UNIVERSITÀ DEGLI STUDI DI PADOVA

FACOLTÀ DI INGEGNERIA INDUSTRIALE

Corso di Laurea in Ingegneria Energetica

ACTIVE POWER CONTROL OF A PV GENERATOR FOR LARGE SCALE PHOTOVOLTAIC POWER PLANTS

Laureando

Nicolò Zanatta

Relatore

Prof. Fabio Bignucolo

Co-relatore

Ana Cabrera Tobar

ANNO ACCADEMICO 2016/2017

Contents

Abstract

The increasing renewable energy penetration together with the price reduction of photovoltaic modules supported the development of large scale photovoltaic power plants connected to the medium and low voltage grid. Many concerns are emerging about the electrical system stability when it is connected to renewable sources. Once, photovoltaic plants where thought to reach always the maximum power point and to extract the maximum power available. Nowadays, there are new challenges that photovoltaic plants have to overcome for ensuring the production and control with a variable energy resource as solar radiation. Photovoltaic generation components and control are being investigated according to new grid requirements proposed by Puerto Rico and South Africa. Thus, new grid rules express the need to reinforce the electrical grid in order to sustain the renewable energy penetration. This dissertation addresses a review of current development for photovoltaic power plants and connected grid requirements. Besides, an overview of current technologies and control methods is presented. A model of the photovoltaic generator is simulated in DigSilent Power Factory with a modified tracking algorithm. The results are analyzed and discussed, integrating also with an economic analysis.

List of abbreviations

- APC: Active Power Control
- APC: Active Power Curtailment
- APR: Active Power Reserve
- CAES: Compressed Air Energy Storage
- CPG: Constant Power Generation
- CSI: Current Source Inverter
- DG: Distributed Generation
- DSL: Dig Silent Language
- ESS: Energy Storage System
- ESU: Energy Storage Units
- FCR: Frequency Containment Resources
- FiT: Feed in Tariff
- FLC: Fuzzy Logic Controller
- FRT: Fault Ride Through
- FSM: Frequency Sensitive Mode
- GCT: Gate Commutated Thyristors
- GSE: Gestore Servizi Energetici
- IGBT: Insulated Gate Bipolar Transistor
- IR: Innertial Response

- IRR: Inner Rate of Return
- LS-PVPP: Large Scale Photovoltaic Power Plant
- LV: Low Voltage
- MA: moving average control
- MICAPAS: Mitigation Control Against Partial Shading
- MIP: Minimum Import Price
- MPP: Maximum Power Point
- MPPT: Maximum Power Point Tracking
- MTR: Minimal Technical Requirement
- NERSA: National Energy Regulator of South Africa
- NOCT: Normal Operating Cell temperature
- NPV: Net Present Value
- PI: Proportional Integral
- PLL: Phase Looked Loop
- PPC: Power Plant Controller
- PPT: Power Point Tracking
- PREPA: Puerto Rico Electric Power Authority
- PVGIS: Photovoltaic Geographical Information System
- PWM: Pulse With Modulation
- RED: Renewable Energy Directive
- RPM: Reduced Power Mode
- SCR: Silicon Controlled Rectifiers
- SOC: State of Charge
- SPWM: Sinusoidal Pulse With Modulation
- STATCOM: Static Synchronous Compensator

- STC: Standard Test Conditions
- SVC: Static Var Compensators
- THD: Total harmonic distortion
- TSO: Transmission System Operator
- VSC: Voltage Source Converter
- VSIC: Variable Step-size Incremental Conductance

Chapter 1

Introduction

1.1 Research requirements

This section presents the principal requirements that are developed in the present work. These requirements respond to the needs due to the diffusion of LS-PVPPs in the electrical grid.

- The control of the PV generator will act in different operating points in order to supply a power according to a reference given by the Transmission System Operator (TSO) to the LS-PVPP;
- Furthermore the system will not have any extra-equipments as Energy Storage Systems (ESS). The whole system has to manage the fluctuations of power only with the Active Power Control;
- The study case to test the PV generator under variable conditions with fast radiation changes will be for three different days in a specific location;
- Economic analysis between the system developed in this dissertation and a system with Active Power Control and ESS.

1.2 Research challenges

The scenario described in the introduction and the research requirements are connected with some challenges that the present dissertation aims to face up. Hence, the objective is not only to develop a new model in DigSilent Power Factory, but also to learn new information regarding devices and regulations connected with renewable energy from PV panels. The following points describe the main challenges of this project.

- **Grid codes**: Understand the requirements of the grid codes considering the active power management;
- **DigSilent Power Factory**: Learn the functionalities of the software and how to run a simulation from which extract significant results;
- **Model**: Understand the characteristics of a PV generator, a PV array and a PV inverter. Develop a proper model of the PV generator on DigSilent Power Factory;
- **Control**: Understand how a traditional MPPT operates and it can be modified to develop a proper control considering the variation of solar irradiation.

1.3 Contribution

According to the research challenges, the work developed in this dissertation consists in:

1. Review of active power controls with a comparison between PV generators with and without energy storage. The main advantages and drawbacks of different technologies and strategies are pointed out;
2. Review of the principal MPPT methods;
3. Development of the model that makes the dc voltage change inside the limits defined by the inverter characteristics;
4. Development of the active power control with a reference power value different from the maximum point;
5. Economic comparison between system with and without energy storage.

1.4 Objectives

General and specific objectives, developed in next chapters, are presented in this section:

- **General objectives:** Development of an Active Power Control for PV generators without energy storage considering a power reference given by the Transmission System Operator. Make a simulation with real data referred to a specific location in which there are fast variations in radiation and temperature. From the results obtained make an economic analysis and get some conclusions;

- **Specific objectives:**
  1. Literature review including a distinction between residential and utilities market in terms of current development and grid code requirements. Describe the main topologies deployed for the PV generators and make a comparison of active power control technologies with and without energy storage systems;
  2. Describe the main characteristics of a PV generator model, focusing particularly on the PV array model, the PV inverter model and the PV inverter control;
  3. List of the main MPPT methods and detailed explanation of the PPT method developed in the present dissertation;
  4. Analyze the results of the study case;
  5. Technical and economic analysis as a consequence of the results obtained in the study case;
  6. Conclude the whole dissertation with a critical analysis.

1.5 Thesis structure

The structure of the thesis is constituted by the following chapters:

- **Chapter 2** is used to provide a general overview about the current development of photovoltaic systems and grid codes connected with these devices. Finally, principal methods for active power control are presented;

- **Chapter 3** focuses on the description of models that constitute the PV array, the inverter and the control structure implemented in the inverter. Various boxes composing the controller and their respective tasks are described;

- **Chapter 4** is used to give a general overview of principal methods to realize an MPPT control. The following section describes the control structure realized in this study and then implemented in the model;

- **Chapter 5** shows the model realized in DigSilent and, particularly, the results obtained in the case study;

- **Chapter 6** discusses the results. In support there is an economical analysis that makes a comparison between two systems with and without Energy Storage;
- **Chapter 7** draws conclusions about all the dissertation.

Chapter 2

Literature Review

This chapter provides a general overview of the topics covered in this dissertation. First of all the literal review starts with a focus into the PV generator typologies. Then, there is a description of the principal typologies of PV plants currently diffused. At the same time, current grid codes related to most important PV plants are presented, focusing on the gaps of these grid codes. Finally, the state of art for power control methods in photovoltaic plants is shown.

2.1 PV generator topologies for LS-PVPPs

The PV generator is a part of the model realized in next chapters and constituted by a PV array and the PV inverters. There are many techniques to connect the PV array with the PV inverters, as described in Figure 2.1 . Each technique has its own advantages and basically there are three main topologies: central, string and multi-string. There is also a fourth basic topology, the ac module integrated, but its application in LS-PVPPs has not been developed yet [1]. This section analyzes the main characteristics of different topologies with a particular focus on their principal advantages and disadvantages. The chapter shows also which is the best technology in relationship with the location and the kind of climate. Some of them are more affected than others by the changing in solar radiation and cloud cover effects.

- **Central topology:** it interconnects several thousands of PV panels to one inverter. Each array has several strings connected in parallel, the strings are composed by PV panels connected in series and strings are connected with inverters. Generally, it is used for large PV systems with high power output. The main characteristics of this topology are low MPPT efficiency and flexibility but high robustness. Owning to the kind of connection, mismatching losses, due to the change of radiation, are very high but, if compared with other technologies, costs are medium and maintenance is not expensive. Central inverters have high dc voltage variations at the dc side because there are many strings connected in parallel and the length of the cable is more important. Conversely there are low ac power losses and low ac voltage variations. This is the most used technology due to its feasibility and the reduced number of operating inverters [1];

- **String topology:** this technique connects one inverter per string. It generates more power than the central topology in non-uniform conditions but costs of installation are high due to greater number of inverters. Moreover, the losses due to partial shading are reduced because each string can operate at its own maximum power point. The string topology increases the flexibility in the design of the PV system as new string can be easily added to the system to increase its power rating. Usually, each string can have a power rating of up to 2-3 kW [1] [2];

- **Multi-string topology:** the multi-string topology connects one PV string to a dc-dc converter for tracking the maximum power point and then several converters are connected to one inverter via a dc bus. This technique is featured by higher efficiency because there is one dedicated MPPT per string. It combines the advantages of strings and centralized topologies as it increases the energy output due to separate tracking of the MPP while using a central inverter for reduced cost. Obviously, investment costs and complexity of installation are greater [1] [2].

The principal topologies have been described, pointing out the strengths and weaknesses. The characteristics of some of these topologies have been well adopted to the development of PV systems. The current trends for PV plants are presented in the next section.

2.2 Current development of PVPPs

In this section are presented the general trends regarding the PV market. Different topics connected with the PV market are tackled. For instance energy policies, the cost decrease and the forecasts for the future years in this area.

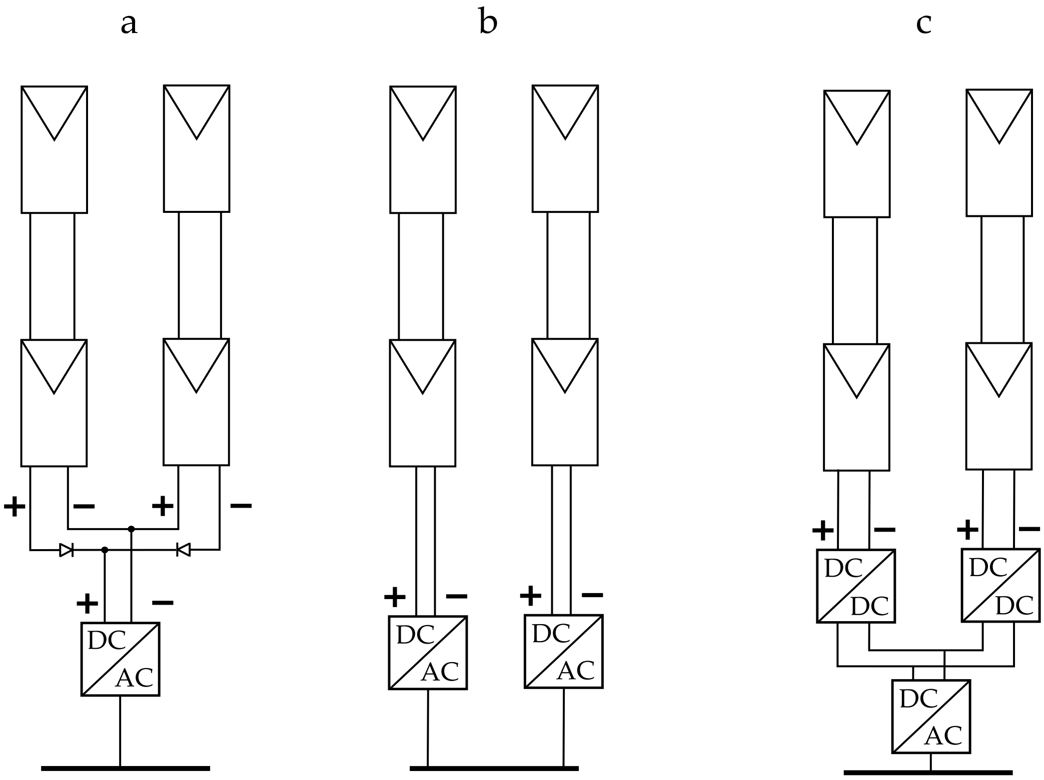


Figure 2.1: PV inverter topologies. (a) Central, (b) string, (c) multistring

The first big development in the PV energy generation happened in Europe (EU) with distributed systems with power lower than 1 MW [3]. This big diffusion interested more the domestic sector thanks to incentive policies [4] [3]. The EU zone has led the growth of PV plants for almost 10 years, owning more than the 70% of the PV global market until 2012 [5]. Incentive policies have strongly helped the boom in the PV market and they have been created at different levels: at a European level and at level of single countries. The Renewable Energy Directive (RED) is a European policy and then there are Feed in Tariff (FiT) policies different for every country. Generally, the FiT is supported by a public tax system [5] [4]. With the end of incentives Europe has known an important decrease in the PV market. As the matter of fact, EU collected a 5 years low, reaching 5,1 GW in 2014 [5] [6]. As described in Table 2.1 and Figure 2.2 , on the other side are emerging new markets that are taking the leadership, among them there is China, Japan and U.S. In fact in 2020 the demand is expected to grow over 97 GW [5]. In 2015 China has become the first country for installed capacity, close to 43,54 GW [7]. The second and the

Table 2.1: Top global solar PV markets prospects [5]

	2015 Total capacity [MW[	2020 Total Capacity Medium Scenario by 2020 [MW]	2016-2020 New capacity [MW]	2016 Compound Annual Growth Rate (%)
China	43381	130381	87	25
USA	25910	85310	59400	27
India	5048	57398	52350	63
Japan	34347	63347	29	13
Pakistan	610	9985	9375	75
Mexico	205	9080	8875	114
Australia	5093	12248	7155	19
Brazil	69	6509	644	149
Korea	3421	9821	6400	23
Egypt	16	4859	4843	214
Philippines	156	3956	38	91
Canada	2371	6056	3685	21
Chile	854	4509	3655	39
Thailand	1444	4654	3210	26
Algeria	268	3053	2785	63
Taiwan	1176	3726	2550	26
South Africa	1122	3457	2335	25
Saudi Arabia	100	2285	2185	87
UAE	24	1786	1763	138
Israel	870	2220	1350	21

third places are occupied by Japan, adding an all-time-high of 11 GW, and USA, adding 7,3 GW [5] [8]. Different factors guided the growth in these countries. As pointed out before, the growth of the PV market is connected with a support policy. Particularly, the increase regards no more the distributed generation, but rather the utility-scale systems. The utility market development has been supported by Fit policies but there is also a new trend in many countries as Saudi Arabia or Mexico where they are using calls for tenders to grant Fit schemes with indirect financing capitals. In this way, they reduce the bidding price and shrink their margins [5] [9]. For instance, in Dubai a record-low of 58,4 USD/MWh bid lead the Dubai Energy and Water Authority to double the original size of their project [5]. Besides, the big diffusion of utility-scale plants can be explained thanks to their easy fruition and the fast connection of the plant to the electrical grid.

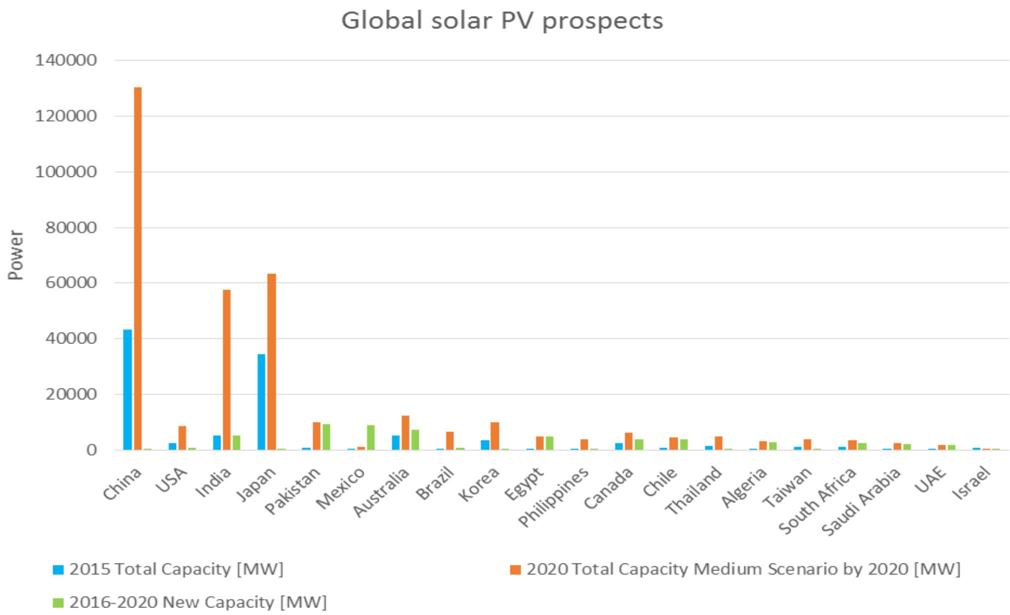


Figure 2.2: Global solar PV prospects [5]

Compared to distributed systems, it is not necessary to set up a sustainable PV on grid market, because costumers do not have be educated to use a plant. On the other side, the strong expansion of utility-scale systems has risen many environmental concerns about the use of agricultural lands and the general weakness of the electrical grid [4]. In fact, in China the lack of transmission grids from areas with high solar power plants density requires frequent power curtailments. This issue leads a slowdown of the utility-scale growth as long as there will not be some energy policies that respond adequately.
Often, policy leaders prefer to see distributed solar on rooftops. In many EU countries, PV systems have been limited in size. Conversely, India or China, with a strong utility-scale market, tried to set up a distributed PV market but with a limited success [5]. As described in Table 2.2 and Figure 2.3, in EU the increase in installed PV principally is due to the utility PV sector. Particularly, UK has known a real boom also thanks to incentive policies. In 2015 UK added 3,7 GW of new solar capacity. While, Spain, once a leader, has almost disappeared from the PV market. Italy, which has led the PV growth in recent years, is in a period of transition and added only 300 MW in 2015 [5] [8]. Respectively Germany and France occupy the second and the third rank adding in 2015 1,5 and 0,9 GW [5]. Then, there are other growing countries such as Netherlands, Turkey, Denmark, Ro-

mania, Hungary, Sweden and Poland. Totally, EU added 7,7 GW of newly connected PV installations. But, in general without the enormous growth of UK, the EU solar market would have remained at levels of 2014 [5].
This strong growth has been characterized also by the contemporary reduction of prices. The solar energy has become more convenient than the wind one. Besides costs for utility systems are more competitive than classical residential roof-tops systems. As the matter of fact, in USA in 2015 the residential rooftop price was about 3,55 $\$/W_{DC}$ while an utility fixed tilt system cost 1,38 $\$/W_{DC}$ and during next years prices are expected to decrease again [10]. U.S.A in 2015 had more than 7 GW of new PV installations thanks to falling prices year by year from 2% to 18% [11]. Once dominated from distributed solar, now the market is led by utility installations, representing the 54% of annual installed capacity. This strong growth is expected to have a dramatic drop because the 30% federal investment tax credit is scheduled to drop to 10% [10].
In South America and Mexico solar installed capacities have grown significantly especially in the utility market in recent years [9]. Mexico and Chile respectively added in 2015 170 MW and 446 MW of new PV installations. The market grew especially in the utility-scale sector [5]. Besides, there are countries that have put support schemes in place for PV electricity, such as Ecuador [5]. In this contest there are new protagonists growing fast. It is expected that during next years they will become leader in this sector. Countries, such as India, for the first time belonged to the top 5 solar markets in the world. India will increase until 100 GW by 2022 [5]. They added 2 GW of PV capacity in 2015 mainly in the utility-scale systems [8]. It means the Indian solar boom has just started. In the African continent also, usually guided by South Africa that installed 200 MW in 2015, the utility-scale market is now starting to get traction in new countries [5].
In conclusion it can be established that 2015 saw a strong growth of the PV market, especially in the utility-scale PV systems. This growth has been led by incentive policies furthermore in countries where a strong PV development has not yet happened, as in Europe with distributed systems. Hence, these countries have become leader in the PV sector and in next years the leadership of the Asia-Pacific area will become more and more important. The cost decrease and the greater competitiveness has been another factor that allowed the fast increase in the utility-scale systems and it has created new business models as the tenders. At the same time the distributed systems did not have the diffusion as past years due to their complexity of installation and less economic convenience. In this scenario the importance of adequate energy policies is fundamental to let a technology grow and spread in the PV market. As the matter of fact, in EU

Table 2.2: Top european solar PV markets prospects [5]

	2015 Total capacity [MW[	2020 Total Capacity Medium Scenario by 2020 [MW]	2016-2020 New capacity [MW]	2016 Compound Annual Growth Rate (%)
Germany	39696	48396	8700	4
Turkey	266	8698	8433	101
France	6511	12781	6270	14
United Kingdom	9149	14174	5025	9
Italy	18613	22613	4000	4
Netherlands	1394	5044	3650	29
Austria	935	3985	3050	34
Spain	5445	7205	1760	6
Poland	84	1702	1618	82
Denmark	791	2291	15	24
Switzerland	1394	2675	1281	14
Greece	2606	3691	1085	7
Belgium	3241	3966	725	4
Romania	1325	1925	600	8
Ireland	4	512	508	160
Rest of Europe	5672	10393	4720	13

the Minimum Import Price (MIP) does not allow to access to lowest-cost modules and slows down the PV market [4] [5].

