufficiently high switching frequency the sine-waves which are obtained have a better quality.

5. **Synchronization**: It usually uses zero-crossing detection on the voltage waveform.

6. **Fault current distribution**: As it was mentioned before, the current is proportional to the amount of light. The panels are usually rated to produce \(1000 \text{ W/m}^2\). Under these conditions the short circuit current possible for these panels is typically only 20 times higher that the nominal current. If the solar radiation is low, then the maximum current under short circuit is going to be less than the nominal full-load current. Then PV systems cannot provide short-circuit capacity to the grid.[3]

7. **Protection requirements**: Four protection requirements have to be taken into account: Overvoltage, undervoltage, overfrequency and underfrequency.
Chapter 3

Operation of grid connected PV power plants

3.1 Fault ride through and reactive power support

PV generators behave differently from conventional generators, such as thermal or nuclear power plants in terms of reactive power output capability, and fault ride through capability, i.e. the ability to remain connected and supply power to the electrical system immediately after a network fault. In areas where PV generators comprise a large share of the generation capacity, this can have a negative impact on the entire network’s stability. For this reason, grid operators are forced to introduce technical standards called Grid Codes which must be fulfilled to add a PV park to the grid.

Until now, decentralized power sources such as PV inverters, had to be disconnected directly from the grid in the event of grid failures. This is now changing fundamentally, therefore these inverters may not be disconnected from the grid in the event of grid failures but they will not feed in any active power. After this, inverters can again feed in active power directly after the fault clearing and stabilize the grid. This is the procedure called limited dynamic grid support LVRT (low voltage ride through) which also occurs if voltage drops. These new requirements are done to avoid an immediate disconnection of PV power generation units which are in the zone affected by the grid and the corresponding voltage dip. Otherwise the loss of such power may not be compensated quickly from other power sources.

As mentioned before, the strategy adopted until now of disconnecting the PV park at first sign of trouble might not be the optimal approach for two reasons: the dynamic support to the grid will be very important for security and stability aspects and because repeated disconnections may have a negative impact on components’ lifetime as well as causing further disturbances on the grid. Thus these two aspects can be improved if the inverter is able to keep connected as long as possible.

There are three main reasons for inverter disconnection during voltage dips: an excessive dc voltage which causes a trip of the corresponding protection relay and
the immediate shutdown of the converter, a trip of the overcurrent relay due to the increased grid current and the loss of synchronism.\[1\]

The active power is transformed by the consumers into warmth, motion or light but the reactive power has no direct advantage. The overall grid is designed by the apparent power and the injection of reactive power leads to a more efficient operation of the grid. The required power factor will lie between 0.95 (leading) and 0.95 (lagging) and the requested power factor will lie between 0.9 (leading) and 0.9 (lagging). At the same time, the supply of reactive power can be either quasi-static or dynamic, either a fixed reactive power target is given or the reactive power is determined using a characteristic curve. In the case of a reactive power target value, the situation is simple: the grid operator defines a fixed target value of the reactive power. This is set once during commissioning. But the reactive power can also be determined in function of the nominal active power.\[1\]

Other requirements which will change due to the future high PV penetration scenario is the power factor of these PV parks, as up to now the inverters were working with unitary power factor. With a big impact on the grid, this will not be possible in the future because it will affect the quality of the power. Reactive power will be included in the system dimensioning.

### 3.2 Introduction to grid codes

The interconnection requirements for utility-connected PV systems are coming into force in several European countries with supporting grid operation and stability. Before 2009, the PV generators which were connected to the power distribution grid were not permitted to take an active role during faults and had to be disconnected during grid faults. Now, as the size of the PV solar farms is becoming bigger, it is required to keep these units working during normal conditions and during disturbances.

Two new requirements are taken into account:

1. **Steady-state condition:** Grid support must be provided by injecting reactive power and contributing to voltage control.

2. **Transient condition:** PV generators will stay connected and injecting short-circuit current during certain grid faults.

These new requirements are being adopted in Germany and in Spain, which are the leader in production, installation and integration of PV technology. In Germany, these requirements are final but the Spanish requirements are temporary.\[1\] Spain is the European country with higher potential in PV because of the weather conditions. Both governments give a lot of subsidies in this field, so these countries have the most extense grid codes in this field. Because of that, it is important to study both countries’ grid codes.
3.3 Germany

The interconnection requirements in Germany, which appear in the new medium voltage grid code are applicable to all the new generating plants which are connected to the medium-voltage network and to the existing generating plants.

From July, 1st 2010, the steady-state condition which states that during a fault, the PV Generators should provide grid support by injecting reactive power.

PV plants must be technically capable to make a limited contribution to the dynamic network support, which is called limited contribution. The generating plant will not be disconnected from the grid during a fault and after the fault the PV generating plant should no extract more inductive reactive power than prior the fault.

From January, 1st 2011, PV plants should provide full dynamic network support, which means that: the generating plant must remain connected when a fault occurs. Figure 3.1 presents a timetable for the participation of PV systems in grid which were explained above.

![Figure 3.1. Timetable for the participation of PV systems in grid management][1]

The German Code can be divided into four important requirements:

1. Steady-state voltage control: The PV generators will participate in the steady-state voltage control where slow voltage changes are kept within acceptable limits.

2. Dynamic network support: The voltage control is related to the event of voltage dips. The aim of this control is to avoid disconnection of the large solar PV farms because they will feed a large amount of power into the grid and the immediate disconnection of these big plants can end in a collapse of the grid.
grid. The generating power plants must remain connected during the fault, must support the network voltage during a fault by feeding reactive current and avoid extracting more inductive current than prior the fault. These conditions apply to all generating plants and therefore also to the PV solar farms. Solar PV farms are considered as type 2-generating plants, i.e. no synchronous generator is connected. Type 2-generating plants must fulfill the following regulations: Generating units must not disconnect from the network in the event of voltage drops to 0 % \(U_c\) of a duration < 150 ms and there are no requirements which oblige the machines being connected to the network when the voltage drops to 30% of the nominal voltage according to figure 3.2.[6] Voltage drops with values above borderline 1 (grenzlinie 1) must not lead to instability or to the disconnection of the generating plant from the network. If the voltage drops at values above borderline 2 (grenzlinie 2) and below borderline 1, generating units will pass through the fault without disconnecting from the network. Feed-in of a short-circuit current during that time is to agree with the network operator.

A general basic requirement is however that all generating plants remain connected to the network in the case of voltage drops above the borderline. Consequently, the network operator only determines the value of reactive current which must be supplied to the network by the generating facility in the event of voltage drops.

3. Active Power Output: The network operator is entitled to require a temporary limitation of the power which is fed in or to disconnect the generation plants due to potential danger to the operation of the system, congestion or

![Figure 3.2. Borderlines of the voltage profile of a type-2 generating plants at the network connection point.][6]
risk of overload on the network, risk of islanding, or risk to the steady-state or dynamic network stability.

The generating units must reduce, at frequency of more than 50.2 Hz, the instantaneous active power with a gradient of 40% of the generator’s instantaneously capacity per Hertz. The active power will be increased again if the frequency returns to a value of \( f < 50.05 \) Hz, as long as the value does not exceed 50.2 Hz, as it can be seen in figure 3.3.

![Figure 3.3. Active power reduction in the case of over-frequency [6]](image)

4. Reactive Power Support: The German Grid Code states that the power plant must be possible to be operated in any point between 0.95 lagging power factor and 0.95 leading power factor. The reactive power support must be adjustable. In order to avoid voltage jumps or fluctuations in active power feed-in, a characteristic with continuous profile and limited gradient must be chosen. It is important to remark that nowadays PV systems are controlled to produce only active power. The reactive power is avoided due to the losses in the inverter, through the lines and transformers. To meet the grid requirements, the inverters are oversized.[6]. An example of reactive power characteristic where the power factor is controlled by active power is given by figure 3.4.

3.4 Spain

The operating Grid Code was first written in March 2005 and refers to facilities connected to transport grid and generating equipment: minimum design requirements, equipment, operation, deployment and security. In October 2008 a second draft of this document was written which contains information on wind and photovoltaic installations or any generating plant which does not have any synchronous generator directly connected to the grid. The requirements will be in effect to the
facilities with deployment dates later than January 1st 2011. The Spanish grid code states the requirements of the response in case of voltage disturbances. The generation facility and its components must be able to withstand, without disconnection any voltage disturbance at the grid connection point with the magnitude and duration profile shown in figure 3.5. The low voltage ride-through requirement

states that the PV power plant must withstand 0% remaining voltage dips of up to 150 ms without disconnecting.

The Spanish Grid Code states that the PV power plant must consume no reactive
3.5. VOLTAGE STABILITY ANALYSIS

Voltage stability is the ability of a power system to maintain steady voltage at all buses in the system after being subjected to a disturbance from a given initial operating condition. Instability that may result occurs in the form of a progressive fall or rise of voltage of some buses.[12]

A criterion for voltage stability is represented in equation 3.1, where \( Q_i \) is the injected reactive power and \( U_i \) is the voltage of the bus.

\[
\frac{dQ_i}{dU_i} > 0
\]  (3.1)

The physical interpretation is that the reactive power injection at a bus \( i \) will result in increasing the voltage magnitude of bus \( i \). Otherwise the system is unstable.[12]

Power system voltage stability involves generation, transmission and distribution. By analyzing the very simple system of figure 3.6 it can be shown that the transmitted apparent power is given in equation 2.2. The transmitted active and reactive power is represented by equation 2.3.

From these equations it can be concluded that the active power (\( P \)) and \( \delta \) are closely coupled and that the reactive power (\( Q \)) and the voltage are closely coupled.[9]

Reactive power cannot be transmitted across large power distances without substantial voltage magnitude gradients. The high angles are due to long lines. Whenever possible, reactive power should be generated close to the point of consumption because the reactive power transfer should be minimized. The reasons are:

- It is inefficient during high active power transfer and requires substantial voltage magnitude gradients.
- It causes high real and reactive power losses.
It can lead to damaging temporary overvoltages following load injections.[9]

Larger equipment sizes for transformers and cables are required.

Voltage problems are expected in developing power systems, such as weak grids. One reason is the intensive use of existing generation and transmission and a second reason is the increased use of shunt capacitor banks.[9]

One method to analyze voltage stability is based on the U-Q curves as shown in figure 3.7. The curves are obtained by a series of power flow calculations. The method that can be used is[12]:

1. A fictitious synchronous generator with $P_g = 0$ without reactive power limits is placed at the load bus to make it a PV-bus without reactive power limits. The net active power at this bus is $P_{GD} = 0 - P_L$.

2. Run power flow calculation for a series of specified voltages from a maximum voltage $U_{Lmax}$ to a minimum voltage $U_{Lmin}$.

3. For each voltage the generated reactive power is calculated, i.e. $Q_g$.

4. $Q_g$ versus voltage is plotted.

In the curves which are represented in figure 3.7 it can be seen that when $Q_g < 0$, the generator consumes reactive power, when $Q_g > 0$, the generator injects reactive power. The critical operating point is the minimum which can be calculated as $\frac{dQ_g}{dU_L} = 0$. Since voltage security is strongly coupled to reactive power, the Q-U curves are a powerful tool to measure reactive power margins at a bus of interest. The operating point in this curves the intersection of the U-Q curve and the generated
3.5. VOLTAGE STABILITY ANALYSIS

reactive power $Q_g$. Sometimes two operating points can be obtained, one stable which is the one which complies the voltage stability criterion shown in equation 3.1 and other unstable. In figure 3.8 two different U-Q curves are shown. For the upper curve, it can be seen that there is no operating point since there is no intersection between the U-Q curve and $Q_g = 0$ and $Q_2 > 0$ would be the minimum requirement of reactive power injection or compensation at the load bus to have an operating point. In the lower curve, there are two operating points, one stable (right one) and one unstable (left one). $Q_1$ is the maximum amount of more reactive load consumption without losing an operating point.

![U-Q curves](image)

**Figure 3.8.** Example 2 of U-Q curves with different.[12]

The U-Q curves present some advantages[9]:

- Voltage security is closely related to reactive power and a U-Q curve gives the reactive power margin at the test bus. The reactive power margin is the MVAr distance from the operating point to either the bottom of the curve or to a point where the voltage has to be reached.

- U-Q curves can be computed at points along a P-U curve to test system robustness.

- The characteristic of test bus shunt reactive compensation can be plotted directly on the U-Q curve. This is useful since reactive compensation is often a solution to voltage stability problems.

- The slope of the U-Q curve indicates the stiffness of the test bus.

- To create a PV-bus minimizes the power flow divergence more that a PQ-bus[9]
Chapter 4

Models of two PV power plants, the grid and a wind power farm

4.1 Model of a 2.5 MW PV power plant

4.1.1 Introduction

In this section a simple model of a 2.5 MW PV solar plant will be presented and explained. This power plant is very similar to the one ABB built in Totana (Murcia) in the south east of Spain. The power plant injects 2.5 MW into the grid and represents the basis of a 15 MW solar PV plant, which will be presented in the following chapter. During this section, the modeling details of all the components and controllers are explained and one simulation of a three phase fault in the connection point will be analyzed. The inverters are controlled to work in the MPP and are controlled to give only active power in the connection point. The model is implemented in DIgSILENT power factory, which is a commonly used simulation tool in the power system sector.

4.1.2 Modeling details

In figure 4.1, the electrical diagram of the 2.5 MW power plant is represented. The diagram contains only few elements. The PV panels and inverter are modeled by a 'Static Generator'. This PV power plant is composed by five PV generators of 500 kVA nominal power. These five generators are connected in parallel to a low voltage bus called 'Photovoltaic LV'. The first winding of two transformers connected in parallel are connected in this low voltage bus. The secondary windings of the transformers are connected to a medium voltage bus, called 'MV Bus', which is the connecting point of the power plant. A block called 'External Grid' is connected, which represents the grid and is the slack bus.
CHAPTER 4. MODELS OF TWO PV POWER PLANTS, THE GRID AND A WIND POWER FARM

In this section, all the components of the PV power plant will be explained in detail.

**PV Generators**

In the model, five blocks of PV generators are used. These blocks model the photovoltaic systems of five different generators from the PV modules to the inverter. In DIgSilent, each generator is modeled as a 'static generator'. This model is used in DIgSilent to model any kind of generator which is not rotating but static. One of the most important application of this generator is PV generators. Each PV generator has a nominal apparent power of 0.5 MV and has only one 'parallel machine'. The function of parallel machines is a simple way to obtain larger PV generators of one, two or more MVA.

For the steady state situation, the load flow is set in 448.8 kW for active power and 0 kVAR in the Photovoltaic _LV bus. In some cases, the PV power plants work with unitary power factor in the grid connection point. So the inverters could be adjusted to cover the reactive power losses in the transformers. At the same time, a different value of reactive power can be set during steady state if there is any particular request from the local system operator. This will be a new requirement as the PV systems are designed to operate at unity power factor due to the fact that this condition produces the most real power and energy.

The injected power is limited by the nominal current of the inverter. Because of that, it is not possible to work at maximum of active and reactive power at the same
time. The capability curve of the inverter can be shown in figure 4.2, where the limit is 0.5 MVA. In this figure the reactive power is represented in the x-axis and the active power is represented in the y-axis. The blue line represents the power limit of the inverter, so the inverter cannot work in values over this blue line. With a constant value of active power and using the capability curve the inverter’s reactive power limits can be obtained. If $P_{PV}$ is the active power value, then $Q_{lim}$ is determined as the reactive power limit. This can be observed in figure 4.3.

During maximum power production, some Q capability can always be achieved by over-sizing the inverter. This is used in the PV power plants to obtain some reactive power which can be used to supply the reactive losses in the different components such as transformers or lines. A reasonable increase of the inverter size by 10% with $S=1.1 \ P_{PV,\ max}$. In this way the reactive capability can be increased from zero to nearly 46% in the maximum power generation condition. This gives a power factor
range between the unity and 0.91 leading/lagging at full active power and a Q ca-

capacity during no sun conditions up to 110%. In figure 4.4 the active and reactive

power capability of the inverter versus the size is represented. The different parts

![Figure 4.4. Relationship between inverter size and its reactive power capability](image)

of the PV generator will be analyzed afterwards, mainly the modeling of the PV
model and the control of the inverter.

**Photovoltaic LV**

This bus is modeled by an AC Busbar, with nominal voltage 0.4 kV(line-to-line).
The steady state voltage limits are 0 p.u. and 1.05 p.u. In this busbar the five
generators are connected as the distances between them are small. In reality, each
generator would have its own low voltage bus, but in modeling these different busses
can be considered as one bus as the transmission losses are very low.

**Step up transformers**

To increase the voltage two three phase transformers are used. Each transformer
has a rated power of 1.25 MVA with nominal frequency of 50 Hz. The nominal
voltages are 0.4/33 kV and the vector group is Dyn11. The short-circuit voltage is
6% and no copper losses are assumed.

**MV Bus**

This is modeled by an AC Busbar, with the nominal voltage of 33 kV (line-to-line).
The steady state voltage limits are 0 p.u. and 1.05 p.u. This busbar represents the
connection point of the power plant to the grid.

**External Grid**

The main values of the external grid are the minimum and the maximum values of
the short circuit power. The short circuit power is assumed to be 30 times higher
than the solar power plant. The minimum short circuit power is 75 MVA.

**PV panels and inverter: modeling and control scheme of the PV system**

All the static generators called 'PV Generator' have the same control. The control system is shown in figure 4.5 and each of the components will be described and analyzed.

**Figure 4.5. Frame of PV System**

**Photovoltaic Model**

The photovoltaic model is shown in figure 4.6. It has three inputs and two outputs. This model determines the V-I characteristic of a single panel, particularly the values of the voltage and current in the maximum power point and calculates the current and the voltage for the solar generator considering the number of series and parallel panels.

The three inputs of the model are, the voltage of the PV array which is $U_{array}$ [V], the irradiation called E [W/m²] and the module temperature called $\theta$ [°C]. The two outputs are the array current $I_{array}$ [A] and the array voltage in the maximum power point $U_{mmp-array}$ [V].
$U_{\text{array}}$ passes through a low-pass filter which in normal conditions is desactivated using $T=0$, by using $T>0$ this filter can be activated. The voltage is divided by the number of series modules, and then the voltage of one PV module is obtained; i.e. $U$.

In the block called PVModule an algorithm is used to calculate the value of voltage and current in the maximum power point in a special condition of irradiation ($E$), temperature ($\theta$) and the voltage of one PV module ($U$). The values obtained are the string current $I$ and the voltage in the maximum power point $V_{\text{mmp}}$. Finally these two values $I$ and $V_{\text{mmp}}$ are multiplied respectively by the number of parallel modules and the number of series modules. Then, the results are respectively $I_{\text{array}}$ and $U_{\text{mmp-array}}$.

**Figure 4.6. Frame of PV System**

**DC Busbar and Capacitor Model**

This block is modeled as a classical DC-link and it is shown in figure 4.7. The model has two inputs and one output. Its aim is to calculate the input DC voltage of the inverter having the values of the array current and active power.