2.3 Grid code requirements

This section introduces the necessary requirements for the integration of renewable energy systems in the electrical grid. Particularly, the references are grid codes given by the Puerto Rico Electric Power Authority (PREPA) and National Energy Regulator of South Africa (NERSA). After that there is a distinction between residential and large scale applications.
The penetration of renewable energy plants lead the TSO to consider new grid requirements in order to enhance the grid stability. The connection of these new plants has to help to achieve the whole grid stability [3]. The Minimal Technical Requirements (MTRs) for grid stability can be categorized as:

- Voltage requirements;
- Frequency requirements;

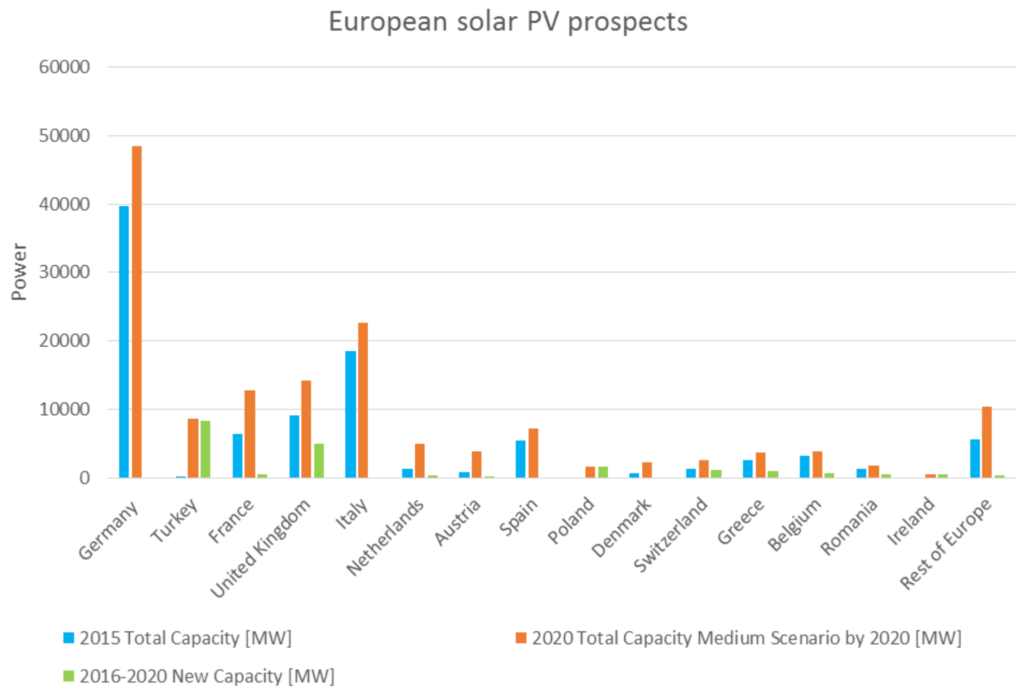


Figure 2.3: European solar PV prospects [5]

- Reactive power requirements.

The requirements define the engineering design of the different elements of a PV power plant and they have to be developed according to the injection of active and reactive power. The development has to be done in pair with an adequate communication system. The devices that have to realize these MTRs are:

- Power Plant Controller (PPC): the PPC is the main control system responsible for generating control references in order to manage the power flow at the point of interconnection. The device operates both control of active and reactive power, communicating with other devices;

- Static Synchronous Compensator (STATCOM): the device injects capacitive, inductive or reactive power in order to meet voltage, power factor or reactive power references according to the PPC control;

- Plug and Play Storage System (optional): in the present dissertation the main objective is to develop a PV active power control without energy storage.

According to grid codes of Puerto Rico and South Africa [12] [13], in order to reach the previous requirements, the PV plant should be equipped with:

- Voltage control;
- Reactive power reference control;
- Power factor control;
- Ramp rate control;
- Active power curtailment control.

All the previous requirements are necessary to reach a good level of quality at the system distribution level and they are well described in [12] and [13]. The electrical energy distributed in the grid is used for different applications. The equipments, which need electrical energy to operate, require also a good power quality. At the same time, owning to various applications, the power quality can be affected by these equipments because they can cause distortion and produce non-sinusoidal current. Generally, a poor power quality means high costs and losses. The cost of poor power quality usually exceeds the cost of measures required for improvement. As consequence, a good power quality permits to reduce the waste of money and this results as a good compromise between the supplier and the costumer [14] [12] [13]. Grid requirements can be distinguished between residential and large scale applications.

2.3.1 Residential applications

EN 50160 is a standard that defines the limits for public supply networks in Europe. It gives the main voltage parameters and their deviation ranges at the costumer's point of common public in low voltage (LV) and medium voltage (MV) electricity distribution system, under normal operating conditions. This standard gives general limits, which are technically and economically possible to obtain in public distribution system, but it does not apply under abnormal operating conditions. Even relatively small deviations from the rated value can cause higher power consumption with additional losses and shorter service life. It is worth to point out that the costumers do not accept any responsibilities when these limits are exceeded but, at the same time, from the consumer's point of view the EN 50160 is not sufficient to guarantee a good level of power quality [14]. The rules that define the voltage quality, following the EN 50160 [15], are:

- Maximum voltage unbalance for three phase inverters: 3%;
- Voltage amplitude variations: max $+/-10\%$;
- Frequency variations: max $+/-1\%$;
- Voltage dips: duration $<$ 1sec, deep $< 60\%$;
- Voltage harmonic levels. Max voltage total harmonic distortion (THD) is 8%.

Various European countries have additional rules governing supply conditions. In Poland the rules of electrical energy distribution are established by the government parameters of the supply voltage and do not refer to EN 50160. Besides, consumers are divided into six groups, depending on their characteristics [14]. In Italy, the AEEG (Italian Regulatory Authority for Electricity and Gas) has put in place a system of incentives and penalties in order to progressively bring continuity levels up to meet European standards. Anyway, in these European standards there is not a clear reference to a real continuity facility. In case of deviations or abnormal conditions the part of grid is automatically excluded to prevent greater damage to whole system. It is still missing a mention of the MTRs previously described. Similarly in the IEEE 1547 (commonly used in America), it is said that any Distributed Resource (DR) connected to a spot network shall not cause operation or prevent re-closing of any network protectors installed in the spot network. Herein, it is explained that the interconnection system shall have the capability to withstand a electromagnetic reference but, in case of fault or any abnormal condition, the system has to be ready to cease energize the affected area in a clearing time[1]. This happens especially when the voltage or the frequency are not included in a particular range and the reconnection does not take place until these values do not come back into a proper range [16]. As previously mentioned, the IEEE 1547 standard does not define the application of devices to reach the MTRs.

2.3.2 Large scale applications

Paper [3] shows the grid codes for the integration of large scale photovoltaic plants in the transmission system. The comparison is made in terms of four technical requirements:

[1]It is the time between the start of the abnormal condition and the DR ceasing to energize the affected area

- Fault ride through (FRT): it explains the time that the PVPP has to stay connected when a fault occurs, after this time interval the PV plant is disconnected from the grid. The PVPP has to remain connected when an over-voltage occurs. The High Voltage Ride Through requirements (HVRT), as the FRT, can be more or less restrictive depending on the TSO and the country grid codes. Especially for the HVRT, the voltage is measured by the injection of reactive power. In some grid codes it is also possible to install some equipments as static var compensators (SVC), STATCOM or capacitor banks [12] [13];

- Voltage and frequency boundaries: these are the ranges in which the PVPP shall operate continuously. For some countries like Germany, Romania, Africa and China the limit is $90 - 110\%$ of the nominal voltage [3]. The time and the range of frequency, which the grid has to withstand, are variable depending on the technology used and if the upper or lower limit is reached. The greater frequency limits are $-3.5 \div 2.5$ Hz. Germany has also a wide frequency range due to the important installation of renewable energy in the national grid [3];

- Active power and frequency control: the control of active power should match the variability of solar energy during the day and it is divided into absolute production, delta production and power gradient (see Figure 2.3). In the requirements of PREPA it is established that in normal operating conditions the system should be able to provide a reduction of active power in the connection point with steps of 10% of the estimated power [12]. Besides, in grid codes of NERSA, the active power capability value shall not be less than 3% of the available power in order to guarantee a reserve for frequency stabilization [13];

- Voltage and reactive power control: conventional power plant have to overcome voltage deviations and to provide reactive power support to the grid. Generally, the reactive support depends on the characteristics of the PV inverter. A typical inverter is designed to operate at the distribution level and does not consider that the voltage has to be kept into a range depending on the TSO. Furthermore, the inverter has to comply the capability curve to match the active and reactive power.

The current state of the electrical grid implies many necessary changes to comply with the minimum requirements given by the grid codes. Regarding the voltage stability, IEEE 1547 does not require that PV systems

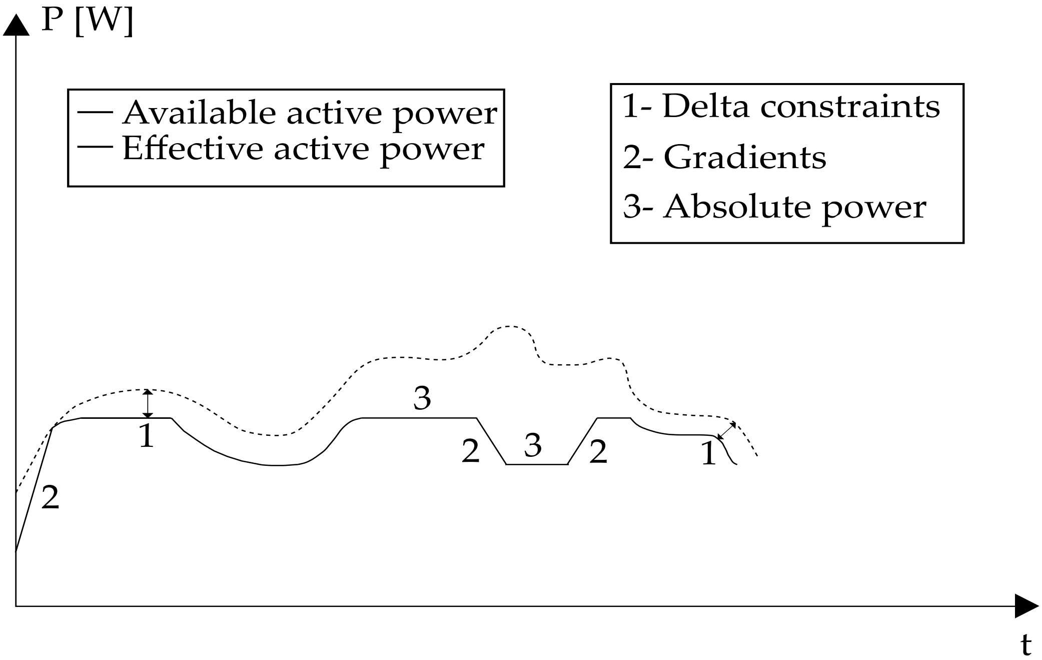


Figure 2.4: Active power control constraints for PVPPs

should provide any voltage regulation at the PCC. Different studies shows that cloud coverage affects the distribution level as the voltage level is not maintained and an optimal placement of the PVPP is important to reduce losses and voltage instability [3]. As in the PV system there is a lack of rotating machines, problems of frequency stability can occur and the lack of power reserve, due to the maximum power operating point, does not help to control the decrement of frequency. Besides, the MPP changes according with the irradiance and when large and quick fluctuations of active power occurs: there may be ramp rates higher than 2.5 MW/min. It is clear that the MPPT causes problems to the stability of the plant but, following the new grid codes, it is no longer necessary to work at the MPP [3]. The IEEE 1547 does not require a power quality control by the PV inverters. However, the increasing penetration of LS-PVPPs requires an inverter control of active and reactive power. A traditional MPPT does not give the possibility to have a complete control of the power quality capability [17].
This chapter has presented the new grid codes, such as PREPA and NERSA requirements, that are used to perform a good quality of the energy transmitted to the consumer. In this way, there is a reduction of electrical losses and the system stability is improved. The standards previously mentioned lack of some requirements to endow PV systems of ancillary services. Ac-

cording to Puerto Rico and South Africa grid codes, in the next chapter different strategies are presented with and without energy storage to realize an active power control of PV generator for PVPPs.

2.4 Active power control of PV generators for PVPPs

There are different methods to realize active power control for electrical grids. It is possible to distinguish strategies with and without energy storage systems. Different technologies are shown, pointing out advantages and disadvantages.

2.4.1 Active power control with ESS

This section focuses especially in methods and technologies that require energy storage systems. It is described the state of art for many technologies and which are the most diffuse.
In [18] are described different regulation strategies to make a PV power ramp limitation using energy storage, each strategy is based on the worst fluctuation model. One of the most used strategies is the classical ramp-rate control ($RR_{classical}$) and the moving average control (MA) [18]. Other studies deepen a step-rate control strategy based on the strict compliance with the maximum ramp constraint rmax. As the sign of the fluctuation is unknown, $RR_{classical}$ method requires a double capacity battery to absorb both the upward and downward variations. The maximum energy stored by the battery is equal to:

$$E_{BAT,MAX} = \frac{0,9}{3600P_N}\left[\frac{90}{2r_{max}} - \tau\right][kWh] \tag{2.1}$$

where P_N is the rated power and the r_{max} is the maximum ramp rate. Then the battery capacity required with this method is defined as:

$$C_{BAT} = 2 \cdot E_{BAT,MAX} \tag{2.2}$$

The generic balance equation is (see Figure 2.5):

$$P_{BAT}(t) = P_G(t) - P_{PV}(t) \tag{2.3}$$

First the inverter try to inject all its power into the grid:

$$P_G(t) = P_{PV}(t) \tag{2.4}$$

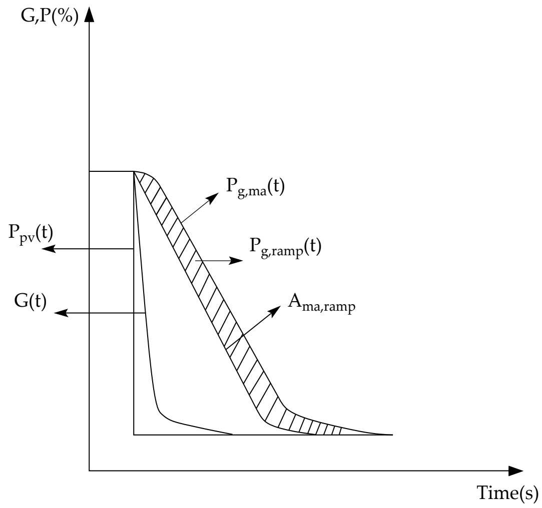


Figure 2.5: How to calculate the storage capacity needed

Then, the power control is activated when the maximum ramp rate is exceeded:

$$\Delta P_{G,1min}(t) > r_{MAX} \tag{2.5}$$

The state of charge (SOC) needed for RRclassical and MA is at least 50% to react properly against upwards and downwards fluctuations [18]. In [18] are also proposed new ways of regulation that halve the capacity of the batteries compared to RRclassical.

- RRinverter: all the inverters are involved in the control of the PV plant to limit the output power and realize a compensation during upward fluctuations. The ESS is deployed only when there are downward fluctuations and this explains why the capacity required is halved;

- RRclear-sky: the control is based on the maximum and minimum power produced by the PV plant. $P_{PV,max}$ corresponds to the power output under clear sky conditions and $P_{PV,min}$ is the power output under complete cloud cover conditions. The difference between the two limits determines the maximum power variation and, as it is a function of the actual power, it is possible to know the state of charge needed (SOC). This strategy takes advantage of the well-known limits of solar radiation and develops a model in which the instantaneous power generated by the PV plant depends on irradiance G(t) and cell temperature $T_c(t)$.

To smooth the active power in LS-PVPPs, TSOs are adding energy storage units (ESU) and/or diesel generators. The ESU carries out the power curtailment and the ramp rate control, while the diesel generator supplies an active power reserve and frequency regulation [3]. Diesel generators are normally used for their well known technology and their reliability. An ibrid diesel-PV system is developed to control the frequency in [19] and it maintains the frequency deviation within $\pm 0,2$ [Hz], despite many issues due to the low operational flexibility of the diesel generator [20].
Batteries store energy in form of chemical energy. Main types of batteries are molten salt, lithium-ion, lead acid and flow batteries. Li-Ion and Lead-acid batteries are widely used for their well known technology and reliability. Principal applications are in vehicles and electronic devices. Batteries have a low cycle life and it is better to minimize their usage when possible. Extremely low and high SOC for this kind of technology should be avoided as well [21].
As mentioned in [22] and in [21] there are also other kinds of storage technologies like pumped hydro that accounts for 99% of a worldwide storage capacity of 127000 [MW] of discharge power [23].This technology is the most widespread type of energy storage in the U.S. (95% and 23,4 [GW]). The leftover 5% is thermal energy storage, flywheels, ultracapacitors and compressed air energy storage (CAES) [21].
Flywheels are a mechanical application that stores energy in the form of kinetic energy: if there is a net torque in the same direction of the angular velocity, a quantity of energy will be stored. Then, energy is released when the net torque is applied and the flywheel works as a generator [21]. Ultracapacitors store energy in form of electrochemical energy by separation of charges between two active electrodes. The electrodes are separated by a porous ion-permeable surface to avoid short-circuits. These capacitors can be series connected to step up the voltage [21]. In [21], it develops an algorithm that can be applied for different technologies to control PV ramp rates with limit RR_{limit}=10%/minute. The algorithm structure cycle through a second by second time series of raw PV plant power output and decides on the dispatch of the ESU power when the RR_{limit} is expected to exceed. The purpose is to minimize the number of ramp rate violations, keeping the energy losses due to charge/discharge cycles at its minimum.

2.4.2 Active power control without ESS

This section gives a general overview of some techniques for the active power control without energy storage.

Conventional Power System Stabilizer (CPSS) produces an electrical torque that is in phase with the rotor speed deviation and it is deployed to compensate deviations of frequency and to damp power oscillations. The main advantage of rotor's speed deviation signal is of being independent from system configurations and procedures. At the same time, the main drawback is the alteration of the voltage profile and the system may lose stability under several disturbances [24]. The CPSS is developed under a linear system model and this may affect the regulation process since the system is non-linear. This kind of controls perform an higher efficiency control. In the CPSS the acceleration or deceleration of the synchronous generator takes an important rule to increase or decrease frequency, it sets up the inertial response of the generator [24]. Paper [25] deals with shading effects in a central topology plant located in northern Chile, considering different PV penetration levels. A shaded module dissipates part of the electric energy in the form of heat (hot spots) and the output power of the PV-PP could change more than 70% in 5-10min. Hot spots can be avoided with bypass diodes but the issue of power reduction still remains. The occurrence of multiple peaks can mislead the MPPT algorithm, trapping it to local peaks due to its inability to discriminate between local and global maximums. The Mitigation Control Against Partial Shading effects (MICAPAS) strategy divides the PV-PP into N sections and everyone operates as in a deloaded mode with a specific reserve level. When there is a shaded area the control orders to that specific section to deploy its active power reserve, thus the output power is smoothed without excessive variations [25]. A control signal (K_d) commands the deployment of the power reserves in case of shading conditions:

$$E_{BAT,MAX} = K_d - \frac{\Delta P}{R_t(\chi)} \tag{2.6}$$

where $R_t(\chi)$ is the total amount of the operating available reserves. If $K_d = 1$ no control actions will be carried out, instead if $K_d < 1$ the control will deploy the active power reserve. The deloaded operation is accomplished by operating at a lower value of voltage than the corresponding MPP value. The dissertation in [26] proposes a modified MPPT algorithm that works in a Reduced Power Mode (RPM) in a hybrid wind-PV system. The classical MPPT works with fixed steps size and during a convergence process it oscillates around the target point, causing issues during fast radiation changings. With the Variable Step-size Incremental Conductance (VSIC) algorithm, it is possible to easily converge because the step-size is variable and it can work compatibly with RPM. The algorithm of this kind of control is shown in Figure 2.6. The algorithm is able to choose the mode

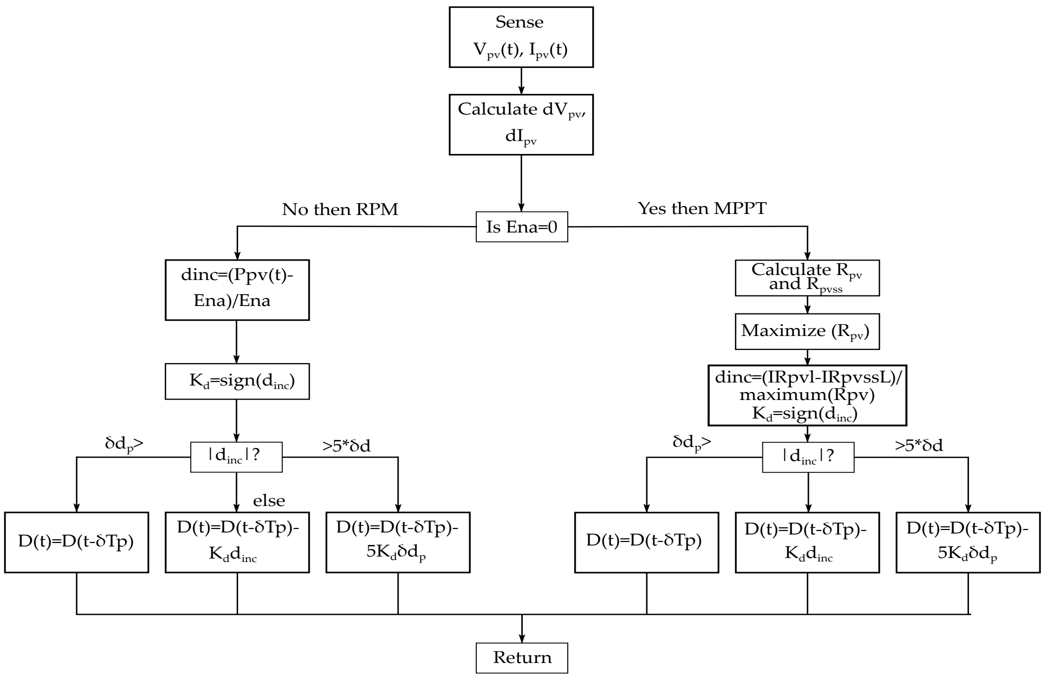


Figure 2.6: Algorithm of VSIC method

depending on the value of the reference signal called Ena. If $Ena \neq 0$ the supervisory controller will send the system into RPM mode. With a step change of solar radiation applied to the PV generator, it is possible to simulate a fast atmospheric condition change. The step is set large enough to make the power changes clear. This simulation demonstrates that the VSIC method is faster than other traditional algorithms. In [27], a constant power generation (CPG) control concept is proposed. As explained, the reduction of active power seems to be more effective in voltage regulation than a reactive power control. First of all, three possible methods are explained in this dissertation:

1. Integrating Energy Storage Systems: The system reaches easily a constant output power through curtailment. The deployment of ESS causes a cost increase and lifetime-limited components are added to the whole system, making it not an optimal approach. Although ESS increases the total expenses, the efficiency and the functions of active power control will improve. The operation mode (MPPT or CPG) depends on the value of the solar radiation and/or temperature;

2. Power Management control: a proper power management at the second level of regulation can help to reach a constant power produc-

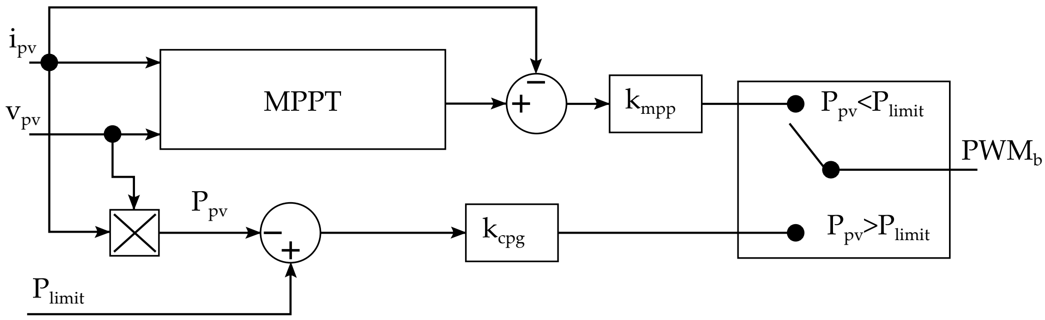


Figure 2.7: Constant power generation by modifying MPPT control

tion. At the same time, the output power of each PV unit is regulated with a central control system. There will be some units working at its MPPT and others in CPG mode. This means that an individual PV inverter should be able to adjust its output power according to the power set points from the central control unit. This control requires a good knowledge of forecasts and advanced communication system between each inverter;

3. Modifying MPPT control: in this option the MPPT algorithm is modified and, when the system is working in CPG mode, there is no need to install extra devices as ESS. The whole system can be divided into the traditional MPPT and CPG operation modes, the choice of one or the other depends on the environmental conditions (see Figure 2.7). The control can be explained with the following equation:

$$P_0 = \begin{cases} \sum_{i=1}^{n} P_{PV}(t), when\ P_{PV}(t) < P_{limit} \\ P_{limit}, when P_{PV}(t) \geq P_{limit} \end{cases} \tag{2.7}$$

When the system exceeds the maximum voltage limit in a highly PV penetrated system, some PV systems have to be cut-off in order to bring the voltage back.
As mentioned in [21] and in [22], an effective control is strictly connected with accurate forecast data and the study case of [28] shows a practical example. Herein [28], it is proposed a hybrid forecasting model for very short-term (15 seconds timescale) PV generation forecasting (see Figure 2.8). The physical PV model, provided with coarse weather forecast, is used as an initial information to the recursive KF block. Based on the

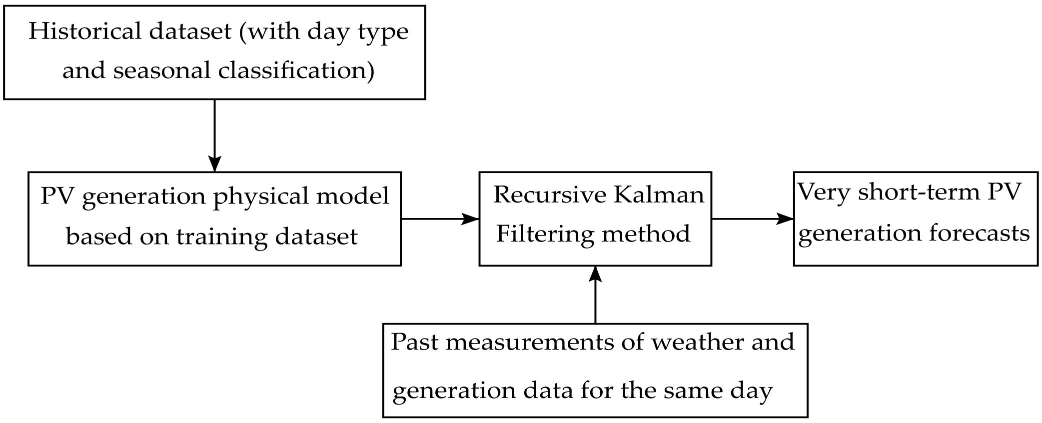


Figure 2.8: Hybrid forecasting model

day today measurements, the KF block[2] modifies the PV generation model to a steady-state condition once there are more data available. With this method the forecasting model can reduce its dependence on historical data and the impact of any bias is reduced. Herein, data forecasts becomes a support tool to manage variations of solar radiation [28]. In the dissertation [29] there is an interesting development of Active Power Curtailment without ESS for wind turbines in residential feeders. The behavior of wind turbines is different from solar generators and the implementation of APC is different. The purpose to prevent over-voltage is obtained through the variation of the pitch from its maximum point of attack to realize the power curtailment. Furthermore, the displacement of the pitch angle is used only when needed. A voltage drop controller estimates the required pitch angle to curtail when the system is close to reach the upper voltage limit [29].

Another interesting control without ESS is proposed in paper [30] that explains the management of Active Power Reserve (APR) with ESS and with curtailment (without ESS). The analysis shows main advantages of the APR without ESS, called internal APR (iAPR). The use of ESS would increase costs for the total installment but at the same time it removes part of the inconvenience due to variability of the solar radiation. It is worth mentioning that batteries have a limited capacity and they can provide an ancillary service only for a definite period of time. Mostly, if the source of energy is variable, batteries will be submitted to high stress and their lifetime will be shorter. The system operator has to generate the total APR

[2]measurement based dynamic prediction methods like Kalman Filtering technique help to reduce processing time

requirements among the total number of the central inverters. The iAPR can be provided in 2 ways [30]:

1. set the DC voltage below MPP voltage. Panels are current sources but the deployment of APR for ancillary services during high slope conditions cause the DC voltage to experience large fluctuations and even converter tripping. Furthermore, the converter sensitivity decreases and it has to recover the energy difference stored in the capacitor due to large fluctuations voltage. In this mode the converter supports an higher energy effort;

2. set the DC voltage above MPP voltage. PV panels operates as voltage sources without inducing large fluctuations during APR deployment. The PV generator now can be directly controlled in power and the DC voltage becomes an intrinsic characteristic. Besides, operating at an increased voltage increases the stability of the converter and helps to avoid converter tripping. There are also less current losses, an increased efficiency and a decrease in the duty cycle that is proportional to the voltage value. The reserve of energy stored in the capacitor is naturally released improving its operations. If the LS-PVPPs participate in total Frequency Containment Resources (FCR), they have to overcome a system planning issue of proper APR allocation which implies a trade-off between low amount APRs, which implies low Frequency Sensitive Mode (FSM), and high amount of APRs, which implies high energy losses due to curtailment. To be able to implement FSM in LS-PVPPs, it needs to have upward and downward APRs.

Due to the nature of solar radiation, LS-PVPPs are energy-limited sources but if they work with iAPR they can supply short-term and mid-term services as FSM and Innertial Response (IR). To achieve ancillary services as described before, LS-PVPPs rely on weather forecasts: the better the forecast service is, the longer the ancillary service will be provided. It is worth mentioning that the ancillary service depends on the quantity of iAPR available and on the time frame. The highest participation factor with iAPR is realized during days with favorable weather conditions [30]. The aim of the LS-PVPP control is to provide the plant with protection, to guarantee maximum energy extraction from the solar source and at the same time to supply grid ancillary services.
Some methods of active power control without energy storage systems have been presented. In the following section there are the conclusions of all the literal review.

2.5 Conclusions of the review

The literal review has presented the principal PV topologies utilized in PV plants. After that, the current development in the PV market has been shown, focusing in the most important aspects. New grid code requirements, necessary to guarantee an adequate development of the electrical grid, are described. According to these new grid codes, there is an overview of the principal methods to realize an active power control with and without ESS.
The most utilized topology is the central one. It can also be justified by the big development of LS-PVPPs. The development of these systems brought out new leaders in the global market, once led by Europe. During next years the strength of Asian-pacific market will be dominant, particularly in China, Japan and U.S.A. In this context new protagonists are also emerging, such as India. The growth in LS-PVPP sector has been eased by a greater competitiveness of prices respect to distributed plants. The contemporary price decrease made large-scale systems more attractive for the investors. New business models are growing, as calls for tenders, that contributes to the PV price reduction. Conversely, in EU the MIP hinders the growth of PV markets. The EU area knew a strong development of distributed systems. But LS-PVPPs struggle to spread owing to environmental concerns and not adequate policies. UK is the only country that experienced a real increase, thanks to inner incentive policies. The market of South America and Mexico probably during next years will develop. According to the current development of PVPPs, new challenges are coming out. Power oscillations from PV systems can weaken the electrical grid. Standards, such as IEEE 1547 and EN 50160, still lack of requirements that well define the characteristics of PV plants. Conversely, some countries, as Puerto Rico and South Africa, are defining new grid code requirements with characteristics of control for: voltage, reactive power, ramp rate, active power curtailment and fault ride through. These characteristics allow PV plants to not represent anymore a negative load but, on the contrary, a support that can provide stability to the grid.
Focusing on the active power control, there are different possible strategies with and without ESS. Methods as $RR_{classical}$ and MA are based on a ramp rate control. More innovative system as $RR_{inverter}$ and $RR_{clear-sky}$ allows to halve the capacity of batteries. All four methods take into account the behavior of solar radiation and ESU is utilized for downward and upward fluctuations. They reduce energy losses and improve efficiency. In some cases it is possible to add also diesel-generators. Batteries combined with a diesel-generator provide ancillary services, as active power reserve and

frequency regulation. Batteries can be of various types and have different characteristics. The most used are Li-ion and Lead-acid because they are well-known and reliable technologies. As explained before, with batteries the total investment cost increases and it is a lifetime limited technology. But, at the same time, the system stability is improved.
Other methods, such as MICAPAS, try to dividing the system into N sections and working in a de-loaded mode. It requires a good cooperation among inverters and the de-loaded mode could be expensive but it improves the grid stability. Thus, this method is not suitable for low PV penetrations and it is better to activate the system only with high variability of radiation. Similarly, the CPG method works with a modified MPPT to attain a constant power output.
Some strategies proposes the use of data forecasts to improve the system management. Surely, this support allows to limit issues connected with high intermittence of solar radiation. Thanks to data forecasts a more efficient control is created. The dependence on historical data and the impact of any bias is reduced.
Generally, PV generator controls without ESS seems to be more cost-effective. The biggest disadvantages are the operative conditions with a lower power. It is interesting to quantify the energy and economic losses due to systems without ESS. Another interesting idea is to improve an iAPR, setting the DC voltage above the MPP voltage. In this way the PV generator is managed as a voltage source and the stability of the converter is improved. Also the efficiency increases and current losses decreases.
Among the various solutions proposed, there are interesting solutions that respond to the demands of new grid code requirements. The new grid codes require to deal with new technological challenges based on new market trends. Thanks to these new rules it is possible to limit some problems connected with the intrinsic characteristics of PV generators. In this way, the development of LS-PVPPs will happen without collateral damages to the electrical grid.

Chapter 3

PV Generator Model and Control

3.1 PV array model

The PV array model and its characteristics are presented in this section. Besides, the PV array dependence from environmental conditions is described. Crystalline Silicon cells are the most diffuse in the PV market and they cover the 85% of the whole market. The initial production was constituted only by Cristal Silicon cells produced with the Czochraslki process because the industrial process was well consolidated for the microelectronic market. Multi-Crystalline Silicon cells have been produced from 1980s. Generally, a solar cell is composed by (see Figure 3.1):

1. a p-type semiconductor substrate (usually Silicon doped with Boron atoms);

2. pn-junction (diffusion of Phosphorous atoms to create n-type layer). The p-type region is positioned in the back and it is called anode, while n-type region, in the front, is called cathode;

3. metallic contacts for circuit connection and to collect the carrier current;

4. front surface composed by an oxidation layer, an anti-reflective coating and there is texturing process.

The photovoltaic effect is generated when the cell is exposed to sunlight. The PV cell characteristic can be represented in a circuit model as a diode and a current source (see Figure 3.2).

The total current in a photovoltaic cell corresponds to:

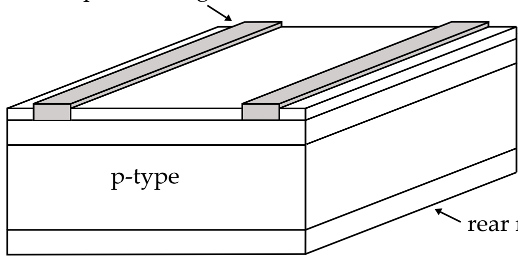


Figure 3.1: Solar cell scheme

$$\begin{aligned} & i = i_{ph} - i_d - i_p \\ & i_{ph,stc} = i_o \cdot \ e^{\frac{v_d}{v_t}} + \frac{V_{oc}}{R_p} \\ & i_d = i_o \cdot \ e^{\frac{v_d}{v_t}} \\ & v_t = k_b \cdot \ N_{ser} \cdot \frac{T_{stc}+273}{q} \end{aligned} \tag{3.1}$$

The previous terms represent respectively the photovoltaic current (i_{ph}), the diode current (i_d), the diode saturation current (i_o) and the Boltzman constant (k_b). The photovoltaic current in STC conditions contains: the diode voltage (v_d), the thermal voltage (v_t), the open circuit voltage (V_{oc}). I_{ph} is called also the photo-current generated by the PV effect and the Shockley solar equation, which represents the ideal characteristic of the cell, is equal to:

$$I = I_{ph} - I_{01} \left(\exp^{\frac{qV}{kT}} - 1 \right) \tag{3.2}$$

The photovoltaic current depends on the solar radiation. Precisely, the equation changes if the radiation is higher or lower than a specific value:

$$\begin{aligned} & i_{phn} = i_{ph,stc} \cdot \frac{G}{G_{stc}}, \ G > 125 \ W/m^2 \\ & i_{phn} = i_{ph,stc} \cdot \frac{0.008 \ G^2}{G_{stc}}, \ G < 125 \ W/m^2 \end{aligned} \tag{3.3}$$

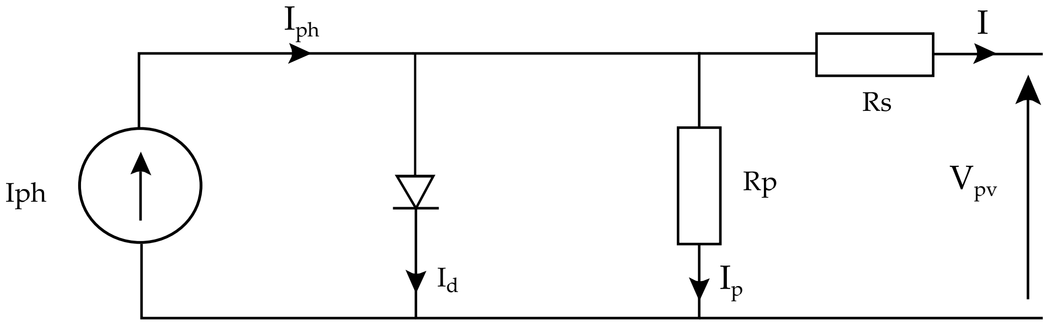


Figure 3.2: Model of a solar cell

The output characteristic of a PV panel is defined by V_{oc} and I_{sc}, respectively the Open Circuit voltage and Short Circuit current. These values are variable during the time and depend on irradiance and temperature. For each module there are representative points provided by the manufacturer in (STC) standard test conditions (G=1000 W/m^2, T_a=25°C and AM1,5) . The max power provided in STC is named peak power. The cell temperature T_c under different conditions than STC is:

$$T_c = T_a + G \cdot \frac{NOCT - 20}{800} \tag{3.4}$$

This temperature affects the value of V_{oc} and furthermore the value of v_t in a PV module:

$$\begin{aligned} v_t &= V_{t,STC} \cdot \tfrac{T_c}{T_{STC}} \\ V_{oc} &= V_{oc,STC} + k_v(T_c - 25) \end{aligned} \tag{3.5}$$

With some approximations it is possible to evaluate the overall current of a PV panel

$$I_{pv} = \frac{I_{ph} - I_d - \frac{v_{pv}}{R_p}}{1 + \frac{R_s}{R_p}} \tag{3.6}$$

The value of current and voltage are also related with the number of panels in series and with the number of parallels, respectively N_s and N_p. The total current of a PV array, the whole voltage of all the arrays in parallel and amount of power will be as follows:

$$\begin{aligned} V_{array} &= \textstyle\sum_{i=1}^{n} V_{pv,i} = N_s V_{pv} \\ I_{array} &= \textstyle\sum_{i=1}^{n} I_{pv,i} = N_p I_{pv} \\ P_{array} &= I_{array} V_{array} \end{aligned} \tag{3.7}$$

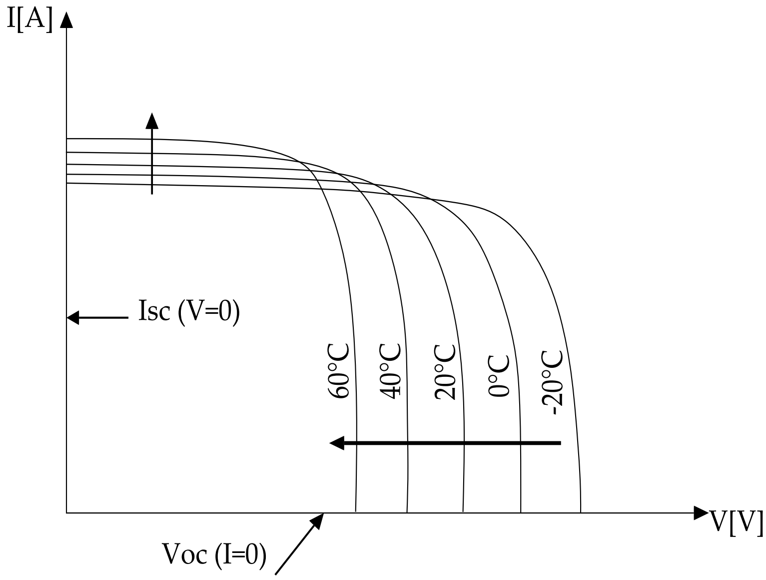


Figure 3.3: Solar cell characteristic with temperature variations

As mentioned before, the behavior of a PV module can be plot measuring V_{oc} and I_{sc} under different values of temperature and irradiance with respect to STC:

- The Short-Circuit current I_{sc} is proportional to irradiance and increase with cell temperature:

$$I_{sc}(T_c, G) = I_{sc}(STC)\frac{G}{1kWm^2}(1 + \alpha(T_c - 25°C)) \tag{3.8}$$

  where α is the temperature coefficient for the crystalline Silicon and is equal to:

$$\alpha = 0,025\%/°C \tag{3.9}$$

- The Open-Circuit voltage V_{oc} decreases with temperature. The decrease of V_{oc} is higher than the variation of I_{sc} (see Figure 3.3):

$$V_{oc}(T_c, G) = V_{oc}(STC) + \beta(T_c - 25°C) \tag{3.10}$$

Instead, the change in irradiance makes I_{sc} to variate more than V_{oc}, which is not effected significantly from sunlight (see Figure 3.4). The power characteristic is derived from the I-V characteristic of the PV module. The power can be analyzed as a function of T and G. It increases until it reaches its maximum in a precise optimum point of voltage (V_{opt}). The maximum

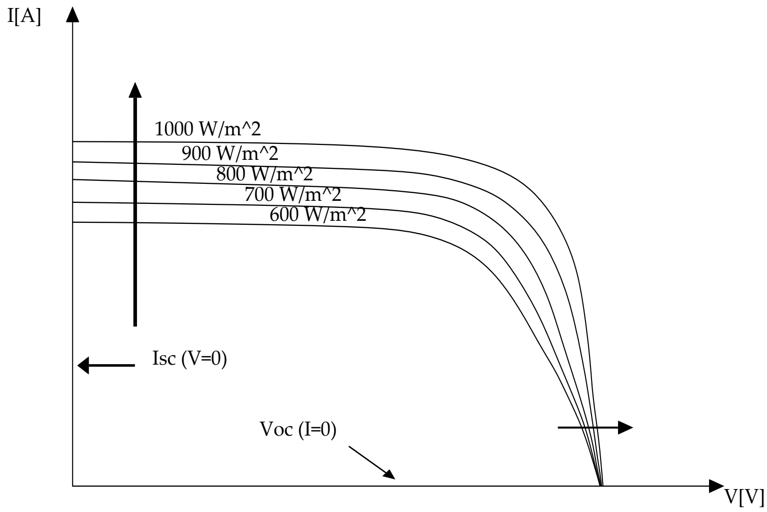


Figure 3.4: Solar cell characteristic as a function of irradiance

power point (MPP) is different for every couple of G and T. These parameters change frequently during a day and the power output of a photovoltaic system never remain constant. Varying G, with a fix radiation, it is possible to show the power changes as a function of T. Another graphic of P-V can be drawn as a function of G, with a fixed T (see Figure 3.6) (see Figure 3.5). Generally, every PV array works at its maximum power point. This point is reached by an MPPT algorithm implemented in the inverter control that continuously is looking for the MPP with respect to any fluctuation of temperature and radiation. The MPPT makes sure that the maximum power is always released at the output.