The active power measurement from the static generator is divided by the DC voltage. The DC current which flows in the input of the inverter is then obtained. The
array current minus the dc current equals the differential current in the capacitor. This current, converted from A to p.u. value is passed through an integrator block. The output value of the integrator block, converted from p.u. to V is the value of the DC voltage in the input of the inverter.

**Figure 4.7.** DC Busbar and Capacitor Model

### Vdc Controller

The Vdc Controller is the highest controller level of the system. It can be seen in figure 4.8 and has six inputs and two outputs. Its aim is to calculate the two reference values of $i_{dref}$ and $i_{qref}$. The lines of active power control and reactive control can be seen also in the figure 4.8. The $u_{dcref}$ value is the $U_{mmp-array}$ which is the value of the dc voltage which should be achieved to have at the input of the inverter block. This value goes through a lower limit block in order to give the maximum value between $u_{dcref}$ and $U_{min}$ in order to keep the minimum allowable value above $U_{min}$. Then this value is compared with $u_{dcin}$ which is the voltage at the dc bus of inverter $u_{dc}$ and $dudcref$ which is the difference between the two previous values. The obtained value, $dp$, is passed through a filter and into the Active Power PI Controller. $K_P$ and $T_{ip}$ are the gain and the integration time constant which is limited by the currents $i_{dmin}$ and $i_{dmax}$. This controller is also
limited by the value $P_{\text{red}}$, which comes from the active power reduction during over-frequency. The output of this PI Controller is $i_d$. $U_{ac}$ is the ac voltage measurement at the output of the inverter. This value is compared with the reference in steady state condition $u_{ac0}$. The difference, $du_{ac}$, is the input of the block reactive power support. This block is written to satisfy the grid code requirement of Spain and Germany about photovoltaic systems. The block regulates the $i_q$ output as a function of the voltage dip in the LV bus where the PV generators are connected. Therefore this block the reactive power requirement capability. The equation of the block is 4.1, where $du_{ac}$ is the value of the voltage dip, which is the difference between the steady state value and the instant value of the LV bus, and the droop is a parameter that can be adapted the desired behavior. During the Thesis, the value of the droop is set to 1 p.u., but this value can be change according to the reactive current that the system operator has agreed in PV power plants. According to this control of the reactive current injected from the inverter, the PV generators will not inject any reactive current in steady state condition because $u_{ac0} = U_{ac}$ and therefore $du_{ac} = 0$ and $i_q = 0$. As it will be shown, the PV power plant will be injecting reactive current to the grid during
faults, according to the voltage dip level, which is a desirable behavior.

\[ i_q = droop \cdot |du_{ac}| \]  

(4.1)

It has upper and lower limitations \( i_{q_{max}} \) and \( i_{q_{min}} \). The output is the \( i_q \).

Finally \( i_d \), \( i_q \) and \( du_{ac} \) are the inputs of a current limiter block whose limit is the maximum value of absolute current and the maximum absolute value of reactive current in normal operation. This limiter gives the final output values of \( i_{d_{ref}} \) and \( i_{q_{ref}} \).

**Measurement Blocks**

During the explanation of the different controllers, some measurement blocks have been mentioned. These blocks only represent the measurement of the instantaneous active power, ac voltage and frequency. This can be done easily in DIgSILENT by using the measurement blocks.

**Active Power Reduction**

To prevent the collapse of the grid, the German Grid Code has a requirement of active power reduction with the frequency. If there is more power available than the demand the frequency of the system increases. The frequency is a good indicator about the surplus of energy. When there is a case of over-frequency, the PV plant must be capable of reducing the active power delivered to the grid. In this case if the frequency is above 50.2 Hz, the inverters must reduce the injected power. The active power is reduced by 40% per Hz. If the frequency reaches 51.5 Hz the inverter is switched off and when the frequency falls below 50.05 Hz, the inverter injects again full available power. The Spanish Grid Code has no active power reduction requirement.

**4.1.3 Simulation results in case of a three phase fault in the connection point**

In this part some simulation results are presented in order to check that the model works well and the expected values of active power and reactive power to the grid are obtained. As mentioned before, this model is the basis to build up the 15 MW PV power plant which will be connected to the grid, which will be further discussed in the following chapters. During this section the values of the simulation parameters are presented as well as the final output active and reactive power to the grid, the voltage in each bus and the active and reactive power generated power by each of the five generators.

**Values of simulation parameters**

Table 4.1 shows the values for DC busbar and capacitor. Table 4.2 shows the values
of the PV Array. According to the values of the table, the fill factor of the PV panel is FF=0.73.

Table 4.3 shows the values of the $V_{dc}$ controller.

**Table 4.1. Values for the DC busbar and capacitor**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity of capacitor on dc busbar</td>
<td>0.0172 µF</td>
</tr>
<tr>
<td>$U_{dc0}$ Initial dc voltage</td>
<td>700V</td>
</tr>
<tr>
<td>$U_{dc}$ Nominal dc voltage</td>
<td>700V</td>
</tr>
<tr>
<td>$P_{nom}$ Rated Power</td>
<td>0.5MW</td>
</tr>
</tbody>
</table>

**Table 4.2. Values of the PV Array**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{I0}$ Open circuit voltage</td>
<td>43.8V</td>
</tr>
<tr>
<td>$U_{mmp0}$ MPP voltage</td>
<td>35V</td>
</tr>
<tr>
<td>$I_{mmp0}$ MPP current</td>
<td>4.58A</td>
</tr>
<tr>
<td>$I_{I0}$ Short circuit current</td>
<td>5A</td>
</tr>
<tr>
<td>Number of parallel modules</td>
<td>140</td>
</tr>
<tr>
<td>Number of series modules</td>
<td>20</td>
</tr>
</tbody>
</table>

**Table 4.3. Values of the $V_{dc}$ controller**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{r}$ Active power measurement delay</td>
<td>0.001s</td>
</tr>
<tr>
<td>$K_P$ Gain of the active power PI Controller</td>
<td>0.005</td>
</tr>
<tr>
<td>$T_{ip}$ Integration time constant of the active power PI Controller</td>
<td>0.03s</td>
</tr>
<tr>
<td>Deadband for AC voltage support</td>
<td>0.1 p.u.</td>
</tr>
<tr>
<td>Droop static for AC voltage support</td>
<td>1 p.u.</td>
</tr>
<tr>
<td>$I_{dmin}$ Minimum active current limit</td>
<td>0 p.u.</td>
</tr>
<tr>
<td>$I_{dmax}$ Maximum active current limit</td>
<td>1 p.u.</td>
</tr>
<tr>
<td>$I_{qmin}$ Minimum reactive current limit</td>
<td>-1 p.u.</td>
</tr>
<tr>
<td>$I_{qmax}$ Maximum reactive current limit</td>
<td>1 p.u.</td>
</tr>
<tr>
<td>Maximum allowed absolute current</td>
<td>1 p.u.</td>
</tr>
<tr>
<td>Maximum absolute reactive current in normal operation</td>
<td>1 p.u.</td>
</tr>
</tbody>
</table>

**Simulation Results in case of a three-phase fault in the connection point**

In this section a simulation of a three-phase fault in the connection point is performed in order to check that the PV Park works. In steady state, each generator is injecting 448.8 MW which corresponds to the MMP. In this case, it is assumed that each generator injects no reactive power, i.e. $\cos \phi = 1$. In the connection point of the external grid the PV park is injecting 2.244 MW and absorbing 0.124 MVAr which gives a $\cos \phi = 0.9985$. This absorption of reactive power is due to the transformers. The voltages in the steady state are 0.9959 p.u in the MV Bus and
0.9944 p.u. in the LV Bus and 700 V in the DC Bus, which is the reference.
A pure three-phase short circuit is simulated in the MV Bus. The short circuit is cleared after 0.5 sec.
Figure 4.9 shows the response of the MV bus’ voltage in p.u., the LV bus’ voltage in p.u., the injected active power to the grid in p.u. \( (S_{\text{base}} = 2.5 \text{ MVA}) \), the DC bus’ voltage in volts and the injected reactive power to the grid in p.u. \( (S_{\text{base}} = 2.5 \text{ MVA}) \). Before and after the fault the correct values of the voltages, active and reactive power are reached. During the fault no active power is transmitted and some reactive power is absorbed due to the transformers. The DC voltage has an upper limit because it is limited by the open circuit voltage of the panel at 876 V, where no active power will be transmitted although the power plant remains connected. It is interesting also to see the response of the active and reactive power

Figure 4.9. a) Voltage in the MV Bus (p.u.) b) Voltage in the LV Bus (p.u.) c) Injected active power in the MV Bus (p.u.) d) Voltage in the DC bus in V e) Injected reactive power in the MV Bus (p.u.)

that the static generators are injecting to the LV bus in figure 4.10. In this figure the injection of the active (red) and reactive power (blue) of a generator is represented. In this figure it can be seen that before and after the fault the generators are injecting 0.8976 p.u. (448.8 kW) of active power and 0.028 p.u. (1.40 kVAr) of reactive power. During the fault 0.0011 p.u. (0.55kW) is injected to the grid and 0.0324 p.u. (16.2 kVAr) of reactive power is injected into the grid.
CHAPTER 4. MODELS OF TWO PV POWER PLANTS, THE GRID AND A WIND POWER FARM

Figure 4.10. Injected active (red) and reactive power (blue) of each generator in p.u.