3.2 PV inverter model

The PV inverter is the point where the power is converted from the DC side (PV array) to the AC side (grid). This device is a crucial part of a grid connected PV system. As well known, the output of the PV panel is DC voltage, but the local utility or grid is AC voltage. Generally, the PV array is connected to the MPPT to optimize the conversion from energy sunlight to electrical power [31]. The efficiency of the inverters usually depends on the load current being a maximum at the nominal output power. It can be as high as 95% but will be lower (75%-80%) if the inverter runs under partial load [32] (see Figure 3.7). The whole system can be configured depending on the number of stages [33]:

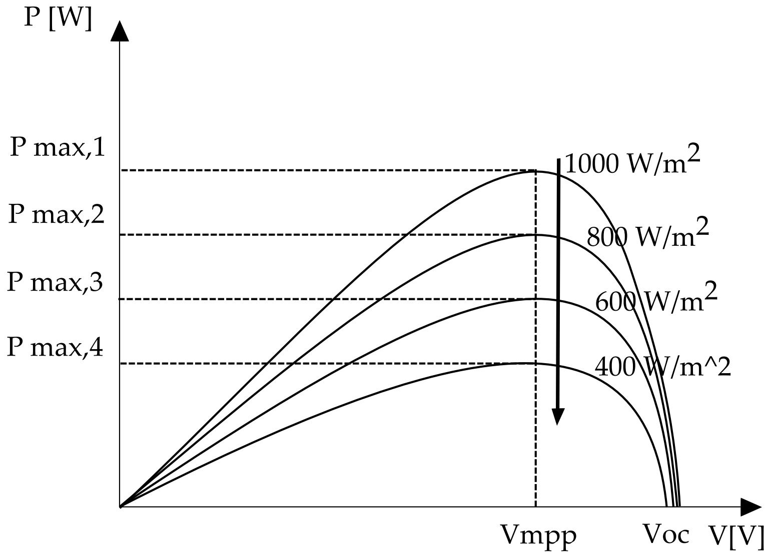


Figure 3.5: P-V characteristic at different radiations with a fixed temperature

- Single-stage configuration: the PV array is directly connected to the DC-AC inverter, then there is a transformer to change the voltage level;
- Two-stage configuration: the DC-DC converter is applied to step-up the PV generated voltage, then there is the DC-AC inverter for the grid interconnection. In this case no transformers are used.

There are two main types of inverters: Voltage Source Converter (VSC) and Current Source Inverter (CSI) [33] [31]:

1. The CSI makes use of Silicon Controlled Rectifiers (SCR) or Gate Commutated Thyristors (GCT) for the switching devices. The main drawback is the requirements of large filters at the output and the input due to the important armonic content. They can control active power while consuming non-controllable reactive power;
2. As design, the VSC uses the Insulated Gate Bipolar Transistor (IGBT). It is deployed for Distributed Generation (DG) application for its easy control and for its better satisfaction of the DG interconnection to the grid. They can control independently active and reactive power and the high switching frequency implies higher losses than CSI technology [34].Three-phase inverters belongs to VSC type and they can generate current that varies in its magnitude and phase angle.

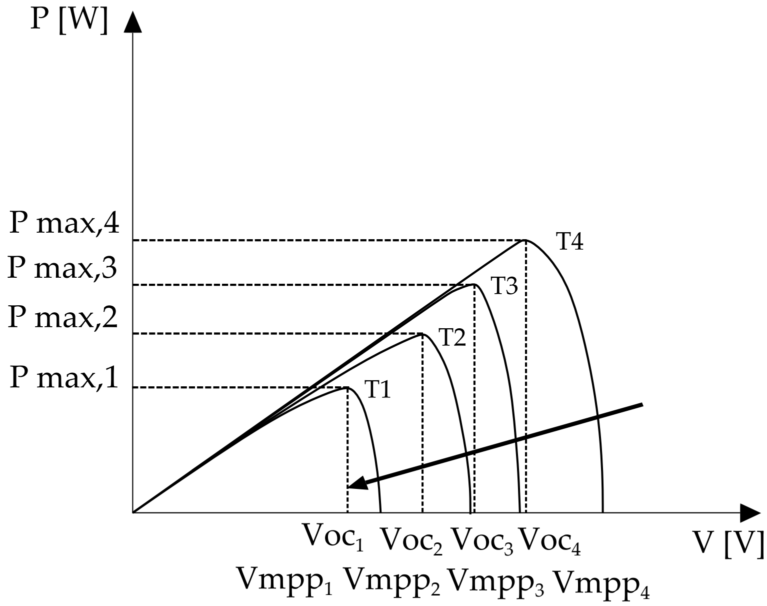


Figure 3.6: P-V characteristic at different temperatures with a fixed radiation

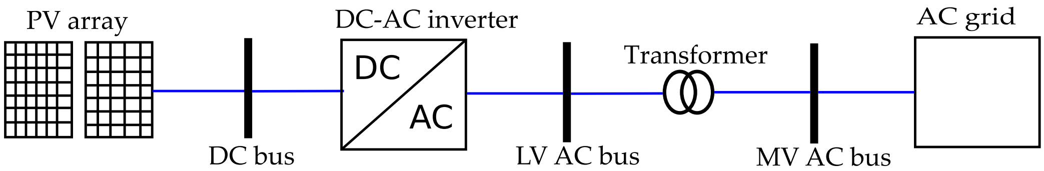


Figure 3.7: PV system components of a grid connected installation

For a LS-PVPP it is deployed a three-phase inverter but one-phase devices also exist [35].

- One-phase inverter: It is a switching circuit which reverses the polarity of its input. The switches may simply be switched alternately at the required frequency of the AC side and produce a square-wave. This simple inverter has no control of the load voltage, then the resultant wave will have an high armonic content. With the Modified Square-Wave Inverters the two pairs of switches do not operate simultaneously but there is a phase shift between them to fix the problem of the high armonic content. The result is that the equivalent sine wave has the same r.m.s. value as the modified square wave . By modulating the duty-ratio the output voltage may be made to variate sinusoidal manner. Besides, by varying the maximum and the minimum of the duty-ratio, the amplitude of the power frequency

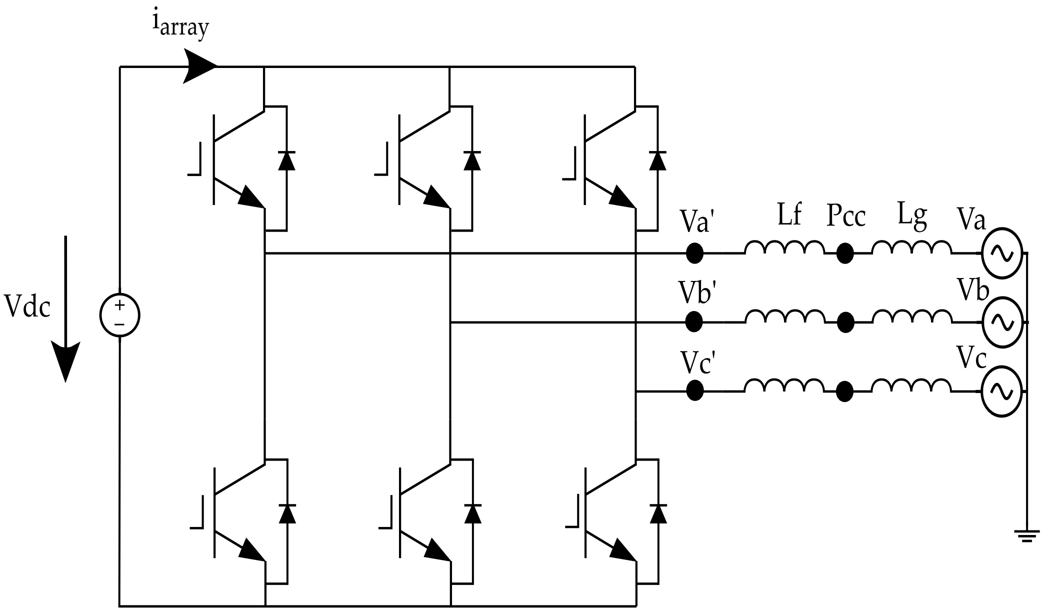


Figure 3.8: Basic circuit of a three-phase inverter

output may be controlled;

- Three-phase inverter: for higher power levels applications. There are three pairs of switches with a phase shift of $120°$ between each pair. As with one-phase inverter, Pulse With Modulation (PWM) technique may be used to produce a quasi-sinusoidal output and to control the output voltage or current. For high power applications the most used switches are IGBTs (see Figure 3.8).

In the present dissertation, one stage VSC inverter is chosen. As modulation technique, the sinusoidal pulse with modulation (SPWM) produces a quasi-sinusoidal output. The modulation index m_a (variable between 0 and 1) is equal to its maximum in this case ($m_a = 1$). Then, the minimum dc voltage is determined using the m_a. The maximum dc voltage will be the open circuit voltage multiplied by the number of panels in series [36]:

$$\begin{aligned} v_{ac} &= \frac{\sqrt{3}}{2\sqrt{2}} m_a v_{dc} \\ v_{dc} &= v_{ac} \frac{2\sqrt{2}}{\sqrt{3}} \\ v_{dc,max} &= v_{oc} N_{ser} \end{aligned} \tag{3.11}$$

It has been presented the principal characteristics of PV inverters, focusing on the number of stages and explaining the differences between VSC and

CSI inverters with their advantages and disadvantages. The next section shows how concretely the inverter helps to improve the stability of the grid focusing on the controllers.

3.3 PV inverter control

The main function of a converter is to exchange energy between two subsystems based on pre-specified performances. The subsystems often have different attributes in terms of voltage/current waveforms, frequency, phase angle and number of phases. Hence, these subsystems cannot be directly interfaced with each other and the different characteristics require different kinds of controls to maintain a good quality of the energy injected into the grid. As the matter of fact, electrical grids are characterized by multiple eventualities such as continuous connection and disconnection of loads, disturbances and resonances resulting from the harmonic currents flowing through the lines, faults due to lightning strikes and mistakes provided by the TSO. Considering these aspects, the first part of this chapter describes the main tasks of a PV inverter control. The second part shows the main blocks that accomplish with the tasks described below and the technique adopted to realize the control. The inverter has to fulfill variable objectives in order to maintain good quality characteristics of the electrical grid:

- Grid synchronization: it represents an instantaneous monitoring of the state of the grid. The objective is to maintain the value of the frequency into fixed limits while transforming from the DC to AC side. Besides, the inverter tunes the voltage with the grid characteristics in terms of phase and amplitude;

- To transmit active and reactive power from the PV generator to the grid. The power factor is kept in a fixed range;

- To keep the DC voltage constant. There is a reference value V_{ref} which the inverter has to reach under V_{DC} variations;

- Conversion from DC to AC side: with SPWM technique, the inverter creates a sinusoidal voltage at its output following the characteristic of a reference value V_{ref}.

To accomplish with these tasks there are different techniques that allow to realize a PV inverter control. First of all, a PV system connected with the grid has to control the power injected monitoring the current that the inverter injects from the panels to the grid [37]. The control scheme is based on a two level cascade control scheme. The inner current control is faster and it allows to regulate the AC current in the q and d components [34]. The inner loop is responsible of the power quality and the protection of the current injected into the grid. Besides, it accomplishes with the compensation of the harmonic components and the dynamic of the system [37]. The outer level controller deals with the regulation of the DC voltage. The control is obtained with a balance between the power averages of the two sides of the inverter. The outer control guarantees the stability of the dynamic of the system and optimizes the regulation. It is $5 \div 20$ times slower than the inner control [37]. The principal components of a PV inverter control are:

1. **Phase Locked Loop control:** The PLL is a control system in which there is an internal frequency oscillator and a phase detector that are controlled to keep angle and angular velocity tuned with an input signal. The output signal of the controller may have the same characteristics. As the matter of fact the PLL control extracts the phase angle from the grid voltage. This angle is used below to transform voltage and current in the dq frame. The basic structure of a PLL consists of three blocks (see Figure 3.9):

    - Phase detector: It generates an output signal proportional to the phase difference between the input signal and the signal generated by the internal oscillator of the PLL;
    - Loop filter: This block presents a low-pass filtering characteristic to attenuate the high-frequency AC components from the phase detector output. Typically, this block is constituted by a first-order low-pass filter or a PI controller;
    - Voltage-controlled oscillator: This block generates at its output a C signal whose frequency is shifted with respect to a given central frequency as a function of the input voltage provided by the loop-filter [38] [37].

2. **Outer current control:** The outer current control regulates the active and reactive power depending on the reference values that the control receives as input. Besides, the control sends a reference current value in the dq frame that is deployed by the inner current control. It makes sure that the capacitor remains charged with the V_{DC} value sent by the PPT control (see Figure 3.9).

3. **Inner current control:** The "dq control" or "vector control" allows to abstract the differential equations, which establish the behavior of three-phase systems, in rotating independent vectors. i_d^* and i_q^* are the current references and they are developed to determine the desired active and reactive power P^* and Q^* (see Figure 3.9).

$$\begin{aligned} P^* &= \tfrac{3}{2}(v_{zq}i_q^* + v_{zd}i_d^*) \\ Q^* &= \tfrac{3}{2}(v_{zq}i_d^* + v_{zd}i_q^*) \end{aligned} \tag{3.12}$$

i_d^* and i_q^* are calculated from the instantaneous power theory and the previous equations can be written as:

$$\begin{aligned} i_q^* &= \tfrac{2}{3}\tfrac{P^*}{v_{zq}} \\ i_d^* &= \tfrac{2}{3}\tfrac{Q^*}{v_{zq}} \end{aligned} \tag{3.13}$$

The reference currents has to be limited according to the physical limitations of the converter [37] [34]. Besides, the inner current control sends the reference voltage value in the *dq* frame to the inverter. The signal has to be modulated in the *abc* frame by the inverter. For this reason, the signal is converted again in the *abc* frame.

4. **DC voltage regulator:** This control is situated inside the outer current control (see Figure 3.9). The DC voltage regulator is required to control the voltage of the DC bus ensuring power balance between the generation source and the power injected into the grid. The control of the DC voltage has to follow a reference value according to a minimum and a maximum limitation. The limitation is given by the inverter. In this case, the Proportional Integral (PI) controller is associated with the DC voltage regulator. The PI controller introduces compensations in the outer voltage control to improve its dynamic response and reduce the errors among the set-point and the average value of parameters to control [34] [37] [39].

5. **Voltage modulation:** The VSC converter can apply the referenced voltages by modulating them with the Pulse With Modulation (PWM) technique. The control signals can be obtained through the comparison between a sinusoidal signal, which acts as a reference voltage, and a triangular signal. The frequency of the sinusoidal signal determines the frequency of the output voltage and the frequency of the triangular signal establishes the number of pulses. The SPWM modulated signals form a three-phase balanced set that configures

amplitude, frequency and phase at the output of the inverter [34] [37] [40] (see Figure 3.9).

6. **PPT control:** Generally, the PV inverter connected with the grid tries to extract the maximum power from the PV system. In the I-V characteristic the MPP depends on the value of temperature and radiation. In this case the MPP is changed with a different value, called P_{ref}, to make a power curtailment when it needs (see Figure 3.9). Previously, the tracking system was thought to reach always the MPP in every condition, now the system is able to choose which are the operating conditions. The new algorithm implemented in the following model knows not only the values of $V_{DC,meas}$ and P_{meas} but also the value of P_{ref}. The power supplied by a PV array varies with load voltage. The voltage value to obtain the operating power point changes quite strongly with array temperature and more slowly with intensity of illumination [35]. As described before, between the power plant and the grid there is an inverter to convert the power from DC to AC. In order to ensure that the power converter is operating at the optimum voltage transformation ratio, it is important to know how it is working with some feedback through a dedicated control. Thus, it comes out the requirement to identify the voltage value at which the array power is obtained and a controller to maintain the array voltage close to this value. There are several approaches to estimate the operating conditions. The most general is to sweep the array current, measure the array voltage and current and deduce the operating point. Another practical way is to change the current of the array and observe if consequently the array power output increases or decreases, then the control should act to move the operating point towards the desired point [35].

In conclusion, it is worth mentioning that this dissertation is going to focus on the PPT control. The other blocks are not analyzed. It is assumed that the other blocks of the PV inverter control are working correctly.
The present chapter has described the principal tasks of a PV inverter connected to the grid. The main blocks that accomplish with these tasks are presented in the second part of this section. The following chapter presents the differences between a traditional MPPT and the new PPT algorithm implemented in the model, especially the PPT control is explained in detail.

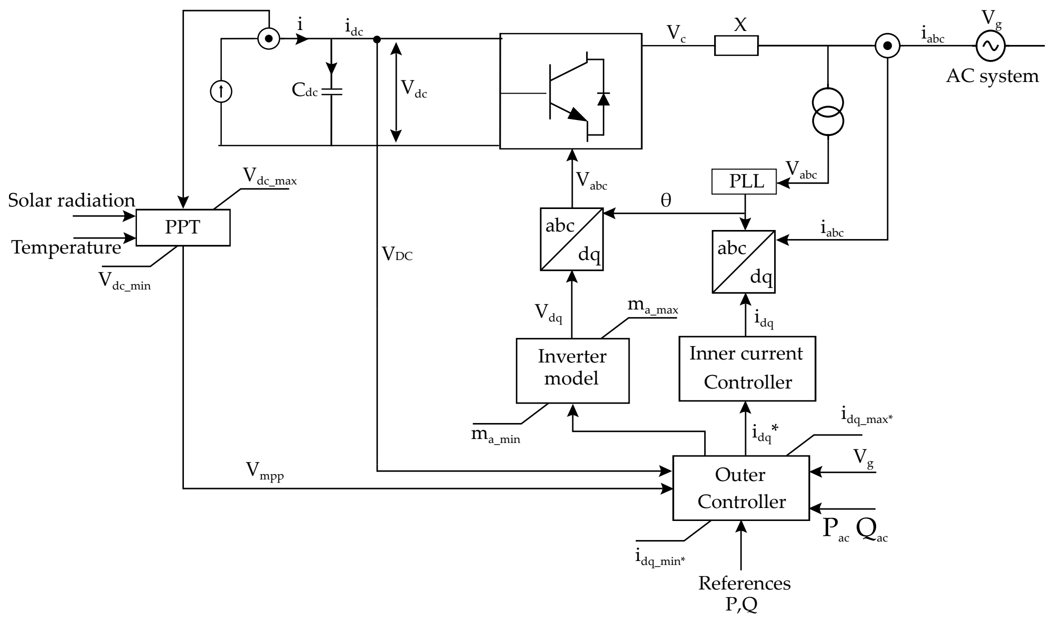


Figure 3.9: PV generator control

Chapter 4

PV Generator Active Power Control

This chapter shows an overview of the principal methods for the MPPT and explains the characteristics of the PPT method developed in this dissertation.

4.1 MPPT

The MPPT is a circuit associated with the utility-interactive inverters that adjusts continuously the dc voltage operating point to extract the maximum power output from a PV array. Despite all the advantages presented by the renewable PV generation, the energy conversion is not high efficient and its initial investment is considered important. Furthermore, the efficiency of the energy conversion varies according to climatic and irradiation conditions. As shown before, the photovoltaic characteristic is non-linear and this makes not so easy to reach the maximum operating point at any time in every load condition. A maximum power point tracker is a device employing a microprocessor to achieve both function of maximum power output and tracking by sampling the output of the array at frequent intervals (usually 30 [ms]). It compares each new value of the array power output with the previous value. If the algorithm recognizes that the power output has increased, then the array voltage will be stepped up in the same direction, otherwise it remains in the previous position. Due to its variable primary energy source, the output power of a PV array is not constant. To overcome this problem, a switch-mode power converter, called Maximum Power Point Tracker (MPPT), is used to maintain the PV array at its MPP. If properly controlled, the MPPT can locate and track the

MPP. But it is worth mentioning that the MPP can variate very fast during a day under partial shading conditions and it is not known a priori in the I-V characteristic. Besides, in some cases it possible to have multiple local maxima and the tracker could be easily confused itself. Thus, the need of a calculation model or a search algorithm because the MPP even depends in a non-linear way on temperature and irradiance [41]. Herein, the most significant methods of the wide range of algorithms are described.

1. **Fixed duty cycle**
   One of the most basic methods that does not require any feedback because the MPP is adjusted only one time and then it does not operate anymore to change again the position of the MPP [41];

2. **Beta method**
   The approximation of the MPP is made through an intermediate variable β that depends on the environmental and photovoltaic characteristics. While the operating conditions change, the β value remains constant at the MPP. β can be calculated using the voltage and the current in a loop control with constant reference [41];

3. **Hill climbing method**
   The hill climbing involves a perturbation in the duty ratio of the power converter. The voltage variation is between a maximum and a minimum value, V_{LO} and V_{HI} respectively. The optimum voltage value V_{opt} corresponds to the maximum output power in a precise time. If the $V_{out} < V_{opt}$ the PV array is treated like a current source, viceversa the PV array behaves like a voltage source . The transition point between the current and the voltage behaviors corresponds to the maximum operating point. Besides, the ΔP is used to understand the direction in which the terminal voltage must be adjusted as it changes of sign when it crosses the MPP. ΔP is the difference between the output power and the P_{sample} and, as the sampling rate is always constant, it is considered as a derivative of the output power that allows to understand its slope . If ΔP> 0 the terminal voltage will be increased, if ΔP< 0 the terminal voltage will be decreased [31];

4. **P&O and modified P&O methods**
   The hill climbing and the P&O algorithms are different ways of envision the same methods. In this case the perturbation happens in the operating voltage of the PV array. P&O is the most diffused algorithm for its ease of implementation. The algorithm adds a perturbation step size ΔD when the power and voltage increase at the same

time, and viceversa, in order to move the operating point towards the MPP. Instead, when power and voltage have a different sign, ΔD is subtracted in the next cycle. The algorithm operates this process continuously until reaching the MPP. It is worth mentioning that the system is oscillating around the MPP and this translates into power losses. An higher precision in the research of the maximum operating point will require at the same time a greater slowness of the MPP tracking system. The implementation of P&O is easy but at the same time there are many issues owing to radiation changes.This can confuse the algorithm because it is no more able to recognize were exactly the MPP is located. Below, the present dissertation shows the main limitations of the P&O method and many solutions proposed by some authors.
When the sunlight decreases, the P-V curve flattens out and the MPPT is not able to understand where is the correct position of the MPP because in comparison the power decrease is less than that of the voltage. Another drawback is the inability to determine when the MPP is reached. Especially in partly cloudy days, the algorithm continues to move itself around the MPP and if the irradiance increases rapidly the MPPT will move away from the MPP to another curve. It is worth to point out that an increase (decrease) of voltage on the right part of the MPP in the P-V curve is different than an increase (decrease) in left part of the MPP. The first one will correspond to a decrease (increase) of power, instead the second one will correspond to an increment (decrement) of power. Sometimes the algorithm could get confuse about the real operating point [42]. There are many solutions proposed to solve these issues. One of simplest is to put in the algorithm a delay that can stop temporarily the perturbation when it has the same sign for several times. This establishes the achievement of the MPP. The variation in the algorithm increases the efficiency, especially under constant radiation, but at the same time slows down the search process. Another idea, in which still remains the trouble of slowness of the algorithm, is to make a power measurement of P_1 at V_1, then change the voltage and measure P_2 at V_2 and finally return at V_1 with a new measurement of $P_{1'}$. The comparison between P_1 and $P_{1'}$ can tell in which direction the irradiance is changing and, at the same time, the complexity of the algorithm would be higher [43].
The oscillation issue around the MPP could be settled reducing the perturbation step size but the decrease of quickness remains a side effect. In turn, a possible solution is to have a gradual reduction of the step size towards the MPP using a fuzzy logic control to optimize

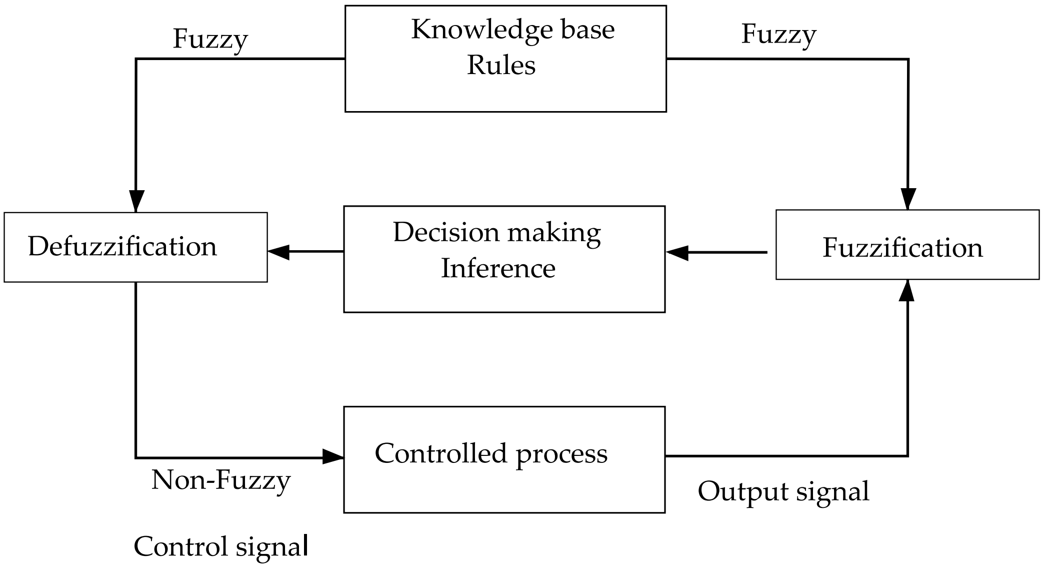


Figure 4.1: Basic fuzzy logic structure

the magnitude of the next perturbation [42]. In [44] before making a new perturbation three power points are compared to understand the direction the algorithm has to take.

5. **Incremental conductance**
The incremental conductance (IncCond) applies the derivative of the PV array power with respect to the voltage to understand the slope of the PV power curve.

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} = 0 \; at \; the \; MPP \tag{4.1}$$

that becomes,

$$-\frac{I}{V} = \frac{dI}{dV} \tag{4.2}$$

These equations are used to determine in which direction the algorithm must look for the MPP. Once the MPP is reached, the MPPT continues to operate at this point until a change in current is measured. The current variation correspond to a change in radiation [41]. This algorithm makes use of the slope of the P-V curve to understand in which part the MPPT is located and the direction has to take the perturbation to apply. The achievement of a fast tracking could be realized with a big step size but, at the end, the algorithm would still oscillate around the MPP. The idea in [45] proposes a method that brings to arrive close to the MPP and then the IncCond algorithm is applied to reach exactly the MPP.

6. **Constant voltage and current**
From the observation of the I-V characteristic it is possible to say that the ratio of the array's maximum power voltage, V_{MPP}, to its open-circuit voltage V_{OC} is approximately constant:

$$\frac{V_{MPP}}{V_{OC}} \cong K < 1 \tag{4.3}$$

The solar array is temporarily isolated and V_{OC} is measured. Then, the MPPT calculates the operating point and the present value of K. Subsequently, the algorithm adjusts the array voltage until the MPP is reached. The operation is repeated periodically. In this method is difficult to determine a correct value of K and the tracking efficiency is lower than other algorithms. Besides, the measurement of V_{OC} requires the inconvenience of a momentary interruption of the PV power that means higher losses. The implementation of a constant current MPPT control that approximates the MPP current as a constant percentage of the short-circuit current can be realized with a switch placed across the input terminals of the converter and switched on momentarily. The process is quite similar to voltage constant control but normally the last one is preferred because it is easier to measure voltage [41].

7. **Fractional open-circuit voltage**
The technique is quite similar to the last one. Herein, it makes use of the following equation:

$$V_{MPP} \approx k_1 V_{OC} \tag{4.4}$$

where k_1 is a constant of proportionality. The approximation establishes that the voltage generated by pn-junction diodes is 75% of V_{OC}. Thus, there is need to measure the V_{OC} and compute the V_{MPP}. Then, a closed-loop control can be applied to reach the MPP. Owning to the approximation, the MPP is never reached with this method but, at the same time, its implementation is very easy and cheap.

8. **Pilot cell**
This technique makes use of a small solar cell, called pilot cell, that simulates in a small-scale the real PV array. As advantage, the measurement of short circuit current or open circuit voltage are made

directly on the pilot cell and then matched with the real plant eliminating the loss of PV power during measurements. In this method there is still the drawback of the K factor and, in addition, the parameters match between the pilot cell and the PV array is not automatic but has to be done carefully. Besides, the pilot cell has to be constantly calibrated adding costs to the whole system [41].

9. **Fractional short-circuit current**
As described by many authors, I_{MPP} is approximately linearly related to the I_{SC} of the PV array:

$$I_{MPP} \approx k_2 I_{SC} \tag{4.5}$$

where k_2 is a proportionality constant and depends on the PV array characteristics. To measure I_{SC} an additional switch is added to the power converter with a general increase of the costs. A method proposes to periodically sweep the PV array voltage from open-circuit to short-circuit to update k_2 and maintain a good MPPT. Another technique of MPP tracking, well described in [46], is to measure the I_{SC} and then adjusting the actual load current to be equal to a desired fraction of I_{SC}.

10. **Modified short-circuit current method**
I_{SC} depends on temperature and radiation both. The combined is taken into account by the following equation [41]. The variation of I_{SC} with temperature is:

$$C_{TI} = fracI_{SCT}I_{SC} = 1 + k_I(T_x - T_C) \tag{4.6}$$

$$with\ k_I = 0.0006\ A/°C. \tag{4.7}$$

The variation of I_{SC} with insolation is:

$$C_{SI} = fracI_{SCG}I_{SC} = fracS_X S_C \tag{4.8}$$

where S_X and S_C are insolations at variable and reference conditions. Finally, the dependence on temperature and insolation is expressed by:

$$I_{SC(TG)} = C_{TI} C_{SI} I_{SC} \tag{4.9}$$

11. **Parasitic capacitance/dc-link capacitor droop control**
Similar to the incremental conductance method but it is also included the effect of the solar cells' parasitic junction capacitance C_P, which

models charge storage in p-n junctions of the solar cell. The difference in efficiency between the parasitic capacitance and the incremental conductance can be noticed in a high-power solar array with many solar modules [41].

12. **dP/dV or dP/dI feedback control**
    The MPPT tracking is performed computing the slope differential power to voltage or differential power to current (dP/dV or dP/dI), then feed it back to the power converter with some control to drive it to zero [41].

13. **Fuzzy logic controller FLC**
    FLC have advantages of working with imprecise inputs, it does not need an accurate mathematical model and it is able to solve nonlinear problems. As described in [24] there are four steps: fuzzification, inference, rule base and defuzzification. Normally five linguistic variables translates the numerical input variables in the fuzzy language but sometimes there are seven levels to realize a more accurate model. Paper [41] proposes a modified fuzzy MPPT algorithm with a scanning and storing procedure to quickly locate the global maximum power point. First there is fast tracking and then, when the algorithm is close to the MPP, the speed decreases to avoid oscillation around the MPP. The method performs fast tracking even under any partial shading condition, with less oscillation in steady-state and very fast transient response.

14. **Load current or load voltage maximization**
    Generally the techniques presented before tend to maximize the PV array power. Herein, maximizing the output power of the converter should maximize also the PV array power, with less power losses. The maximization of the load power is handled with either the load current or the load voltage and only one sensor manages the process.

15. **Neural network**
    Neural network is well adapted for micro-controllers and usually has three layers: input, hidden and output layers. The number of connection nodes is variable. The input information generally are PV array or environmental parameters, then at the output is composed by several signals to drive the power converter close to the MPP. It is worth mentioning that the neural network has to be trained depending on the characteristic of the PV array and periodically it needs an update because the PV characteristics change during the time [41].

Table 4.1: Characteristics of different MPPT method [41]

MPPT technique	PV array dependent	True MPPT	Analog or digital	Periodic tuning	Convergence speed	Implementation complexity	Sensed parameters
Hill climbing/PeO	No	Yes	Both	No	Varies	Low	Voltage,current
Incremental conductance	No	Yes	Digital	No	Varies	Medium	Voltage,current
Fractional V_{OC}	Yes	No	Both	Yes	Medium	Low	Voltage
Fractional I_{SC}	Yes	No	Both	Yes	Medium	Medium	Current
Fuzzy logic control	Yes	Yes	Digital	Yes	Fast	High	Varies
Neural network	Yes	Yes	Digital	Yes	Fast	High	Varies
RCC	No	Yes	Analog	No	Fast	High	Voltage,current
Current sweep	Yes	Yes	Digital	Yes	Slow	High	Voltage,current
dc Link capacitor droop control	No	No	Both	No	Medium	Low	Voltage
Load I or V maximization	No	No	Analog	No	Fast	Low	Voltage,current
dP/dV or dP/dI feedback control	No	Yes	Digital	No	Fast	Medium	Voltage,current
Array reconfiguration	Yes	No	Digital	Yes	Slow	High	Voltage,current
Linear current control	Yes	No	Digital	Yes	Fast	Medium	Irradiance
I_{MPP} **and** V_{MPP} **computation**	Yes	Yes	Digital	Yes	N/A	Medium	Irradiance,temperature
State based MPPT	Yes	Yes	Both	Yes	Fast	High	Voltage,current
OCC MPPT	Yes	No	Both	Yes	Fast	Medium	Current
BFV	Yes	No	Both	Yes	N/A	Low	None
LRCM	Yes	No	Digital	No	N/A	High	Voltage,current
Slide control	No	Yes	Digital	No	Fast	Medium	Voltage,current
β **method**	No	Yes	Digital	No	Fast	High	Voltage,current
System oscillation method	No	Yes	Analog	No	N/A	Low	Voltage
Constant voltage tracker	Yes	No	Digital	Yes	Medium	Low	Voltage
Lookup table method	Yes	Yes	Digital	Yes	Fast	Medium	Voltage,current,irradiance
Online MPP search algorithm	No	Yes	Digital	No	Fast	High	Voltage,current
Temperature method	No	Yes	Digital	Yes	Medium	High	Voltage,current,temperature
Three point weight comparison	No	Yes	Digital	No	Varies	Low	Voltage,current
POS control	No	Yes	Digital	No	N/A	Low	Current
Biological swarm chasing MPPT	No	Yes	Digital	No	Varies	High	Voltage,current,irradiance
Variable inductor MPPT	No	Yes	Digital	No	Varies	Medium	Voltage,current
INR method	No	Yes	Digital	No	High	Medium	Voltage,current

Table 4.1 summarizes the principal MPPT methods and their characteristics.

4.2 PPT

As explained before, the traditional MPPT is principally focused on the maximization of the PV array output power. But the extraction of the maximum power is strictly connected with the variability nature of primary energy source. As consequence, the output power is subjected to frequent power oscillations that, in turn, affect the grid to whom the plant is connected. The intense growth of source with photovoltaic energy led to consider the impairment of the electric grid as an issue of primary importance. Instead of strengthen the electric grid, whose process is expensive and adequate only for a brief period of time, preferably the PV array con-

trol is modified so that it contributes to strengthen the whole grid. This process is relatively more economic and the general efficiency of the grid will be increased. The PV plant was seen has negative load but now it has an active role of compensation.
Another important aspect is that the control has been developed without an auxiliary system of energy storage. In this way it is avoided the use of another auxiliary system and costs are reduced. As well known, in a partly cloudy day the radiation can vary rapidly and then the battery should deal with fast voltage variations to attain a constant output power. This process might submit the battery under an important stress and reduce considerably its life-time. It is worth considering also the battery investment and verify the real effectiveness from an economic point of view.
The new algorithm operates a power curtailment when $P_{AV} > P_{REF}$. Conversely, the traditional MPPT is always looking for the maximum power extraction. With the new technique the active power cut can be utilized to make compensation and contribute to manage the active power. The power reference can be fixed according to a compromise. It is necessary to observe which is the production of a plant depending on the variations of radiations and temperature during the most significant months. In this way will be easier to establish a value of power reference. The losses connected with the power curtailment should not be excessively high otherwise the deployment of a modified PPT algorithm would not be convenient. On the other side the P_{REF} value should not be too high because the PV plant would follow to work as there is no modified MPPT algorithm.
It is worth making a comparison, with a real study case, between a plant working with a traditional MPPT and another one with a modified PPT. This study would allow to understand the entity of the losses in either cases. It is important to consider also if the modified PPT effectively performs the active power compensation. Besides, it is not for sure the algorithm will be able to follow without any retard the variations of radiation and temperature. As pointed out before, the traditional MPPT sometimes makes confusion and generates a series of errors that brings to an operating point different from the MPP in a precise moment.
In this dissertation has been developed two methods. The first one that has brought to some errors in the algorithm and the second one that has been implemented in the DigSilent model.

- **Development of the first method:**
  The first method has been developed considering the characteristic equations according to a single diode model. These equations con-

tain the dependence from temperature and irradiance. They express the behavior of a PV cell. The starting expressions are the following:

$$\begin{aligned} & i = i_{ph} - i_d - i_p \\ & i_{ph,stc} = i_o \cdot \ e^{\frac{v_d}{v_t}} + \tfrac{V_{oc}}{R_p} \\ & i_d = i_o \cdot \ e^{\frac{v_d}{v_t}} \\ & v_t = k_b \cdot \ N_{ser} \cdot \tfrac{T_{stc}+273}{q} \end{aligned} \tag{4.10}$$

where i_d is the diode current and i_p the parallel current. In order then there is the diode voltage (v_d), the thermal voltage v_t, the open circuit voltage (V_{oc}), the diode saturation current (i_o) and the Boltzman constant (k_b). Considering non STC conditions, the equations change in the following way:

$$\begin{aligned} & i_{phn} = i_{ph,stc} \cdot \tfrac{G}{G_{stc}}, \ G > 125W/m^2 \\ & i_{dn} = i_{on}[e^h - 1] \end{aligned} \tag{4.11}$$

where:

$$h = \frac{v_{pv} - i_n R_{ser}}{v_{tn}} \tag{4.12}$$

Considering these new values, the system of equations is:

$$\begin{cases} i_n = \frac{i_{phn} - i_{dn} - v_{pv}/R_p}{1 + R_s/R_p} \\ P_{array} = i_n v_{pv} N_{ser} N_{par} \end{cases} \tag{4.13}$$

Applying the Taylor-Maclaurin series expansion, it is possible to simplify the i_{dn} term as:

$$i_{dn} = i_{on}[e^h - 1] \cong \ h \cdot i_{on} \tag{4.14}$$

From this point the development of the analysis brings to a final equation:

$$\frac{P_{Wm}}{N_s Np}(1 + \frac{R_s}{R_p}) = V_{ref}^2 \left[\frac{i_{on}}{v_{tn}} \cdot \frac{R_s}{R_p} - \frac{1}{R_p} - \frac{i_{on}}{v_{tn}} \right] + i_{phn} v_{pv} \tag{4.15}$$

The equation is placed to deploy it in the DigSilent Power Factory model. The main aim is to obtain a voltage control with a constant output power. The model has been implemented with real data to simulate a fast change in radiation and temperature during several partial cloudy days. The result from the simulation has not been the satisfactory and the active power control was not realized. After some attempts to fix the system of equations and make the whole model work properly, it has been reached the conclusion that the equation development was wrong. Probably, the simplification made in the term i_{dn} brought to build an unstable model. As the matter of fact, the system did not give a good feedback under variations of radiation and temperature. Running, the model might accumulate a series of errors and this explains why there is a great delay of response. It has been observed that the voltage control was not able to follow effectively the simulation alterations.