Regarding the German Grid Code, it would be important to analyze the dynamic network support, in order to avoid disconnecting the solar PV park when a fault occurs. As mentioned before, the solar PV parks are considered to be type 2-generating plants. This machine cannot be disconnected when the voltage drops to 0% of the nominal voltage, which would be the case of this simulation. The PV power plant reaches the steady state condition in about 100 ms after the fault in case of the DC bus and it is practically immediate in the case of the MV and LV buses. So the German Grid Code is completely fulfilled.

In figure 3.5 it is represented how the response of the voltage should be according to the Grid Code. The recovery of the voltage should be completed within 500 ms, so this requirement is fulfilled.

In both grid codes, it is stated that the PV power plant must consume no reactive power at the connection point during the fault and must have the ability of a voltage recovery after the fault. So this requirement is completely fulfilled.

4.2 Model of a 15 MW PV power plant

4.2.1 Introduction

In this section a model of a 15 MW PV plant is presented. This model is based on the 2.5 MW PV plant presented in the previous section. During this section the interconnection between the models of 2.5 MW are presented in order to build up a 15 MW PV plant, so the controllers of each generator are similar to the 2.5 MW PV power plant. This 15 MW PV power plant has a nominal power 15 MW to the grid and is the model which is going to be used in the interconnection to the grid.
4.2. MODEL OF A 15 MW PV POWER PLANT

4.2.2 Modeling details

In figure 4.11, the scheme of the 15 MW PV plant is presented. It consists of 6 groups of 5 static generators each. Each group has the same model as the 2.5 MW PV plant seen in figure 4.1. In the model of the 15 MW, each group is connected to the MV PV park bus, which has a nominal voltage of 33kV, via a line (in figure 4.11, these lines are called lines 1-6). And the MV PV park is connected to the MV grid bus through line 7. In order to dimension the lines, two different kinds of lines have to be dimensioned independently because they are supporting different currents and powers. The lines have been dimensioned according to the data of ABB represented in figure 4.12[10]. The two types of lines are according to the figure 4.11:

- Lines 1,2,3,4,5 and 6: The lines are supporting a nominal current of 
  \[ I_n = \frac{2.5\text{MW}}{\sqrt{3}\times 33\text{kV}} = 43.7\text{A} \]. According to the table in figure 4.12, for a rated voltage between 10-70 kV the section is 95 mm$^2$. With this value for the cable section, the resistance, inductance and capacitance per km for the positive and the negative sequence can be obtained from the tables in figures 4.13 and 4.14. The values that are obtained are:
  - \( R' = 0.193 \ \Omega \text{km} \)
  - \( L' = 0.43 \ \mu\text{H} \text{km} \)
  - \( C' = 0.17 \ \mu\text{F} \text{km} \)

Figure 4.11. Model of a 15 MW PV Plant
For the zero sequence, the values are:
\[ R'_0 = 0.772 \ \Omega_{\text{km}} \]
\[ L'_0 = 1.72 \ \text{mH}_{\text{km}} \]
\[ C'_0 = 0.17476 \ \mu\text{F}_{\text{km}} \]

The length of these lines is 400 m

- **Line 7:** Line is supporting a nominal current of \( I_n = \frac{15\text{MW}}{\sqrt{3} \cdot 33\text{kV}} = 262.4\text{A}. \)

According to the table in figure 4.12, for a rated voltage between 10-70 kV the section is 185 mm\(^2\). With this value of section, the resistance, inductance and capacitance per km for the positive and negative sequences can be obtained from these tables in figures 4.13 and 4.14. The values that are obtained are:

\[ R' = 0.124 \ \Omega_{\text{km}} \]
\[ L' = 0.4 \ \text{mH}_{\text{km}} \]
\[ C' = 0.2 \ \mu\text{F}_{\text{km}} \]

For the zero sequence, the values are:

\[ R'_0 = 0.996 \ \Omega_{\text{km}} \]
\[ L'_0 = 1.6 \ \text{mH}_{\text{km}} \]
\[ C'_0 = 0.2050 \ \mu\text{F}_{\text{km}} \]

The length of this line is 1 km.

With the dimension of the lines, the model of the PV Power Plant is fully modeled.

---

**Table 1.** Section of the cables

<table>
<thead>
<tr>
<th>Cross section conductor</th>
<th>Cables in Ground</th>
<th>Cables in Air</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flat formation</td>
<td>Trefoil formation</td>
</tr>
<tr>
<td></td>
<td>Crossbonded</td>
<td>Both ends</td>
</tr>
<tr>
<td>mm(^2)</td>
<td>65(^\circ)C</td>
<td>90(^\circ)C</td>
</tr>
<tr>
<td>95</td>
<td>220</td>
<td>215</td>
</tr>
<tr>
<td>150</td>
<td>280</td>
<td>270</td>
</tr>
<tr>
<td>185</td>
<td>320</td>
<td>385</td>
</tr>
<tr>
<td>240</td>
<td>370</td>
<td>445</td>
</tr>
<tr>
<td>300</td>
<td>420</td>
<td>505</td>
</tr>
<tr>
<td>400</td>
<td>480</td>
<td>575</td>
</tr>
<tr>
<td>500</td>
<td>550</td>
<td>660</td>
</tr>
<tr>
<td>630</td>
<td>625</td>
<td>755</td>
</tr>
</tbody>
</table>

**Figure 4.12.** Section of the cables[10]
4.2. MODEL OF A 15 MW PV POWER PLANT

4.2.3 Simulation results in case of a three phase fault in the connection point

In this section some simulation results are presented in order to check the model active and reactive power to the grid. A pure three phase fault has been performed in the MV Grid bus. The short-circuit power of the external grid which is connected at this point is 450 MVA. In steady state, the PV park is injecting 13.4625 MW to the grid and absorbing 0.7275 MVAr from the grid, which gives a $\cos \phi \simeq 1$. This absorption of reactive power is due to the transformers. The voltages in the steady
CHAPTER 4. MODELS OF TWO PV POWER PLANTS, THE GRID AND A WIND POWER FARM

state are 0.9986 p.u in the MV PV park bus of each group, 0.9965 p.u. in the LV buses of each generator and 700V in the DC buses of each generator.

A pure three-phase short circuit is simulated in the MV bus. The short circuit is cleared after 0.5 sec. The MV PV Park’s voltage in p.u., the LV buses’ voltage in p.u., the injected active power to the grid in p.u., the injected reactive power to the grid in p.u. ($S_{\text{base}} = 15$ MVA) and the injected active and reactive power of each generator are depicted.

![Graphs showing voltage and power](image)

**Figure 4.15.** a) Voltage in the MV Park Bus b) Injected power to the grid c) Injected reactive power to the grid d) Voltage in the DC bus

In figure 4.15, the voltage in the MV park bus is depicted and it is shown that they stay within limits. Also, in the same figure, the injected active power is represented, before the fault the PV power plant was injecting 0.8975 p.u. ($S_{\text{base}} = 15$ MVA) which is 13.4625 MW. During the fault, the PV Park is not injecting any active power. The injection of reactive power is also plotted. Before the fault and after the fault, the PV power plant is absorbing 0.0515 p.u. ($S_{\text{base}} = 15$ MVA), which is 0.7275 MVAR. During the fault the PV is injecting 0.0015 p.u. ($S_{\text{base}} = 15$ MVA), which is 0.0225 MVAR. So it complies the part of the Grid Codes where the PV plant has to inject reactive power during a fault. The DC voltage is also shown and reaches approximately 876 V during the fault, which corresponds to the open circuit value of the PV panel. When the fault is cleared after 500 ms a transient can be seen in the three plots.
In figure 4.16, the voltage in the LV buses for each group is shown. Before and after the fault the correct values of voltage are reached which are 0.9965 p.u. During the fault a voltage of 0.0584 p.u. is reached due to the transformers. Finally, a plot of

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{voltage_in Lv_buses.png}
\caption{Voltage in the LV Buses of each generator}
\end{figure}

the injected active and reactive power of one static generator can be seen in figure 4.17. Each generator will have the same response of the active (red) and reactive (blue) power. The injected active power (red line) before the fault and after the fault is 0.8976 p.u. \((S_{\text{base}} = 0.5 \text{ MVA})\), which is 448.8 kW. During the fault, the generator are injecting approximately 0 kW of active power. The generator before and after the fault is absorbing 0.0109 p.u. \((S_{\text{base}} = 0.5 \text{ MVA})\) which is 5.5 kVAr. During the fault each generator is injecting 27.55 kVAr to the grid. Regarding the

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{active_reactive_power.png}
\caption{Injected active power(red) and injected reactive power(blue) of one generator}
\end{figure}
CHAPTER 4. MODELS OF TWO PV POWER PLANTS, THE GRID AND A WIND POWER FARM

German Grid Code, it would be important to analyze the dynamic network support, in order to avoid disconnecting the solar PV park when a fault occurs. This will be discussed in greater detail in chapter 7. As mentioned before, the solar PV parks are considered type 2-generating plants. This machine cannot be disconnected when the voltage drops to 0% of the nominal voltage, which would be the case of this simulation. The PV power plant reaches the steady state condition in about 110 ms after the fault in case of the DC bus and it is practically immediate in the case of the MV and LV buses. So the German Grid Code is completely fulfilled. Regarding the Spanish Grid Code, in figure 3.5 it is represented how the evolution of the voltage should be according to the Grid Code. The recovery of the voltage should be completed within 500 ms, so this requirement is fulfilled. In both Grid Codes, it is stated that the PV power plant must consume no reactive power at the connection point during the fault and must have the ability of a voltage recovery after the fault. So this requirement is completely fulfilled.

4.3 Model of the grid

The grid where the PV power plant is connected represents one part of Västerås’ grid. There have been some changes from the original model of the grid. This grid can be seen in figure 4.18. A zoom of the red circle can be seen in figure 4.19.

In this model, the external grid represents the connection to a bigger grid. This external grid is connected to a 132 kV terminal via an impedance to the primary bus. By changing the values of this impedance, the short circuit power of the primary grid can be changed. In normal conditions, the primary bus has a short circuit power of 450 MVA, which is around 30 times bigger than the injected power of the PV power plant. Two different values of impedance are chosen to make the grid weaker. An impedance of $8.4 + j \cdot 25.2$ p.u. is used to have a short circuit power of 225 MVA at the primary bus, which is 15 times bigger than the PV power plant and an impedance of $16.3 + j \cdot 48.5$ p.u. is used to have is used to have a short circuit power of 150 MVA at the primary bus, which is ten times bigger that the nominal power of the PV power plant. These two values of short circuit power are used to model two different weak grids. The term weak grid is used when the grid voltage is strongly influenced by load changes and is a grid where it is necessary to take the change in voltage due to load limitations in account. In case of solar PV power plants, the amount of active power that can be absorbed by the grid at the connection point is limited because of the lower voltage limit.

The primary bus is connected to a medium voltage bus called MV bus via a transformer of 13.804% of short circuit reactance and 188.1636kW of copper losses. In normal conditions only this transformer is connected. To improve the behavior of the grid a similar transformer is connected in parallel and it will be used only in the static analysis performed via the U-Q curves. The PV power plant is connected to the MV Grid bus and it will be connected to the MV bus via a transformer with the following characteristics: 33/ 11kV, short circuit impedance 6% and 16
MVA of rated power. To this MV bus several loads, transformers and lines are connected. Approximately the demand of active and reactive power is $P=14.26$ MW and $Q=6.97$ MVAr. When the PV power plant is connected and injecting the power corresponding to the MMP point, the active power demand will be practically supplied by the PV power plant.

4.4 Model of a wind power farm

An aggregate model of a wind power plant is being used to compare a wind power plant with the PV power plant. The wind power plant is modeled as a DFIG of 15 MW of rated power and $\cos \phi = 1$. The prime mover, consisting of a pitch-angle controlled wind turbine, the shaft and the gear-box drives a slip-ring induction generator. The stator of the DFIG is directly connected to the grid, the slip-rings of the rotor are fed by self-commutated converters. These converters allow controlling the rotor voltage in magnitude and phase angle and can therefore be used for active and reactive power control. [14]

The scheme of the DFIG is represented in figure 4.20. The wind power plant has a rated power of 15 MW. This power plant injects 15 MW of active power and is working with a $\cos \phi = 1$; in nominal condition the injected reactive power is equal to zero. This wind power plant is connected to the grid via a transformer of 11 kV/25 kV with a short circuit reactance of 6%.
Figure 4.18. Scheme of the grid

Figure 4.19. Zoom of the red circle of figure 4.18
Figure 4.20. Scheme of the Wind farm
Chapter 5

U-Q curves of the PV power plant

In order to analyze the behavior of the grid in steady state when the PV power plant is connected, the U-Q curves are obtained. Two types of U-Q curves are obtained: when the injected active power of the PV plant varies and when the short circuit power of the grid varies.

5.1 U-Q curves of the PV power plant when the injected active power varies

The U-Q curves for the power PV plant have been represented for different values of nominal power of the power plant from 15 MW to 0 MW. Two analysis are performed, the first one with only one transformer working and the second one with both transformers working. It is important to analyze the behavior of the PV power plant when the injected active power varies as depending of the level of the sun’s irradiation, the PV power plant will inject a different level of active power. Figure 5.1 shows how the voltage-current characteristic varies when the irradiation of the sun varies. The power output of the MPP decreases when the irradiation level decreases. In order to study the impact of this in steady state condition, the U-Q curves are obtained when the active power injected by each generators decrease.

In the following table the values of the injected power of each generator and the nominal power of the PV park are shown in the table 5.1.

In all cases the PV generators are working with $\cos \phi = 1$, so the generators are not injecting any reactive power.

By running the script in D IgSilent of the U-Q curves at the connection bus of the PV park by different values of nominal power of the power PV plant, the plots with one transformer working are in figure 5.2.

In order to analyze the behavior of the PV park in normal voltage levels a zoom of these curves can be seen in figure 5.3. In both plots a lower voltage limit of 0.95 p.u. is represented by a dashed line.

In order to get the correct values of the load flow and to avoid any numerical problems in the load flow, the option no initialization has to be enabled to avoid
Table 5.1. Table which represents the nominal power of the PV power plant and the injected power of each generator

<table>
<thead>
<tr>
<th>Nominal power of the PV park (MW)</th>
<th>Injected active power of each generator (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>448.8</td>
</tr>
<tr>
<td>12</td>
<td>359.04</td>
</tr>
<tr>
<td>9</td>
<td>269.28</td>
</tr>
<tr>
<td>6</td>
<td>179.52</td>
</tr>
<tr>
<td>3</td>
<td>89.76</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.2. Values from the load flow when the nominal power varies when one transformer is working

<table>
<thead>
<tr>
<th>Nominal power of the power plant (MW)</th>
<th>Voltage at the connection point (p.u.)</th>
<th>Injected active power of the PV power plant (kW)</th>
<th>Injected reactive power of the PV power plant (kVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.9885</td>
<td>-0.01</td>
<td>137</td>
</tr>
<tr>
<td>3</td>
<td>0.9892</td>
<td>2691</td>
<td>107</td>
</tr>
<tr>
<td>6</td>
<td>0.9893</td>
<td>5380</td>
<td>-18.3</td>
</tr>
<tr>
<td>9</td>
<td>0.9888</td>
<td>8066</td>
<td>-131</td>
</tr>
<tr>
<td>12</td>
<td>0.9877</td>
<td>10749</td>
<td>-341</td>
</tr>
<tr>
<td>15</td>
<td>0.9859</td>
<td>13429</td>
<td>-616</td>
</tr>
</tbody>
</table>

having a flat start in the load flow. From these U-Q curves, the value of the reactive power which has to be extracted from the grid to obtain a voltage level can be obtained.

Table 5.2 shows the nominal injected active power of the PV power plant, the voltage in the connection point, the injected active power and the injected reactive power.

From this table, it can be concluded that the more active power that the PV power plant is injecting, the more reactive power that consumes from the grid to maintain approximately the same voltage level. In the cases of 0 MW and 3 MW, the PV power plant is injecting reactive power to the grid due to the lines. The PV power plant consumes reactive power when the injected active power increases above these values.

In table 5.3, according to the U-Q curves the values of the maximum reactive power that need to be extracted from this bus when the injected active power of the power plant varies are represented. These values are obtained to avoid that the voltage drops below 0.95 p.u. at the connection point of the PV power plant. A maximum deviation of +/- 5% will be considered during the whole chapter. When the generators are not injecting any active power, the PV power plant consumes
5.1. U-Q CURVES OF THE PV POWER PLANT WHEN THE INJECTED ACTIVE POWER VARIES

Table 5.3. Maximum reactive power that needs to be extracted to get a minimum value of voltage when one transformer is working

<table>
<thead>
<tr>
<th>Nominal power of the PV power plant (MW)</th>
<th>Voltage at the connection point (p.u.)</th>
<th>Maximum reactive extracted (kVar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.95</td>
<td>4825</td>
</tr>
<tr>
<td>3</td>
<td>0.95</td>
<td>4879</td>
</tr>
<tr>
<td>6</td>
<td>0.95</td>
<td>4811</td>
</tr>
<tr>
<td>9</td>
<td>0.95</td>
<td>4617</td>
</tr>
<tr>
<td>12</td>
<td>0.95</td>
<td>4299</td>
</tr>
<tr>
<td>15</td>
<td>0.95</td>
<td>3859</td>
</tr>
</tbody>
</table>

Table 5.4. Values from the load flow when the nominal power varies when both transformers are working

<table>
<thead>
<tr>
<th>Nominal power of the power plant (MW)</th>
<th>Voltage at the connection point (p.u.)</th>
<th>Injected active power of the PV power plant (kW)</th>
<th>Injected reactive power of the PV power plant (kVar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0040</td>
<td>-0.01</td>
<td>140</td>
</tr>
<tr>
<td>3</td>
<td>1.0042</td>
<td>2691</td>
<td>112</td>
</tr>
<tr>
<td>6</td>
<td>1.0041</td>
<td>5380</td>
<td>26</td>
</tr>
<tr>
<td>9</td>
<td>1.0038</td>
<td>8066</td>
<td>-119</td>
</tr>
<tr>
<td>12</td>
<td>1.0033</td>
<td>10749</td>
<td>-322</td>
</tr>
<tr>
<td>15</td>
<td>1.0025</td>
<td>13430</td>
<td>-586</td>
</tr>
</tbody>
</table>

active power from the grid due to the lines.
As the PV power plant is consuming reactive power from the grid when the injected active power increases, less reactive power can be extracted from this point.
By running the script in DiGSilent of the U-Q curves at the connection bus of the PV park by different values of nominal power of the power PV plant, the plots when both transformers are working are in figure 5.4.
In order to analyze the behavior of the PV park in normal voltage levels a zoom of these curves can be seen in figure 5.5. In both plots a lower voltage limit of 0.95 p.u. is represented by a dashed line.
From these U-Q curves, the value of the reactive power which has to be extracted from the grid to obtain a voltage level can be obtained.
Table 5.4 shows the nominal injected active power of the PV power plant, the voltage in the connection point, the real injected active power and the injected reactive power.
From this table, the more injected power that the PV power plant is injecting, the more reactive power that is consumed from the grid to maintain approximately the same voltage level. In the cases of 0 MW, 3 MW and 6 MW, the PV power plant is injecting reactive power to the grid, but it consumes reactive power when the
injected active power rises. When both transformers are working, there is a better
distribution of the voltages and the injected reactive power. There is not a big
change in the injected active power, if it is compared when only one transformer is
working.