- **Development of the second method:**
After this first attempt that did not bring to good results, a new algorithm has been developed. The basic idea is the same of a traditional MPPT with P&O method (see Figure 4.2). In this case the reference parameters are P_{REF} and V_{MPP} but the process remains essentially the same: it proceeds step by step incrementing of a small amount the voltage. Subsequently the system observes which are the effects of the perturbation and then decides in which direction will go the next disturbance. The logic under this modified MPPT method is a comparison between P_{REF} and P_{MEAS} and between V_{MPP} and V_{MEAS}. If $P_{REF} > P_{MEAS}$ and $V_{MEAS} < V_{MPP}$ it means that the operating point in the P-V curve is between the reference and the MPP points. Since the target is to reach the MPP, then the system proceeds incrementing step by step the voltage (see Figure 4.3). Instead, if the second statement ($V_{MEAS} < V_{MPP}$) is not true, then it means that the MPP is between P_{REF} and P_{MEAS} and the algorithm decreases the voltage value. It is worth to point out that in these conditions the system will never reach the P_{REF} value, for instance in a cloudy day. Thus, it is preferable to make the model work like a traditional MPPT. The algorithm in this situation will try to extract always the maximum power available. In other words, there is no power curtailment. Conversely, when $P_{REF} < P_{MEAS}$ it means the model is working with a power value bigger than P_{REF}. In this case there is a power curtailment: the voltage is gradually reduced until the achievement of the reference value. In this way the power is also reduced (see Figure 4.4). It is easy to observe that the P&O logic remains always the same. The adoption of this algorithm takes advantage of its simplicity and from this point the complexity increases a step more. Besides, the modification of the control does

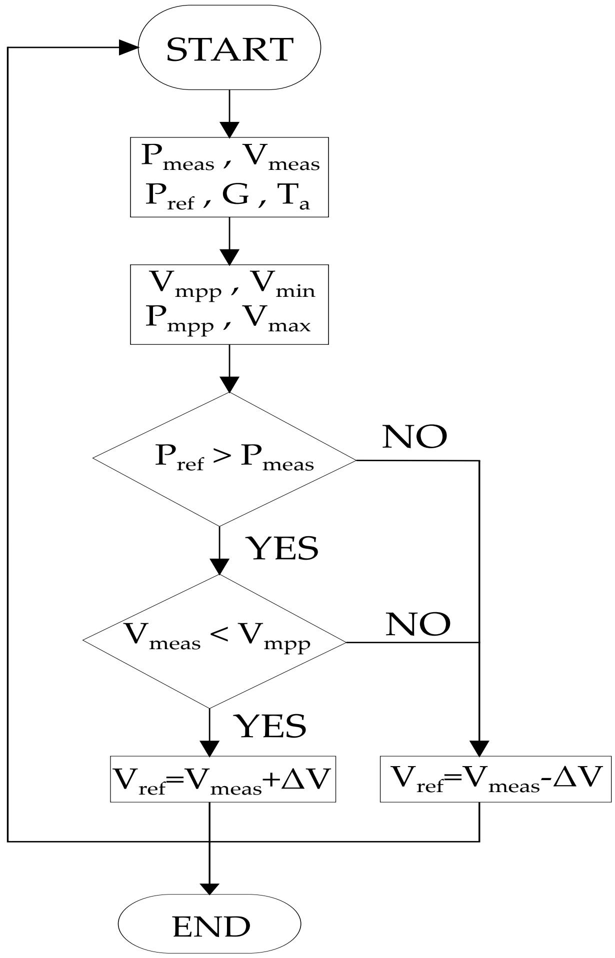


Figure 4.2: PPT algorithm

not require additional costs and this might be extremely competitive if compared with an APC with ESS in a real case study. The main drawback of this technique is its slowness to react under fast variations of temperature and radiation. This might cause some issues to reach the MPP or a constant output power. Established these characteristics, it might be really interesting to test the model under a real case study in which there are fast changes of the environmental conditions.

In conclusion, this chapter has presented different methods to create a MPPT algorithm. After that, the main characteristics of the algorithm implemented in this dissertation has been shown. The next chapter applies the algorithm in the model with real study cases.

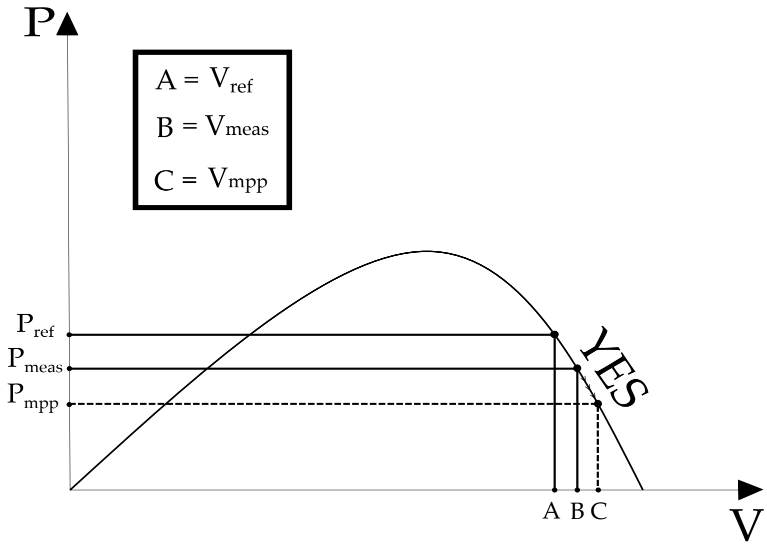


Figure 4.3: PPT algorithm case example 1

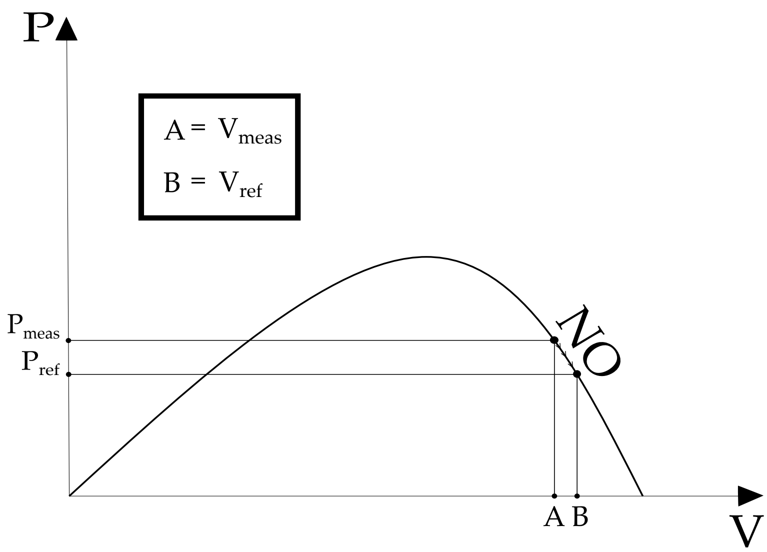


Figure 4.4: PPT algorithm case example 2

Chapter 5

Simulation and Results

The aim of this chapter is to test the control developed in a 0,6 MW PV generator. The generator is tested under variable solar irradiance and temperature with an only one power reference. For this purpose, the PV generator model and control is implented in DigSilent Power Factory.

5.1 General model in DigSilent Power Factory

This section describes the PV generator implemented in DigSilent Power Factory considering its control characteristics and general details. Additionally, the chapter presents the simulation when the PV generator is applied in three different scenarios. The results obtained are presented (see Figure 5.1). As described in previous chapters, the PV system is connected to the grid without any energy storage system. There is an inverter with its capacitor bank between the DC and AC side and then a three-winding transformer before the external grid. Figure 5.1 shows the basic model represented with an electrical circuit.

5.1.1 PV array

The PV array is represented in this software as a current generator. In order to make this block to behave like a PV module, the characteristics of the PV generator are implemented in the model. The response of this block under variations of temperature and radiation corresponds to that of a photovoltaic system. The PV module YL 280 P$-$35b series of Yingli Solar Manufacturer is used as benchmark to describe the behavior of the whole PV system. The following tables shows the principal parameters of this PV module. Regarding the PV system, there are 175 arrays in parallel

Table 5.1: Electrical parameters at STC

Module type		**YL 280 P$-$35b**
Power output	[W]	280
Power output tolerances	[%]	$+/-3$
Module efficiency	[%]	14.4
V_{mpp}	[V]	35.5
I_{mpp}	[A]	7.89
V_{oc}	[V]	45.0
I_{sc}	[A]	8.35
Max. system voltage	[V]	1000 V_{DC}

Table 5.2: Parameters of thermal characteristics

NOCT	$[°C]$	46 $+/-$ 2
Temperature coefficient β of I_{sc}	[W]	$+0,0006$
Temperature coefficient α of V_{oc}	$[1/K]$	$-0,0037$
Temperature coefficient gamma of P_{mpp}	$[1/K]$	$-0,0045$

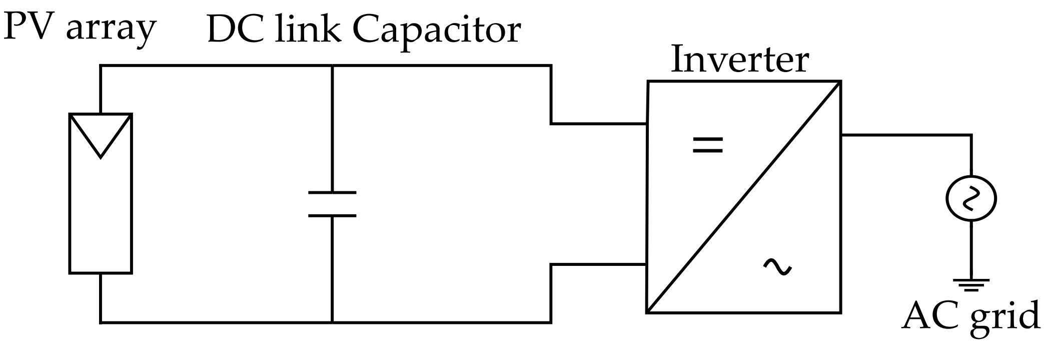


Figure 5.1: Circuit representation of the model implemented in DigSilent Power Factory

and each array is composed of 15 modules in series. Totally, there are 2625 panels in a row that works together in a central topology.

5.1.2 Inverter

The inverter between the DC and AC side can be represented in DigSilent Power Factory by a PWM converter. The benchmark for the inverter is SMA SUNNY CENTRAL 800 CP XT. Below, the table sums up the main characteristics of the inverter employed for the simulation in the Power-Factory model. The PV system connected to the DC bus along with a DC link capacitor and then the PWM converter is shown in Figure 5.2.

5.1.3 Control frame

The control explained in Chapter 3 Section 3.3 is developed in DigSilent Power Factory by using the DigSilent Programming Language (DSL) (Appendix 1). Thus, the PV generator model and control in DSL can be represented in a control frame as it is illustrated in Figure 5.3. Each of the blocks are described briefly.

- **Trafo:** this slot represents the transformer. It needs to step-up the voltage to the desired level;
- **Park:** it applies the park transformation in order to work in the dq frame. This slot allows to deploy the reference currents i_d and i_q;
- **PLL:** the PLL controller is a control system that generates an output signal whose phase is related to that of an input signal;

Table 5.3: Characteristics of the inverter

Technical data	**Sunny central 800CP XT**
Input(DC)	
Max. DC power (@ cos $\varphi = 1$)	898 kW
Max. input voltage	1000V
$V_{MPP,min}$ at I_{MPP}<$I_{DC,max}$	530 V
MPP voltage range (@ 25°C/ @ 50°C at 50 Hz)	641 to 850V/583 to 850V
Rated input voltage	641V
Max. input current	1400A
Max. DC short-circuit current	2500A
Number of independent MPP inputs	1
Number of DC inputs	9
Output AC	
Rated power (@ 25°C/nominal AC power (@ 50 °C))	880 kVA/ 800 kVA
Nominal AC voltage/ nominal AC voltage range	360V/ 324 to 414V
AC power frequency/range	50 Hz, 60 Hz/ 47 to 63 Hz
Rated power frequency/rated grid voltage	50 Hz /360V
Max.output current/max total harmonic distortion	1411A/ 0,03
Power factor at rated power/displacement power factor adjustable	$1/0,9$ leading to 0,9 lagging
Feed-in phases	$3/3$

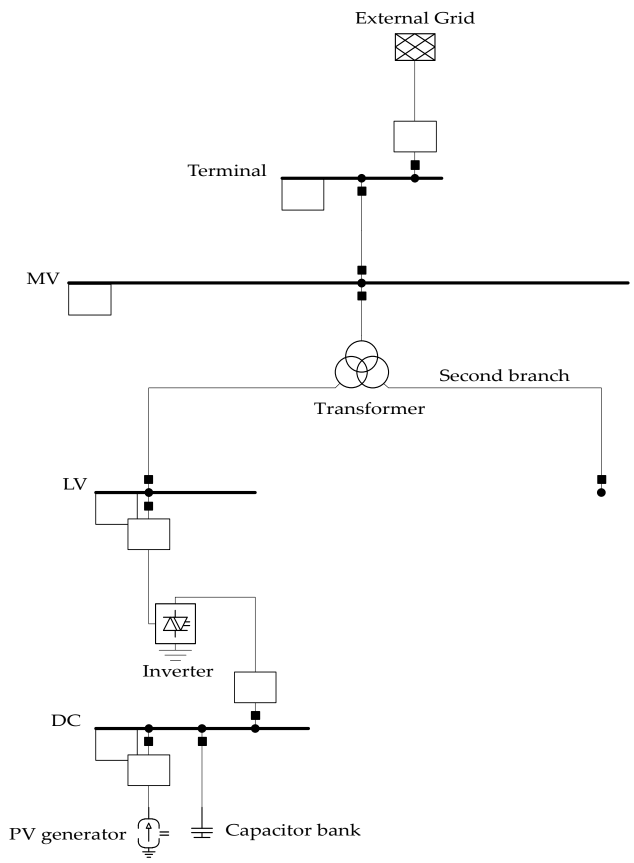


Figure 5.2: Representation of the model in DigSilent Power Factory

- **Inverter:** as shown in Figure 5.3, it receives the input signals i_d and i_q in the *dq* frame. The output signals $I_{DC,meas}$ and $V_{DC,meas}$ are used as input for the controller;

- **Array model:** this slot contains all the information about the PV module characteristics. Besides, it is connected with a data slot that provides data about radiation and temperature. The characteristic of the PV panels are implemented as DSL codes and the real data are read in this block;

- **Inverter Control:** this is the most important part of the whole system. It has different tasks to perform and they are described in detail in precedent chapters. This slot allows to perform a control of active

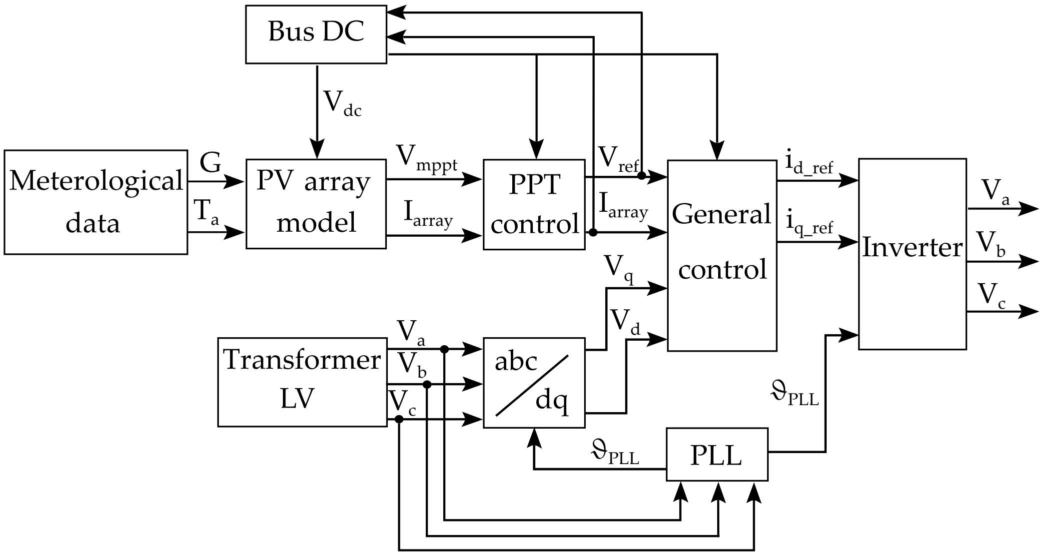


Figure 5.3: Representation of the control in DigSilent Power Factory

power according to the DC output voltage of the PV system. The inputs of the controller are the measured values of V_{DC} and I_{DC}, the reference voltage in the *dq* frame and the voltage value coming from the PV array. The controller outputs are sent to the inverter. In this block it is also implemented the DC voltage regulation.

This section has described briefly various slots that composes the model realized in DigSilent Power Factory. Besides, the tables contains parameters representing principal characteristics of the PV module and inverter.

5.2 Study case

In this section some simulations and results are presented in order to check the PPT control under variable solar irradiance and temperature. For this purpose, the reference power considered is 20% of the maximum power that the PV generator can supply according to PREPA grid code. Main requirements are specified to perform adequately the simulations. Besides, the selected location and the motivation of this choice are described. Finally, this section shows the results for the three days of simulation.
Data implemented in the model have been chosen with a principal requirement. It would be interesting to run a simulation with data that translate fast variation of radiation and, eventually, temperature, even if slower due to its inertia. Another important aspect regards measurements: they have

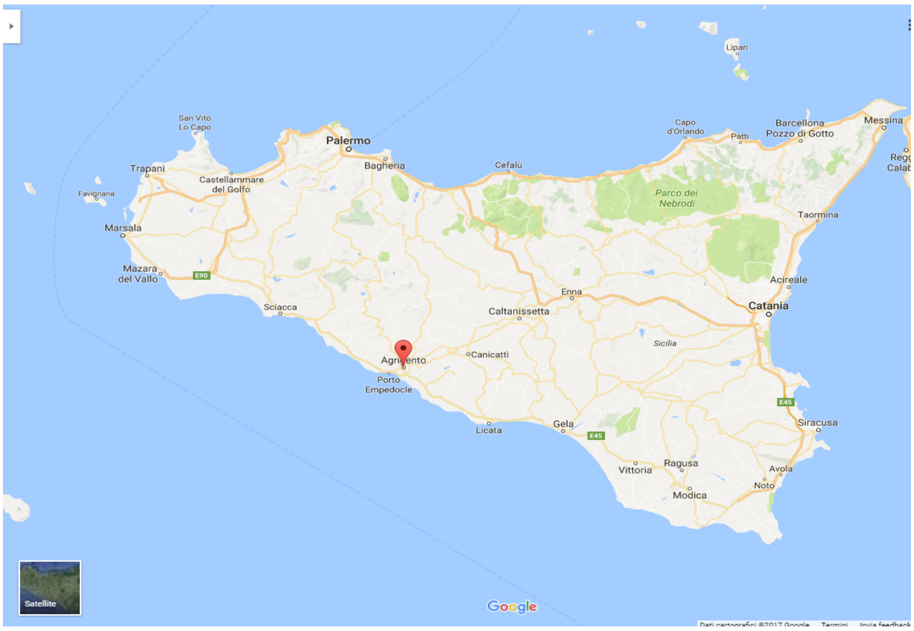
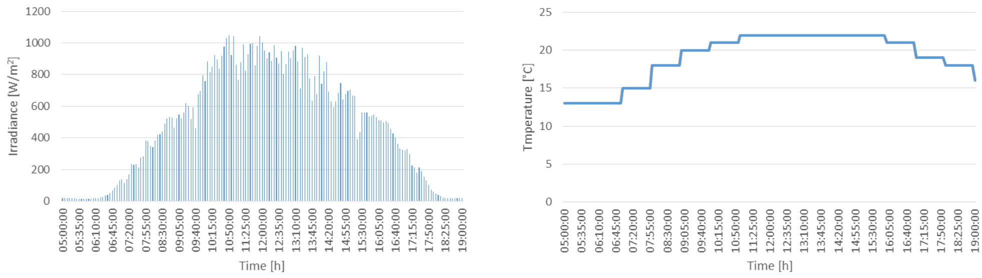


Figure 5.4: Geographic position of Agrigento

to be taken in brief intervals of time. In this way it is possible to point out the variations of radiation.
Following this line of thought, a real location is chosen which is: Agrigento. This city is located at the southern part of Sicily in Italy (see Figure 5.4). As this location is close to the Africa region and has an altitude of $37°18'32.9$"N, the days can be sunny and in some moments of the day some clouds can appear. This ambient characteristics make that a PV generator can struggle to supply a constant active power.

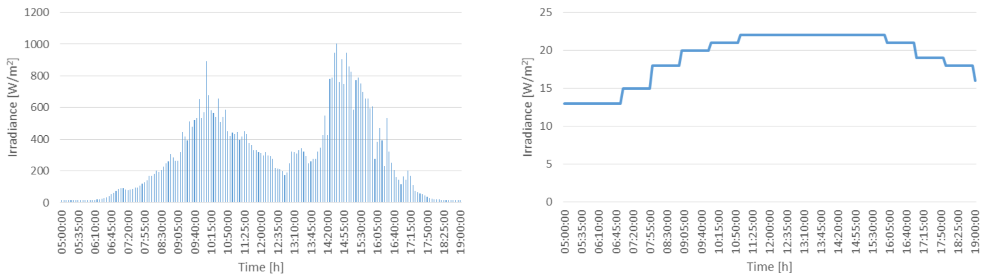
To see how the PPT works, three days have been selected as significant. The 17^{th}, 18^{th} and 19^{th} of August,2014 are the days of benchmark for the case study. The measurements are taken starting from 7 a.m. to 7 p.m. Over this range of time it does not make sense to continue with the simulation because there is not enough sun-light to produce a great amount of energy. The profile of solar irradiation and ambient temperature for each day are illustrated in Figures 5.5 to 5.7.