In table 5.5, according to the U-Q curves the values of the maximum reactive power
that need to be extracted from this bus when the injected active power of the power
plant varies are represented. These values are obtained to avoid that the voltage
drops below 0.95 p.u. at the connection point of the PV power plant. When the
generators are not injecting any active power, the PV power plant consumes some
active power from the grid due to the lines.

As the PV power plant is consuming reactive power from the grid when the injected
active power increases, less reactive power can be extracted from this point. When
two transformers are working, more reactive power has to be extracted from the
connection point to reach a low value of voltage.

### 5.2 U-Q curves of the PV power plant when the short
circuit power of the grid varies

The U-Q curves for different short circuit power of the grid are obtained when the
PV power plant is injecting 15 MW of active power. The idea is to see the influence
of the PV power plant when it is connected at different types of grid, especially the
weak ones, where the voltage can reach very low values. Strong or weak grids are
relative terms. For any given wind power installation of installed capacity P (MW)
the ratio \( R_{SC} = \frac{S_{SC}}{P} \) is a measure of the strength. The grid is strong with
respect to the installation if \( R_{SC} \) is above 20 to 25 times and weak for \( R_{SC} \) below 8
to 10 times.[15] Three different levels of short circuit power of the grid are selected:
\( S_{cc} = 150 \text{MVA} \) (approximately ten times more than the injected active power
of the PV power plant) in black, \( S_{cc} = 225 \text{MVA} \) (approximately fifteen times more
than the injected active power of the PV power plant) in green, \( S_{cc} = 450 \text{MVA} \)
(approximately thirty times more than the injected active power of the PV power
plant) in blue. According to the definition above, \( S_{cc} = 450 \text{MVA} \) can be consid-

#### Table 5.5. Maximum reactive that needs to be extracted to get a minimum value
of voltage when both transformers are working

<table>
<thead>
<tr>
<th>Nominal power of the PV power plant (MW)</th>
<th>Voltage at the connection point (p.u.)</th>
<th>Maximum reactive extracted (kVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.95</td>
<td>9110</td>
</tr>
<tr>
<td>3</td>
<td>0.95</td>
<td>9108</td>
</tr>
<tr>
<td>6</td>
<td>0.95</td>
<td>9008</td>
</tr>
<tr>
<td>9</td>
<td>0.95</td>
<td>8767</td>
</tr>
<tr>
<td>12</td>
<td>0.95</td>
<td>8482</td>
</tr>
<tr>
<td>15</td>
<td>0.95</td>
<td>8016</td>
</tr>
</tbody>
</table>
5.2. U-Q CURVES OF THE PV POWER PLANT WHEN THE SHORT CIRCUIT POWER OF THE GRID VARIES

erved as a strong grid and \( S_{cc} = 150 \text{ MVA} \) can be considered as weak grid. The U-Q curves represented in figure 5.6 are obtained when only one transformer is working. A lower voltage limit of 0.95 p.u. is represented by a dashed line.

In order to analyze the behavior of the PV park in normal voltage levels a zoom of these curves can be seen in figure 5.7.

In table 5.6, the voltage in the connection point, the real injected active power and the injected reactive power depending on the short circuit power of the grid are shown.

\[ \text{Table 5.6. Values from the load flow for different values of } S_{cc} \text{ of the grid when one transformer is working} \]

<table>
<thead>
<tr>
<th>Short circuit power of the grid (MVA)</th>
<th>Voltage at the connection point (p.u.)</th>
<th>Injected active power of the PV power plant (kW)</th>
<th>Injected reactive power of the PV power plant (kVAr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.9421</td>
<td>13462</td>
<td>-701</td>
</tr>
<tr>
<td>225</td>
<td>0.9640</td>
<td>13462</td>
<td>-657</td>
</tr>
<tr>
<td>450</td>
<td>0.9859</td>
<td>13462</td>
<td>-616</td>
</tr>
</tbody>
</table>

When the short circuit power of the grid decreases, the voltage at the connection point also decreases, and for instance, in the case of the lowest short circuit power of the grid, i.e. \( S_{cc} = 150 \text{ MVA} \), the voltage is too low. In order to get an operation point for this case, some reactive compensation should be added.

From the U-Q curves the maximum reactive power that has to be extracted from the connection point in the case that the voltage is in the limit, i.e. 0.95 p.u., can be obtained and it is shown in table 5.7.

\[ \text{Table 5.7. Maximum reactive power that needs to be extracted to get a minimum value of voltage when the } S_{cc} \text{ varies and one transformer is working} \]

<table>
<thead>
<tr>
<th>Short circuit power of the grid (MVA)</th>
<th>Voltage at the connection point (p.u.)</th>
<th>Maximum reactive extracted (kVAr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.95</td>
<td>0</td>
</tr>
<tr>
<td>225</td>
<td>0.95</td>
<td>893.5</td>
</tr>
<tr>
<td>450</td>
<td>0.95</td>
<td>3859</td>
</tr>
</tbody>
</table>

In the case of \( S_{cc} = 150 \text{ MVA} \), a reactive power compensation is needed to reach the desired voltage value.

The U-Q curves are represented in figure 5.8 when both transformers are working. In order to analyze the behavior of the PV power plant in normal voltage levels a zoom of these curves can be seen in figure 5.9.

Table 5.8 shows the voltage at the connection point, the real injected active power and the injected reactive power depending on the short circuit power of the grid. From these U-Q curves, the value of the reactive power which has to be extracted...
Table 5.8. Values from the load flow for different values of $S_{cc}$ of the grid when both transformers are working

<table>
<thead>
<tr>
<th>Short circuit power of the grid (MVA)</th>
<th>Voltage at the connection point (p.u.)</th>
<th>Injected active power of the PV power plant (kW)</th>
<th>Injected reactive power of the PV power plant (kVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.9611</td>
<td>13462</td>
<td>-663</td>
</tr>
<tr>
<td>225</td>
<td>0.9817</td>
<td>13462</td>
<td>-624</td>
</tr>
<tr>
<td>450</td>
<td>1.0025</td>
<td>13462</td>
<td>-586</td>
</tr>
</tbody>
</table>

from the grid to obtain a voltage level can be obtained. Table 5.9, the nominal injected active power of the PV power plant, the voltage in the connection point, the real injected active power and the injected reactive power are shown.

Table 5.9. Maximum reactive power that needs to be extracted to get a minimum value of voltage when the $S_{cc}$ varies and both transformers are working

<table>
<thead>
<tr>
<th>Short circuit power of the grid (MVA)</th>
<th>Voltage at the connection point (p.u.)</th>
<th>Maximum reactive extracted (kVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.95</td>
<td>616.2</td>
</tr>
<tr>
<td>225</td>
<td>0.95</td>
<td>3152</td>
</tr>
<tr>
<td>450</td>
<td>0.95</td>
<td>8016</td>
</tr>
</tbody>
</table>

From these results, it can be concluded that the operation of the grid improves when both transformers are working. Although the voltages when the short circuit value is 150 MVA are very low, they are above 0.95 p.u. and some reactive power can be extracted from the connection point.

After this analysis, it can be concluded that the PV power plants should be connected in points where the grid is strong in order to avoid low levels of voltages. According to this results, they should be connected at points where the short circuit power of the grid is 10-15 times bigger than the injected power of the PV power plant.

5.3 Conclusions of the U-Q curves

From the U-Q curves the amount of reactive power that needs to be extracted from one point for a voltage level be obtained. This is useful, because in case the reactive power demand increases, the steady state voltage of the PV power plant can be predicted. In all the curves a lower voltage limit of 0.95 has been set, to keep the voltage above 0.95 p.u. From these curves, the value of the maximum reactive power that needs to be extracted in order to reach the minimum voltage limit can be obtained.

From the U-Q curves it is shown that the grid has a better behavior when both
transformers are working. In order to improve the behavior of the grid, the other transformer should be connected.

From the U-Q curves when the injected power varies, it is shown that when the PV power plant inject more active power, less reactive power can be extracted from this point, so the PV power plant is absorbing more reactive power when it increases the active power injection.

From the U-Q curves when the short circuit power of the grid varies, it is shown that the PV power plant should be connected at points that have a $S_{sc}$ at least 10-15 times bigger that the injected active power, to keep the voltage above 0.95 p.u. From these curves, the variation of the voltage when the $S_{sc}$ of the grid is obtained. It can be studied the influence of the weak grid in the power plant’s voltage.

In general, the unstable points where $\frac{dQ}{dU} < 0$, according to the voltage stability criterion are also represented. But in this case, these points would lead to very low voltages. But in general it is useful to know how much reactive power can be extracted in order to avoid stability problems.

From the U-Q curves it is also easy to analyze the behavior of the power plant when a capacitor is connected, and how it will affect the voltage of the PV power plant. As mentioned before, the slope of the U-Q curve indicates the stiffness of the test bus.
Figure 5.1. Variation of the U-I characteristic when the irradiation of the sun varies.
5.3. CONCLUSIONS OF THE U-Q CURVES

Figure 5.2. U-Q curves of the power PV park when only one transformer is working when the injected power varies
Figure 5.3. Zoom of the U-Q curves of the power PV park when only one transformer is working when the injected power varies.
Figure 5.4. U-Q curves of the power PV park when both transformers are working when the injected power varies
Figure 5.5. Zoom of the U-Q curves of the power PV park when both transformers are working when the injected power varies
Figure 5.6. U-Q curves of the power PV park when only one transformer is working when the $S_{cc}$ of the grid varies.
Figure 5.7. Zoom of the U-Q curves of the power PV park when only one transformer is working when the $S_{cc}$ of the grid varies.
Figure 5.8. U-Q curves of the power PV park when both transformers are working when the $S_{cc}$ of the grid varies.
Figure 5.9. Zoom of the U-Q curves of the power PV park when both transformers are working when the $S_{cc}$ of the grid varies.
Chapter 6

Simulation of several cases of voltage dips

Voltage dips are short decreases in rms voltage caused by a short-duration increase in grid current due to motor starting, transformer energizing or faults in the electric supply system. Voltage dips have been proven to be one of the most important aspects of power quality.[13] A voltage dip of X % means that the voltage at the PCC is (1-X %) p.u. Five cases of voltage dips are performed at the PV power plant’s MV bus, called MV Grid bus shown in figure 4.19: 100%, 80%, 60%, 40% and 20%. In order to simulate these voltage dips a three-phase fault is performed for different values of fault resistance. The fault is cleared after 500 ms, in order to see better the behavior of the different variables during the transient. The grid codes are referred to a fault of 150 ms, but if the requirements are fulfilled for a fault of 500 ms, they will be fulfilled for a shorter clearing time. Table 6.1 shows the values for the resistance corresponding to a certain voltage dip.

The outputs which are analyzed are the voltage at the MV Grid bus, the active and reactive power output of the PV power plant, the voltage at the DC bus, the injected active and reactive power of each generator and the voltage at the LV bus. For the case of the 100% voltage dip, a pure three phase fault is performed. The response of the voltage where the fault is performed, the active power output, the voltage in the DC bus and the reactive power output are plotted in figure 6.1. In the first plot the voltage dip is represented. Prior to the fault, the PV power plant operates at nominal voltage with a feed-in power of 100%.

<table>
<thead>
<tr>
<th>Voltage dip</th>
<th>Fault resistance(Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>0</td>
</tr>
<tr>
<td>80%</td>
<td>2</td>
</tr>
<tr>
<td>60%</td>
<td>4.2</td>
</tr>
<tr>
<td>40%</td>
<td>7.1</td>
</tr>
<tr>
<td>20%</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Table 6.1. Values for the resistance for a certain voltage dip
plant is injecting 0.897 p.u. of active power to the grid which is 13.445 MW, during the short circuit, the PV power plant is injecting 30 kVAR. Before the fault the voltage in the DC bus is 700 V, during the short-circuit the voltage in the DC bus rises until approximately 876 V, which corresponds to the open circuit voltage of the panels and after the short circuit the voltage at this bus reaches its nominal value of 700 V. The voltage corresponds to the open circuit value of the voltage, and the behavior of the plant during the short circuit for this case will be explained in greater detail in chapter 7 and compared with the behavior of a wind farm. The voltage at the connection point of the PV power plant drops to 0 p.u. during the transient and reaches its nominal value of 0.982 p.u. after the short circuit. Prior to the fault, the PV power plant is absorbing 0.041 p.u. of reactive power. As the $S_{base}=15$ MVA, the absorbed reactive power is 615 kVAR. During the fault, the PV power plant is injecting 0.002 p.u., which is 30 kVAR. In 120 ms after the short circuit is cleared, the transient is ended. The reactive power absorbed of the PV power plant is due to the lines and transformers as each generator is injecting no reactive power and the whole PV power plant is absorbing 615 kVAR from the grid, so these are the reactive power losses of the power PV plant.

In figure 6.2, the active and reactive power of a generator is plotted. Each generator has the same response of the injected active and reactive power. Prior to the fault, each generator is injecting 0.449 MW of active power and they are not absorbing any reactive power from the grid. During the fault, 0.002 p.u. of active power is being injected and 0.053 p.u. of reactive power which is 26.5 kVAR. The total injected power of the generators is $30 \cdot 0.449 = 13.47$ MW and the injected active power is 13.445 MW so the losses in the lines are 25 kW. During the transient, the losses are close to zero.

The response of the voltage in the LV bus of each generator is represented in figure 6.3. Prior and after the fault the voltage in the LV buses is 0.983 p.u. and during the fault the voltage drops to 0.058 p.u. due to the transformers. During the voltage dip, according to the equation 4.1, $\Delta u_{ac} = 0.983 - 0.058 = 0.925$ p.u.; therefore the q-current injected by the inverter is $i_q = 0.925$ p.u. and the reactive power injected by the inverter is $0.925 \cdot 0.058 = 0.054$ p.u. during the fault, which is the value shown in figure 6.2. Thus, the PV generators are injecting reactive current during the fault, which is a good behavior and complies the grid codes’ requirements.

A voltage dip of 80% is performed. In order to perform this, a three phase fault with a 2Ω resistance is performed. The response of the voltage where the fault is performed, the active power output, the voltage in the DC bus and the reactive power output are plotted in figure 6.4. In figure 6.5, the injected active and reactive powers of each generator are represented. In figure 6.6 the voltage in the LV bus of each generator is represented.

A voltage dip of 60 % is analyzed. In order to perform this, a three phase fault with a 4.2 Ω resistance is performed. the response of the voltage where the fault is performed, the active power output, the voltage in the DC bus and the reactive power output are plotted in figure 6.7. In figure 6.8, the injected active and reactive powers of each generator are represented. In figure 6.9 the voltage in the LV bus of
each generator is represented. A voltage dip of 40% is analyzed. In order to analyze this, a three phase fault with a 7.1 $\Omega$ resistance is performed. The response of the voltage where the fault is performed, the active power output, the voltage in the DC bus and the reactive power output are plotted in figure 6.10. In figure 6.11, the injected active and reactive powers of each generator are represented. In figure 6.12 the voltage in the LV bus of each generator is represented.

A voltage dip of 20% is analyzed. In order to analyze this, a three phase fault with a 12.5 $\Omega$ resistance is performed. The response of the voltage where the fault is performed, the active power output, the voltage in the DC bus and the reactive power output are plotted in figure 6.13. In figure 6.14, the injected active and reactive powers of each generator are represented. In figure 6.15 the response of the voltage in the LV bus of each generator is represented.

In table 6.2, a summary of all the variables during the fault is shown. In conclusion, when the voltage dip is bigger less active power is injected from the PV power plant and the voltage in the DC bus is higher. The reactive current injection of the inverter is equal to the voltage dip in the LV bus, therefore it will be higher when the voltage dip is higher. The reactive power injection of the inverter depends on this reactive current and the voltage level, so it will reach its maximum at the 50% voltage dip.

<table>
<thead>
<tr>
<th>Voltage dip</th>
<th>Injected active power of the power plant during the voltage dip (p.u.)</th>
<th>Injected reactive power of the power plant during the voltage dip (p.u.)</th>
<th>Voltage of the DC bus during the voltage dip (V)</th>
<th>Injected reactive current by the inverter during the voltage dip (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>0.002</td>
<td>0.002</td>
<td>876</td>
<td>0.925</td>
</tr>
<tr>
<td>80%</td>
<td>0.066</td>
<td>0.143</td>
<td>871</td>
<td>0.736</td>
</tr>
<tr>
<td>60%</td>
<td>0.193</td>
<td>0.211</td>
<td>863</td>
<td>0.547</td>
</tr>
<tr>
<td>40%</td>
<td>0.397</td>
<td>0.198</td>
<td>847</td>
<td>0.356</td>
</tr>
<tr>
<td>20%</td>
<td>0.674</td>
<td>0.104</td>
<td>812</td>
<td>0.166</td>
</tr>
</tbody>
</table>

According to the German Grid Code and the figure 3.2 that summarizes how a type-2 generating plant, such as PV power plant, it can be stated that the requirements are fulfilled. In any voltage dip of a duration of 500 ms, the recovery of the PV power plant is produced within 150-200 ms. In case of shorter voltage dips, the recovery will be faster. It is recommended that the PV power plant should be connected although the active power is reduced. According to the table, the PV power plant will inject more short circuit current the higher the voltage dip.
is, which is a good behavior and promotes the quick recovery of the voltage after
the voltage dip. This fulfills the requirement stated in the German grid code which
states that the PV power plants must inject short-circuit current during the faults.
The figure that summarizes the Spanish Grid Code in case of voltage dips was
shown before in figure 3.5. This figure shows that the requirements that have to
be fulfilled are less restrictive than the German Code’s ones. So the Spanish Code’s
requirements are fulfilled. After a fault of 150 ms, the PV power plant should
recover from a voltage dip of 80% within 500 ms. In this model, this requirement
is completely fulfilled as it is shown in figure 6.13.
Figure 6.1. Voltage dip of 100%: a) Voltage in the connection bus of the PV power plant b) Injected active power of the PV power plant c) Voltage in the DC Bus d) Injected active power of the PV power plant

Figure 6.2. Voltage dip of 100%: Injected active (red) and reactive power (blue) of each generator
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Figure 6.3. Voltage dip of 100%: Voltage in the LV bus of each generator

Figure 6.4. Voltage dip of 80%: a) Voltage in the connection bus of the PV power plant b) Injected active power of the PV power plant c) Voltage in the DC Bus d) Injected active power of the PV power plant
Figure 6.5. Voltage dip of 80%: Injected active (red) and reactive power (blue) of each generator

Figure 6.6. Voltage dip of 80%: Voltage in the LV bus of each generator
Figure 6.7. Voltage dip of 60%: a) Voltage in the connection bus of the PV power plant b) Injected active power of the PV power plant c) Voltage in the DC Bus d) Injected active power of the PV power plant

Figure 6.8. Voltage dip of 60%: Injected active(red) and reactive power(blue) of each generator
Figure 6.9. Voltage dip of 60%: Voltage in the LV bus of each generator

Figure 6.10. Voltage dip of 40%: a) Voltage in the connection bus of the PV power plant b) Injected active power of the PV power plant c) Voltage in the DC Bus d) Injected active power of the PV power plant
Figure 6.11. Voltage dip of 40\%: Injected active(red) and reactive power(blue) of each generator

Figure 6.12. Voltage dip of 40\%: Voltage in the LV bus of each generator
Figure 6.13. Voltage dip of 20%: a) Voltage in the connection bus of the PV power plant b) Injected active power of the PV power plant c) Voltage in the DC Bus d) Injected active power of the PV power plant

Figure 6.14. Voltage dip of 20%: Injected active(red) and reactive power(blue) of each generator
Figure 6.15. Voltage dip of 20%: Voltage in the LV bus of each generator
In order to compare the model of a 15 MW PV power plant and a 15 MW wind farm, a pure short circuit is performed in the connection point with a clearing time of 150 ms.