It is important to point out that in the first day, the maximum temperature corresponds to 22 $°C$ and the maximum radiation is about 1048 W/m^2. This case is interesting because the global trend of the radiation has an hill form which is the ideal one. But if the single measurements



(a) (b)

Figure 5.5: Recorded data for day 1 (a) Solar radiation, (b) Temperature



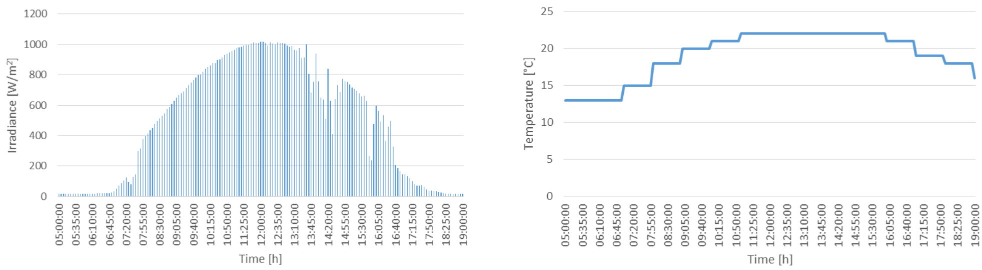
(a) (b)

Figure 5.6: Recorded data for day 2 (a) Solar radiation, (b) Temperature

are observed there are positive and negative peaks rather relevant. For instance, around 3.30 p.m. there is a great drop of radiation, probably due to rainfall or cloud coverage, and then a sudden increase. Hence, it is worth to observe how the system respond in this case.

The solar irradiance in the second day, however, presents more fluctuations than the case before. It has two pics: one at 9:30 am and the other close to 13:30 pm. This type of radiation may be difficult to manage especially during the principal hours of the day-light when there are many loads connected. The maximum values of radiation and temperature during this day are respectively 1002 $[W/m^2]$ and 22 $[°C]$.

In the 19^{th} of August the radiation has a good trend during the first part of the day, then there are some small variations. A sunny day is also important to analyze in order to study to behavior of the system in normal situations. The maximum values of radiation and temperature during this day are respectively 1017 $[W/m^2]$ and 22 $[°C]$.



(a) (b)

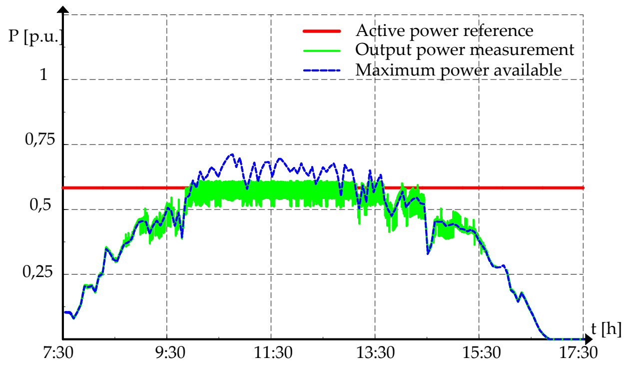
Figure 5.7: Recorded data for day 3(a) Solar radiation, (b) Temperature

Taking into account this data, then the PV generator was tested using the active power control for a given active power which was explained in Chapter 4. For this study, the power reference that the PV generator has to follow is equal to 0.6 p.u. The corresponding results of the output power when this control is used are illustrated in Figure 5.8 (green line). In the same figures, it is also illustrated the possible output power in the case that only the MPPT control is used (blue line).

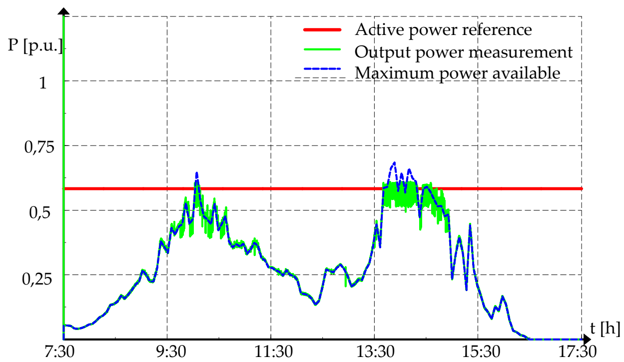
From Figure 5.8 it is possible to understand that the system is following the variation of radiation during the day when the reference of active power is higher than the maximum possible power. However, when the PV generator can supply more active power than the reference then the control is applied. It can be observed that for each day, the response of the active power is different as the solar radiation changes. In the first day, it can be seen that the control follows the power reference from 10:00 to 13:00. Meanwhile the second day, the reference only can be achieved from 13:00 to 14:00. Finally, the third day the power reference can be followed from 9:30 to 13:00.

Because the control of active power depends on the variation of dc voltage, it is also necessary to see how the dc voltage varies during the day. Thus, the profile of dc voltage for each day using the control is illustrated in Figure 5.9. The variation of dc voltage goes from 0.6 p.u to almost 0.75 p.u due to the limitations imposed by the PV inverter.

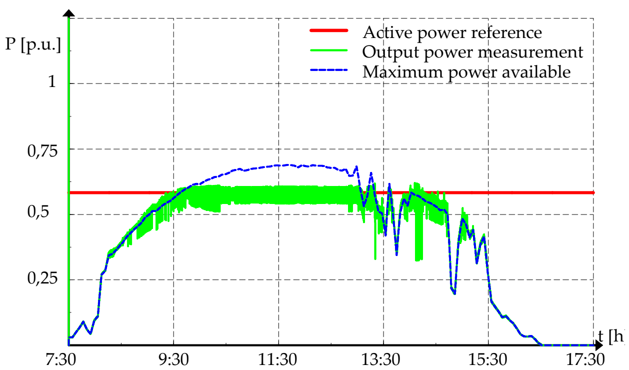
Chapter 5 has described the main characteristics of the model built in DigSilent Power Factory. Data have been chosen based on peculiar characteristics and with the will to test the system under different conditions. Finally, the results of the simulations have been shown through the most important graphs. In the next chapter the results will be discussed.



(a)



(b)



(c)

Figure 5.8: Results for active power (W) (a) Day 1, (b) Day 2, (c) Day 3

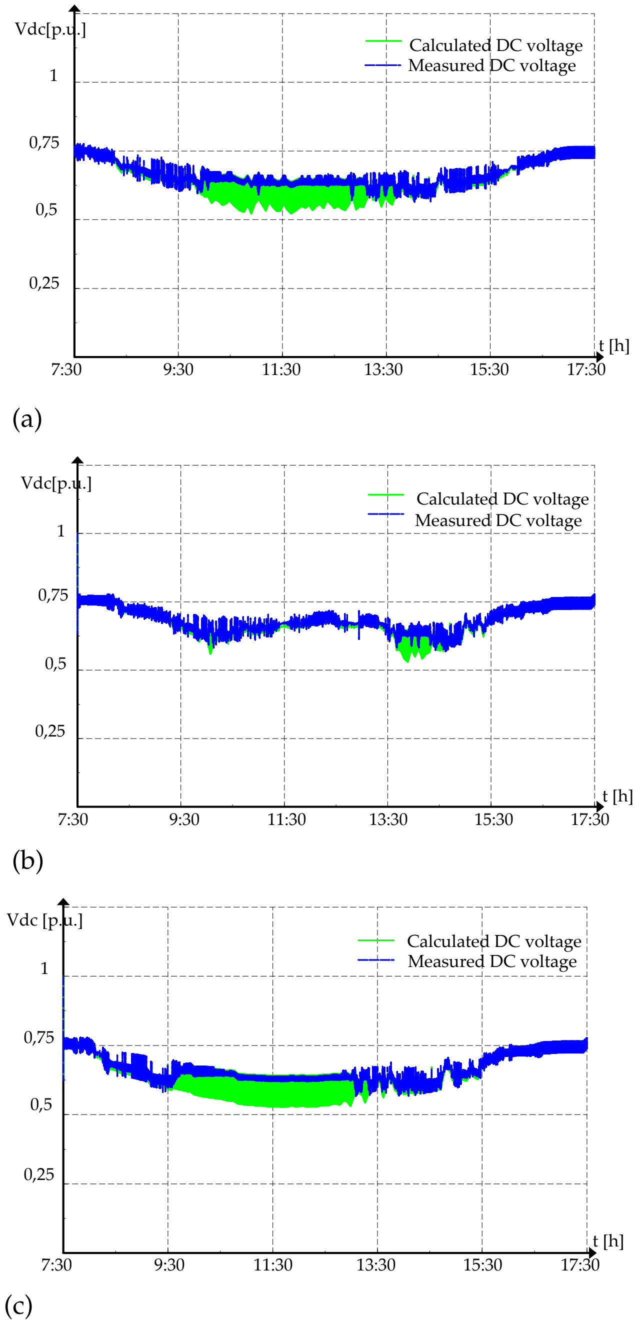


Figure 5.9: DC voltage profile (V) (a) Day 1, (b) Day 2, (c) Day 3

Chapter 6

Discussion

Chapter 6 first presents a critical analysis about the results obtained and then it shows an economic analysis between a system with energy storage and another one only with Active Power Curtailment.

6.1 Technical analysis

The results to analyze are essentially the profiles of voltage and power, under different values of radiation and temperature.

6.1.1 Voltage

The PV system is working with the modified PPT control. According to the results of Figure 5.9, it is possible to observe how the measured voltage follows the array voltage. According to the purpose of the project, the DC voltage is set free to variate depending on the values of radiation and temperature. The wide range of oscillations of the green line is due to the algorithm. Iteration per iteration it is looking for the reference voltage value. These graphs are important because demonstrate that the system responds to external stresses. Besides, in the algorithm there are some voltage limitations due to the inverter operating conditions. These limits are respected. Hence, all these aspects are proofs that the algorithm is working in the right way.

6.1.2 Power

Figure 5.8 shows the behavior of the power profile. The power profile behaves as expected. From the graphics it is possible to deduce that the

tracking system is following the fixed value of P_{ref} under variations of the solar radiation. This points out the feasibility of the control. When the power output is lower than the value fixed in the algorithm, then the system works at its MPP. In this case the tracking system works as there was a normal MPP algorithm. Instead, when the available power is greater than the reference value, then the system carries out a power curtailment. The P_{ref} value has been hypothesized to perform a 20 % power curtailment that may allow to see the curtailment carried out by the system.
It is important to notice that there is a communication delay between the control and the measured value in a certain moment. When there is an high number of iterations and fast variations of the solar radiation, those communication delays can generate errors in the tracking system. When the variations are more sudden and intense, it possible to note that the system responds with a certain delay. The delay accumulation is connected with the PI controller. This part of the system is not well calibrated. In future works it may be interesting to optimize the whole PV control model in order to make it work in this kind of conditions.

6.2 Economic analysis

This section presents an economic analysis with the aim to justify the idea that has been developed in this dissertation. Particularly, two economic parameters are analyzed in order to compare two different technical solutions of the PV system. Besides, the variation of stored energy percentage is shown.
The location chosen for the economic analysis is Rome. Data of solar radiation and temperature have been obtained from PVGIS. Measurements are taken for every month with an interval of 15 minutes. The PV data come from real data sheet of a module called YL 280 P-35b. The module characteristics are described in Table 5.1 and Table 5.3.
According to PREPA grid codes, a 20% power curtailment has been set up with respect to the maximum power available with these conditions.
The economic study has the objective to compare different situations. The first one where the PV control performs only the power curtailment. The second one where there is an ESS and a part of the curtailed energy is stored and then sold. The comparison between the two technologies is made in terms of Net Present Value (NPV) and Inner Rate of Return (IRR). In this analysis have been considered different scenarios for a period of 20 years. The variables are the energy price, which can increase or decrease during next years. The second variable is the battery price that probably

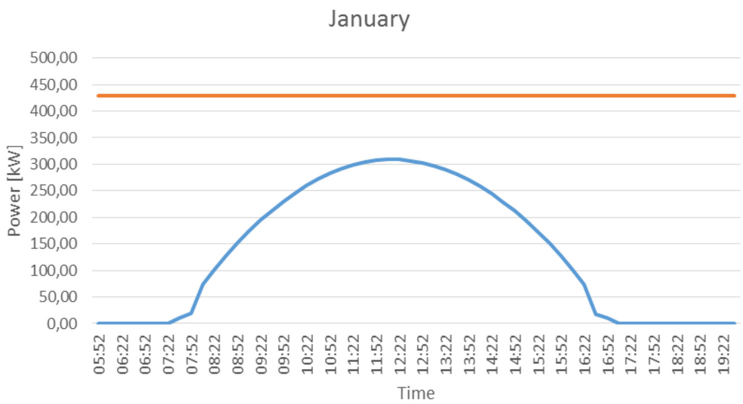


Figure 6.1: Power curtailment in January

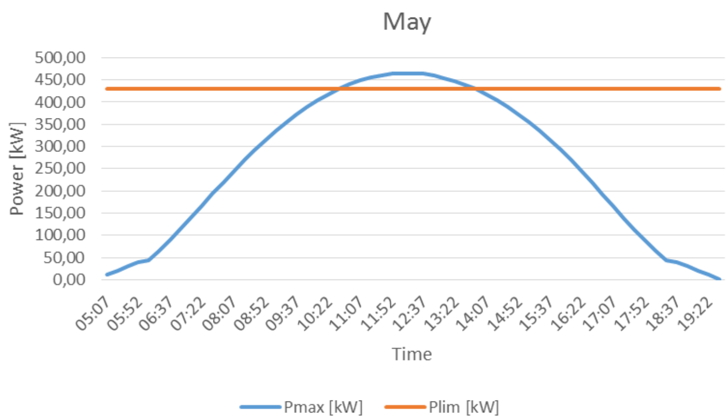


Figure 6.2: Power curtailment in May

will decrease in the next future. As it easy to understand, the power curtailment is more important during summer months, whereas in the wintry period the system works the most of the time at its MPP (Figure 6.1 Figure 6.2 Figure 6.3 Figure 6.4). Energy prices change following a positive and a negative trend, as described in Table 6.1. The base case price is referred to real data of September 2016, taken from GSE. The average price belongs to F1 period from 8 a.m. to 19 p.m. During these hours there is the highest price and generally the loads are greater.
Regarding the battery typology for the energy storage, the best solution is a Lithium-ion battery. As described in [47] this technology owns high efficiency, low self discharge and long cycle life. For instance, other kinds of batteries as lead-acid has a lower investment cost but higher Operation&Maintenance (O&M) costs [48]. The price of batteries also changes.

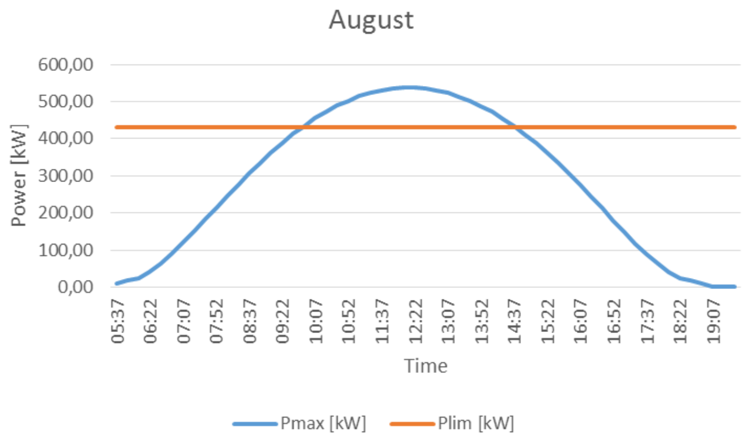


Figure 6.3: Power curtailment in August

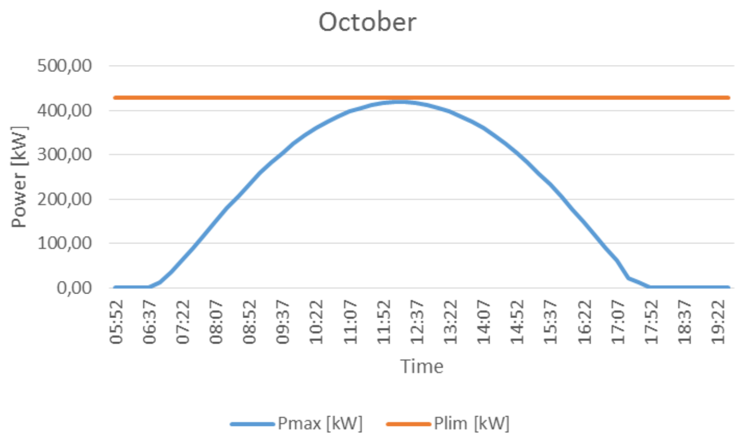


Figure 6.4: Power curtailment in October

There are six cases, starting from the base case. Herein, the most probable situation will be the reduction of prices during next years. A price increase is not considered in this dissertation (see Table 6.2).

The amount of stored energy is equal to the 20% of the curtailed energy. Table 6.3 describes the main characteristics of battery deployed for the economic analysis.

With this configuration and according to YINGLI SOLAR data sheet, the PV system produces and curtail the following values of energy described in Figure 6.5. The curtailed energy corresponds to the 2,93% of the maximum energy that the PV system is able to produce without power curtailment. With batteries the PV system is able to store the 35,3% of the curtailed energy. Whereas, the remaining 64,7% of energy is not stored.

Table 6.1: Prices of energy

	Base case	.2	.3	.4	.5	.6
(1) Positive trend [euro/MWh]	47,22	47,5	47,75	48	49,5	49,75
(2) Negative trend [euro/MWh]	47,22	47	46,75	46,25	45,75	45,5

Table 6.2: Prices of batteries

	Base case	.2	.3	.4	.5	.6
(4) Negative trend [euro/kWh]	690	600	550	500	400	300

Table 6.3: Battery characteristics

Li-Ion battery	
$V_{battery}[V]$	700
$Capacity[kAh]$	0,13
$Stored\ energy$	20%
η_{CS}	0,85
DOD	0,9

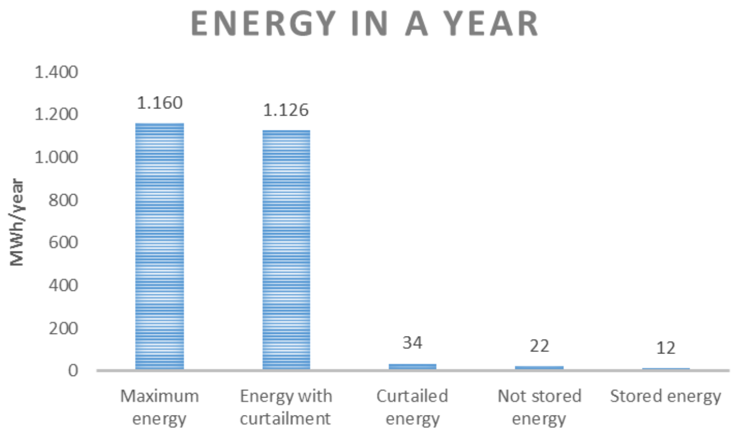


Figure 6.5: Values of energy in a year

From the results of different scenarios some conclusions can be drawn.