Figure 7.1.a shows the injected active power of the PV power plant (in red) and the injected active power of the wind power plant (in blue). Prior to the fault and after the fault both power plants are injecting 0.987 p.u., which are 13.455 MW. In order to compare the behavior of both power plants, they must have the same setpoint. The settling time of the PV power plant after the short circuit is smaller than the wind power plant’s one. As mentioned before for the PV power plant this settling time is around 120 ms, meanwhile the wind power plant’s one is around 2 s, but around 1.5 s the active power value is very close to the nominal value. The settling time of the wind farm could be reduced by changing the parameters of the controllers, but in any case, this time would be always higher that the PV power plant’s settling time due to the mechanical inertia. In the case of the PV plant, only electrical aspects are considered, as there is no rotating machine. Therefore the transients will be faster.

The reactive power output of both power plants is plotted in figure 7.1.b. Prior to the fault and after the fault the PV power plant is absorbing 0.041 p.u. of active power which is 615 kVAr. The wind power plant is injecting 0 p.u. During the fault, the PV power plant is injecting 0.002 p.u. of reactive power and the wind power plant is injecting no reactive power. Therefore, the behavior of both plants is very similar when the reactive power output of the power plant is analyzed. As explained in chapter 6, the injected reactive current of the PV inverter is 0.925 p.u., the reactive power of each generator is 0.054 p.u. According to this, the behavior of the PV power plant during the fault is better than the wind farm’s behavior because the PV power plant is injecting reactive current during the fault, meanwhile the wind farm is not injecting reactive current. The grid codes state that injecting reactive current during faults is a desirable behavior, so according to
CHAPTER 7. COMPARISON OF THE PV POWER PLANT WITH A WIND POWER FARM

Figure 7.1. (a) Injected active power of the PV power plant (in red) and the wind power plant (in blue). (b) Injected reactive power of the PV power plant (in red) and the wind power plant (in blue). (c) Voltage at the PCC of the PV power plant (red) and the wind power farm (blue).

This, the PV power plant has a better behavior, as the PV generators are injecting reactive current. The wind power farm is working with a \( \cos \phi = 1 \) at the PCC, meanwhile the PV power plant is consuming reactive power to cover the losses of the transformers and lines. In steady state, the wind farm has a better behavior as it is injecting 0 p.u. of reactive power, meanwhile the PV power plant is absorbing 615 kVAr. Just after the fault is cleared, the wind power plant is consuming 1.4 p.u. of reactive power, which is 21 MVAR, meanwhile the PV power plant is injecting 0.561 p.u., which is 8.415 MVAR. This shows that just after the fault is cleared, the PV inverters are injecting reactive current, meanwhile the wind farm is absorbing reactive current.

Regarding the active and reactive power absorption during the fault, the PV power plant has a better behavior as the settling time after the fault in the active power is lower than the wind’s farm, and the PV generators are injecting reactive current during the fault. It is important to highlight that the transient after the fault in the case of the PV power plant takes into account electromagntetical phenomena, meanwhile the wind power plant as well as electromagntetical phenomena takes into account mechanical phenomena, which are much slower.

The voltage at the connection point of both power plants is plotted in figure 7.1.c.
Prior to the fault and after the fault the voltage at the connection point of both power plants is 0.988. The two curves are practically overlapping. In the case of the PV power plant the voltage is recovered slightly faster than in the wind farm. Concerning the grid codes, both power plants have a very similar response in the voltage after the fault. Both power plants fulfill the German and Spanish grid codes concerning the dynamic network support, as the voltage level reaches its nominal value within 150 ms.

Concerning the steady state condition, both power plants have a similar voltage level at the PCC.

Finally the most important difference between both plants is the behavior during the fault. In the case of the wind farm, during the fault there is an excess of energy that will accelerate the machine as it is shown in figure 7.2. As mentioned before, the transient of the wind farm after the fault is much slower than the PV power plant’s transient. In the case of the PV power plant, no mechanical variables are involved during the fault as there is no machine. During the fault the voltage at the DC bus, increases until 876 V as it can be seen in figure 7.3. During the fault, the capacitor is storing 2.3854 mJ that can be calculated according to the equation 7.1, where \( C \) is the capacitor’s capacity and \( V_2 \) and \( V_1 \) are the voltages during and before the fault respectively. This excess of energy is consumed as heat (Joule losses). In general, in the physical model, a resistance is connected with a chopper in order to evacuate this excess of energy. When the voltage rises to a high value, the resistance is connected and the energy is consumed as heat, to avoid damaging the inverter.

\[
\Delta E = \frac{1}{2} \cdot C \cdot (V_2^2 - V_1^2) \quad (7.1)
\]

To analyze how the PV generator behaves during the fault, the characteristic curve of the PV generator has to be analyzed and was shown in figure 2.2. In normal condition, the PV generator is working at the MPP. When the fault occurs, the current of the generator is equal to zero and the voltage rises to 876 V which is the open circuit voltage, as it can be seen in table 4.2, where the open circuit voltage of

![Figure 7.2. Speed of the generator](image-url)
one generator is $43.8 \cdot 20 = 876$ V. According to this, the PV generator is connected to the grid when the fault occurs although it is not generating any active power during the fault, as the working point is in $(876, 0)$ in the V-I characteristic. Summarizing everything, it is stated that the behavior of the PV power plant during the fault is better because of the reactive current injection, also the behavior during the fault of the PV generators according to the active power injection is better, because the excess of energy during the fault is very low, as the PV generators are producing no active power during the fault according to the voltage-current characteristic of the PV panel, so there is no excess of energy that must be evacuated. This is a good behavior because it will lead to faster transients after the reconnection as there are no mechanical variables involved. The most important thing that should be studied at this point and which is suggested as future work is the re-synchronization after the fault in order to check if the inverters provide a fast re-synchronization after the fault.
Chapter 8

Conclusions and future work

The report shows two different system aspects of grid connected PV power plants: the static behavior of the PV power plants and the dynamic behavior when different levels of voltage dips occur.

The effect of connecting PV power plants to the grid is analyzed. After analyzing the U-Q curves for different values of injected active power it can be stated that, when active power injection of the PV power plants increases, the reactive power consumption is increasing as well in order to maintain approximately the same voltage level.

After the analysis of the U-Q curves when the short circuit power of the grid varies, it can be concluded that PV power plants should be connected at points where the short circuit power is at least 10-15 times bigger than the nominal power of the PV power plant to maintain a reasonable voltage level.

From the simulation of the voltage dips, it has been shown that this model fulfills both German and Spanish grid codes. The LVRT requirement prevents the loss of a good portion of the power, while the reactive power support allows for a better behavior in terms of voltage values in PCC. The analysis of these grid codes allows us to understand the future requirements in the field of renewable energy sources, with the objective to permit a high penetration of unconventional power sources in the grid.

When wind power technology and PV power technology are compared, it is concluded that in steady state condition, both technologies have a similar behavior. After a short circuit, both technologies have a similar behavior, as the response in voltage is very similar. The restoring of the injected active and reactive power of the PV power plant is faster because of the control of the inverter and the voltage-current characteristic of the PV panel. PV power plants have no mechanical parts, therefore the transients will not be influenced by the inertia of the machine and will be faster. The voltage response at the PCC for both technologies is very similar. During the three phase short circuit, the turbine tends to accelerate during the fault, meanwhile the PV power plant is not producing active power according to the U-I curve of the PV panel although it is receiving sun’s irradiation, the PV
inverters are only injecting reactive current during the fault.
As future work, the model should be improved. In this thesis, the model consists on
generators which are working at the MPP and $\cos \phi = 1$. The addition of an AVR
in the generators or other kind of voltage controller will be something interesting
to study to improve the model, where the voltage is fixed to 1 p.u. and how this
fact would affect the other variables, such as reactive power.
As future work it should be interesting to study the case of over-voltages and how
the PV power plant behaves in this case. In this field, more literature of over-
voltages should be studied.
The re-synchronization after the faults of the model of PV power plant should be
analyzed. It should be also interesting to analyze if the model fulfills the grid codes
in this aspect, more literature should be studied and also analyze the part of the
model where the active power is reduced in case of over-frequency.
Bibliography


[7] Red Electrica Española 'Procedimiento de Operacion 12.3'