- The power curtailment extends the pay-back time of the PV plant. It is a disadvantage to consider, furthermore for an investor that needs relatively brief pay-back times;
- In this analysis the plant power is relatively low. The scale effect may reduce the pay-back time. Besides, eventual incentives connected with auxiliary services may increase the competitiveness of the power curtailment;
- In every configuration, with a energy price decrease or increase, the APC solution is better than the ESS technology. Besides, considering a probable decrease of PV module price during next years, the competitiveness of APC would have a further increase;
- In various cases with ESS, investments and O&M are always higher due to the installation of batteries. For the investors it is another aspect to consider when it is necessary to make an economic analysis;
- Comparing Figure 6.6 and Figure 6.7, it is possible to observe that NPV values are slightly lower for the case with ESS. After 20 years, in the APC case NPV values are always higher than 0, whereas in the second case NPV is always negative. In the ESS case investment costs are important. Besides, after about 10 years batteries have to be replaced. These factors considerably affect the NPV value. There are also maintenance costs for batteries that reduce the final gain. Focusing on the energy price variations, the APC case has increasing NPVs

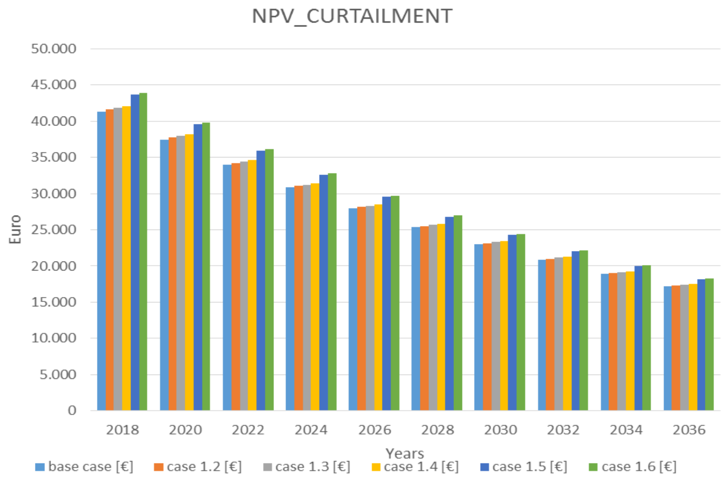


Figure 6.6: Energy price increase in case of only power curtailment

with higher energy prices. It means that power curtailment losses do not really affect the final net value. Conversely, with rising energy prices, the losses of not stored energy become more important compared to incomes of stored energy. This aspect affects substantially the NPV value;

- Comparing Figure 6.8 and Figure 6.9, it is confirmed what has been described previously. The APC technology is more sensitive to variations of energy prices. As the matter of fact, an hypothetical envelope curve, which puts together all the NPV values case per case, has an higher slope in the active power curtailment case. The PV system with active power curtailment and its competitiveness closely depend on the amount of energy that is able to sell;

- With fixed prices of energy and PV modules, supposing a battery price of 300 $euro/kWh$, then this technology may be more interesting and competitive (see Figure 6.10). It is not excluded that in the next future the APC with an energy storage system will be the most utilized technology in this field;

- The IRR values are not really high. These characteristics are partly due to the power curtailment and partly to the small size of the PV plant. The IRR values variate from 2 $\%$ to 4 $\%$ in the APC case. Whereas, IRR values are always negative in the ESS solution. Investment and maintenance costs are too high in the ESS case and the pay back time is higher than 20 years. Only in case of a battery prices

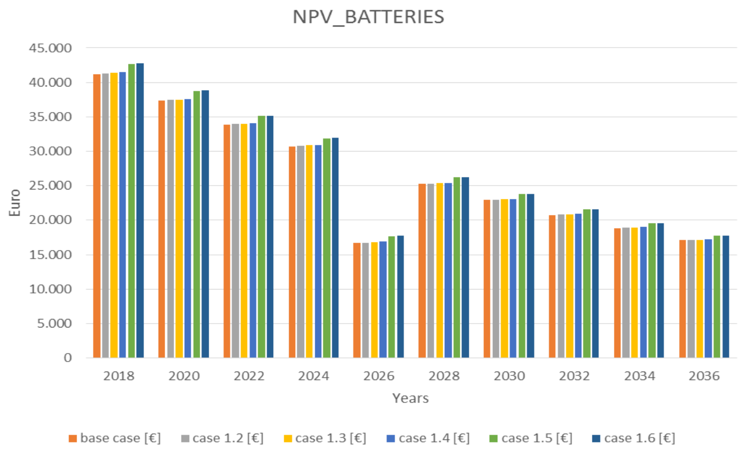


Figure 6.7: Energy price increase in case of power curtailment with batteries

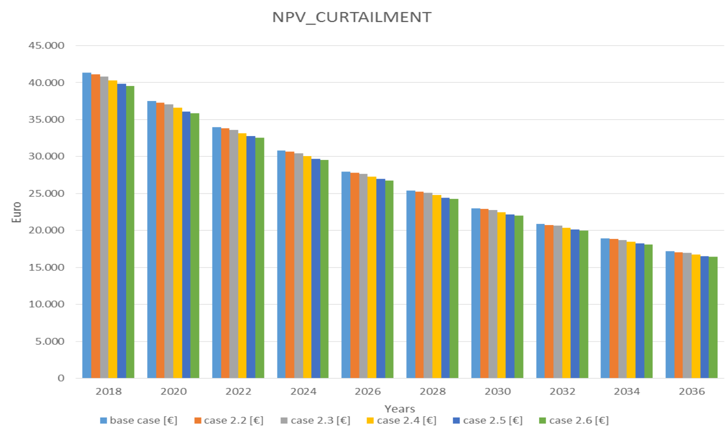


Figure 6.8: Energy price decrease in case of only power curtailment

reduction, this technology seems to be more attractive.

In this section Figure 6.11 presents different percentage of energy storage. Obviously increasing the percentage of storage, investment costs for batteries and O&M grows proportionally. Supposing to draw the envelope curve for the points of the stored energy, it is possible to observe that the slope is changing. Around the 70% of stored energy, the slope decreases. After this point could be less interesting to store further energy in batteries. Figure 6.11 is also interesting to know the percentages of stored and not stored energy with the PV system in this configuration.
The results of economic analysis have been presented, focusing on variable prices of energy and batteries. For this analysis two economic parameters

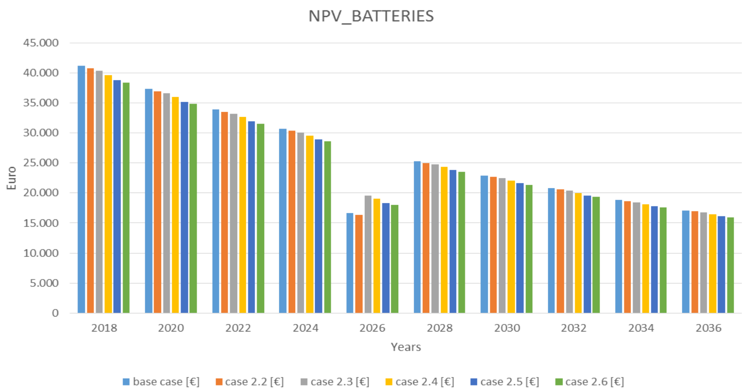


Figure 6.9: Energy price decrease in case of power curtailment with batteries

have been selected in order to describe the results. Besides, a graph with different percentage of storage has been described.

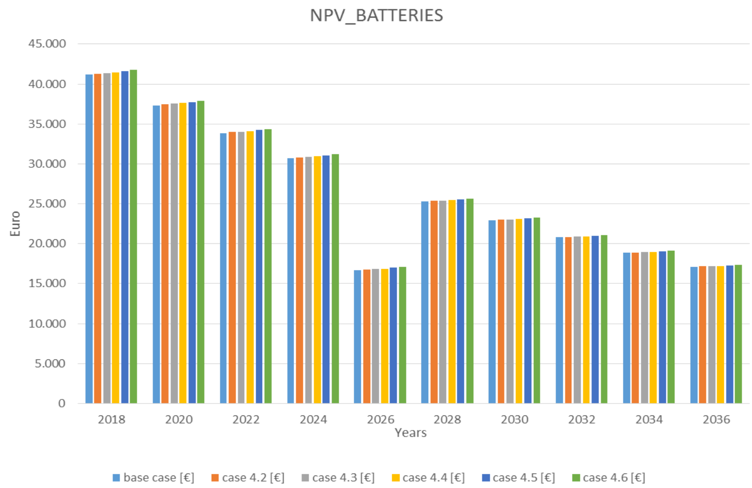


Figure 6.10: Battery price decrease in case of power curtailment with batteries

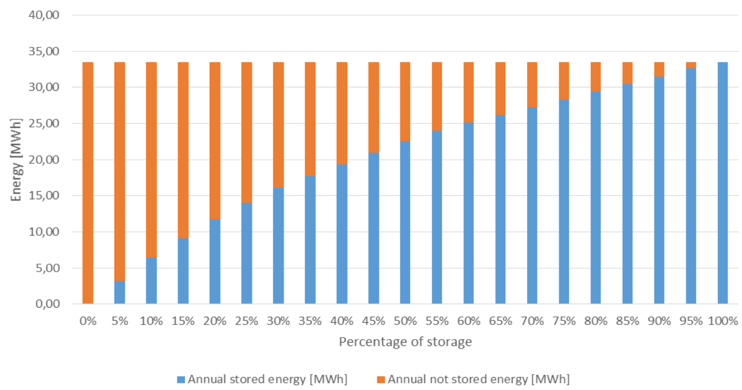


Figure 6.11: Percentage of stored energy

Chapter 7

Conclusions

This chapter reviews the project's objectives, defined in sections 1.2 and 1.4, and compares with the achievements of this work.

7.1 Review of objectives and achievements

At the beginning of the project different objectives have been set. The achievement of some objectives at the early stages of the project was crucial.
The required foundation knowledge gained in the first months, by reviewing the existing literature on grid code requirements, PV generator topologies, models and controls resulted extremely important. Without these foundations it would not have been possible to develop to DigSilent model.
After this work of literature review, other two months have been necessary to learn commands in DigSilent Power Factory software, to understand the model and to implement the algorithm. Finally, as insight, an economical study has been developed. During the writing work, the results from the simulation and the economical analysis have been discussed.
From these achievements some conclusions can be argued:

- The most utilized PV topology is the central one. This trend is connected with the diffusion of large-scale systems. Thanks to the LS-PVPPs, particularly the Pacific-Asiatic market, is knowing a boom never registered before. As the matter of fact, new leaders are leading the global context. With them other countries, such as India, are emerging and in the next future they will be a world power in this field. On the other side, Europe is experiencing a transition period, waiting for the end of the MIP and for more adequate policies in the large-scale PV market. The LS-PVPPs boom is due also due to their higher economic competitiveness compared to the distributed technology;

- The importance of grid codes in line with the development of PV systems is fundamental. For instance, China without indications that regulate the PV development is forced to curtail the PV power, limiting the growth in this field. New grid codes have been made in several countries. They give some indications to realize a right development of the LS-PVPPs when connected to the electrical grid. Generally, many standards still lack of specific requirements in this sense;

- One of the method to control active power in PV systems is using energy storage. For instance, Li-ion batteries are the best according to their performance characteristics. However, high costs and a limited cycle life make batteries less attractive. Other technologies are also interesting as thermal resistors, flywheels, ultra-capacitors and CAES. They did not have the same diffusion as batteries, anyway there are various practical examples. Instead, the pumped hydro case is largely utilized. It allows to take advantage of a natural resource without any environmental impact. Its only limit is connected with the geographical area that not always allows to realize this kind of installations;

- The solution without ESS requires a better understanding of the PV generator's operation. The information for this field is still missing as PV generators has always supplied power at the maximum possible. Most of information comes from wind installations. There are different methods available, each one with strengths and weaknesses. The importance of meteorological forecasts is emerging in order to improve the management of the power under variations of radiation and temperature, as described in the hybrid forecasting model. Another statement is the de-loaded mode, under the MPPT. The power peaks are smoothed and the active power reserve is used to compensate the oscillations of the PV system. The final objective is to reach a constant active power output. Variable step-sizes are also interesting to reach faster the operating point, as described in the VSIC method;

- There are different strategies to realize a MPPT algorithm. Some of the most famous are the P&O, the hill climbing and the fuzzy logic controller. Some techniques try to solve typical issues as convergence speed and the algorithm complexity. Methods can also be distinguished depending on the measured parameters. The feasibility simplicity of some algorithm, such as the P&O, allowed their faster diffusion. As the matter of fact, other methods, such as the neural network or the pilot cell, are too complex or require an high number of sensors, hence they have not been developed;

- Until now the MPPT algorithm has been thought to reach always the maximum power operating conditions. According to these characteristics the PV inverter control has been developed to comply electrical standards to support the costumer without providing grid support functions. Due to the LS-PVPPs market trend, PV inverters has to improve their performances according to new grid codes requirements. The proposed algorithm of this dissertation may be the initial foundation from which starting to comply the grid code objectives;

- In this thesis, the control of active power at a given reference power has been developed without energy storage. The control uses the same concept of the P&O algorithm, but what changes is the reference power. The system response respects the conditions given at high solar irradiance but in low irradiance the system only can supply the maximum energy possible. In this case, the power reference has kept constant during the day;

- The economic analysis points out some important aspects about the technology chosen in this dissertation. First of all, the power curtailment extends the return time of the investment. At the same time renouncing to an higher energy production, the electrical grid takes advantage of a greater stability. Generally, the economic feasibility of the only APC system is higher than the ESS solution. As explained, the ESS technology is expensive, furthermore for this kind of applications;

- An advantage of the ESS is the lower dependence on energy prices. Whereas, the convenience of the only APC solution is more variable, without having the possibility to store energy. Anyway, the APC solution allows to reach a constant power output without adding extra equipments. Besides, a probable reduction of PV price will increase the competitiveness of this application. In the same way, the price decrease of batteries in the next future will make this technology more attractive for investors.

However, both solutions still need to be optimized to accomplish with the grid code requirements that has been defined. Providing ancillary services, in the next future PV systems will be able to improve the grid stability with an active role.

7.2 Future work

Despite building a successful model that met all the objectives, as the student's knowledge in the field and design skills improved, the model was found to be susceptible of further improvements.

- Test the control in a LS-PVPP with several number of PV generators;
- Optimize the value of the reference power during the day;
- Develop the ramp rate and power reserves control for a complete active power management;

Appendix 1

The DIgSILENT Simulation Language (DSL) allows to realize control models and other components or routines of an electrical power system. The DSL is implemented with a special syntax for the model formulation. The DSL model is structured in the following hierarchical way: DSL block definition, built-in models and common models, and composite models. This hierarchical order is essential to generate a power system capable of running inside the time domain simulation.
The composite model is an interface used to manage blocks connected with machines or systems. Hence, it is composed by common model, measuring devices and the network elements requiring control. Generally, the common model includes general models with transfer functions and control system equations to be implemented. Transfer functions and control systems represent the block diagram.
The DSL FACTS is an implementation methodology for devices with four stages:

1. DSL programming: the composite frame with the interactions between all the objects has to be depicted in a block-frame diagram page. The necessary controllers, one per each page, have to be implemented in block-frame diagram pages;

2. Model initialization: this is a fundamental operation to make in order to have the correct link between the controllers and the grid;

3. Linking the outputs of FACTS controllers to physical grid objects: the mathematical expressions, which relate the physical magnitudes implemented in the system and are regulated by the controllers, are determined;

4. Interfacing controllers and active grid objects: the last step consists in the proper connection between the programmed controllers and the active grid. For this reason the controllers are masked as common models and the composite frame as a composite model.

General DSL Syntax

- **Line length:** the maximal line length is 80 characters. Longer lines have to be broken by using the & sign in the first column of the continuing line. Line breaking cannot be used within names or strings.
- **Case sensitivity:** All keywords, names, functions, variables, models, macros, etc. are case sensitive.
- **Blanks:** All blanks are removed when the DSL code is processed. Exception: blanks in strings are kept.
- **Comments:** The ! sign causes the remaining line to be interpreted as a comment. Comments are removed when the DSL code is processed.

DSL Variables

A DSL may use five different types of variables:

1. Output signals: Output signal variables are available as input signals to more complex DSL models;
2. Input signal: Input variables may originate from other DSL models or from power system elements. In the latter case, currents and voltages, as well as any other signal available in the analyzed power system, become available to the DSL model;
3. State variable: State variables are time-dependent signal generated and used within the DSL model itself;
4. Parameters: Parameters are 'read only' numbers which are set to alter the behavior of the DSL model;
5. Internal variables: Internal variables are defined and used in the DSL model to ease the construction of a set of DSL equations.

DSL Structure

DSL models are constructed of three parts:

1. The interface part: states the model name, title, classification and variable set. This part is set in the first page of the block diagram dialogue;

2. Definition code: in the equation part of the DSL model is used to define parameter properties and initial conditions;

3. Equation code: all equations necessary to build up the simulation models are included. The set of equations defines a set of coupled differential equations which describe the transfer functions between the input and output signals. These transfer functions may range from simple linear, single-input single-output functions, to highly complex non-linear, non-continuous, multi-input, multi-output functions.

Acknoledgements

Voglio ringraziare tutte le persone che mi hanno sostenuto e aiutato nello sviluppo di questo progetto sia da casa che a Barcellona dove ho avuto la possibilità di conoscere persone fantastiche.
I want to thank all the people that supported and helped me in the development of this project both from home and in Barcelona where I had the possibility to meet beautiful people.

Prima di tutto vorrei ringraziare il professor Fabio Bignucolo, relatore della tesi. Mi ha permesso di svolgere questa esperienza, fornendomi consigli utili per affrontare questo progetto.
First of all I would like to thank Prof. Fabio Bignucolo, the thesis supervisor. He allowed me to have this experience, giving me helpful advices to face this project.

Ringrazio il professor Oriol Gomis Bellmunt e Ana Cabrera Tobar che mi hanno seguito in ogni passo della mia esperienza. Vi ringrazio per avermi fatto sentire come se fossi a casa e per l'enorme disponibilità che avete dimostrato nei miei confronti.
I thank Prof. Oriol Gomis Bellmunt and Doctor Ana Cabrera Tobar that followed me in every step of this experience. I thank you to let me feel like I was at home and for your great availability.

Ringrazio tutto il gruppo del Citcea che mi ha accolto.
I thank all the Citcea team that welcomed me.

Vorrei ringraziare tutta la mia famiglia: Papà, Mamma e mio fratello Mattia. Mi avete sempre sostenuto in questo lungo percorso senza mai dubitare delle mie capacità. Vi ringrazio per le possibilità che mi avete dato e per la persona che mi avete fatto diventare.
I would like to thank all my family: my dad, my mom and my brother Mattia. You always supported me in this large journey without never doubting about my abilities.

Ringrazio Laura, quasi una sorella per me. Grazie per essere sempre stata al mio fianco nei momenti felici e in quelli meno felici. Anche grazie a te ho potuto raggiungere questo traguardo.
I thank Laura, almost a sister for me. Thanks for being always at my side during happy and unhappy moments. Also thanks to you I could reach this goal.

Un grazie alla mia amica e compagna di studi, Irene. Le risate, le litigate e i miliardi di ore in cui siamo stati assieme sono indimenticabili. Ho trovato un grande sostegno in te e una amicizia insostituibile.
Thanks to my friend and companion of studies, Irene. Laughs, quarrels and billions of hours that we spent together are unforgettable. I found a great support from you and your friendship is irreplaceable.

Grazie a Giuliano e Simone. Siete sempre stati presenti per me ed è come se vi conoscessi da una vita. La festa con voi non manca mai!
Thanks to Giuliano and Simone. You have always been there for me and it is like I knew you my whole life. The party with you is never missed!

Grazie ai coinquilini, a tutto il tempo che abbiamo condiviso insieme. Siete stati come una seconda famiglia.
Thank to my flatmates and to all the time that we shared together. You have been as a second family.

Un grazie a tutti i ragazzi ("fioi"), a tutte le splendide amicizie che ho avuto la fortuna di incontrare in questo cammino.
Thanks to all of you guys, to all the beautiful friendships that I had the pleasure to meet in this journey.

Ringrazio Padova, le serate padovane, le cene e tutte le belle esperienze che porto sempre con me.
Thanks to Padova, Padova's nights, dinners and all beautiful experiences that I always bring with me.

Ringrazio Barcellona. La sua vitalità è unica. La speranza è quella di tornarci presto!
Thanks to Barcelona. Its vitality is unique. I hope to come back soon!

Infine vorrei ringraziare mio Zio Michele. Manchi veramente tanto, non passa un giorno senza che io ti pensi. Se sono diventato ciò che sono oggi lo devo anche a te! Grazie!

Finally, I would like to thank my uncle Michele. I miss you so much, there is not a day without thinking about you. If I became who I am today, it is owed also to you! Thank you!

Bibliography

[1] A. Cabrera-Tobar, E. Bullich-Massagué, M. Aragüés-Peñalba, and O. Gomis-Bellmunt, "Topologies for large scale photovoltaic power plants," *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 309–319, 2016.

[2] H. Abdel-Gawad and V. K. Sood, "Overview of connection topologies for grid-connected PV systems," *Canadian Conference on Electrical and Computer Engineering*, pp. 1–8, 2014.

[3] A. Cabrera-Tobar, E. Bullich-Massagué, M. Aragüés-Peñalba, and O. Gomis-Bellmunt, "Review of advanced grid requirements for the integration of large scale photovoltaic power plants in the transmission system," *Renewable and Sustainable Energy Reviews*, vol. 62, pp. 971–987, 2016.

[4] (IEA) International Energy Agency, *Trends 2016 in Photovoltaic Applications. Survey Report of Selected IEA Countries between 1992 and 2015*. 2016.

[5] EPIA, "Global Market Outlook for Solar Power / 2016 - 2020," no. February, p. 40, 2016.

[6] International Energy Agency, "Next Generation Wind and Solar Power," *International Energy Agency books online*, 2016.

[7] D. L. Fox and H. E. Jeffries, "Air pollution," *Analytical Chemistry*, vol. 55, pp. 233R–245R, apr 1983.

[8] W. E. Commission, P. V. S. Report, and F. E. Technologies, *PV Status Report 2016 PV Status Report 2016*. No. October, 2016.

[9] IRENA, *Renewable Energy Market Analysis: Latin America*. 2016.

[10] E. Summary, "U . S . SOLAR MARKET INSIGHT Executive Summary About the Report," no. December, 2014.

[11] "U.S. Solar Market Insight: 2016 Year in Review Executive Summary," p. 20, 2017.

[12] O. Y. D. E. Calidad, S. D. E. Centrales, and S. Y. Centrales, "Código de redes fotovoltaico," no. 8774, pp. 1–30, 2013.

[13] NERSA, "Grid Connection Code for Renewable Power," vol. 9, no. July, p. 122, 2016.

[14] H. C. D. A. Markiewicz and A. W. U. o. T. Klajn, "Voltage Disturbances," *Power quality Application Guide*, vol. 5.4.2, pp. 4–11, 2004.

[15] R. Teodorescu, M. Liserre, and P. Rodriguez, "Grid Converters for Photovoltaic and Wind Power Systems Copyright Wiley 2011 Chapter 3 Chapter Grid Requirements for PV International Regulations," 2011.

[16] S. Committee, "IEEE Standards," *Technology*, no. March, 2004.

[17] D. Version and E. Technology, "Grid Support in Large scale PV Power Plants using Active Power Reserves By," 2014.

[18] "Title : Comparison of Control strategies for PV power ramp-rate limitation using energy storage system Authors : Íñigo de la Parra , Javier Marcos , Mikel Muñoz and Miguel García,"

[19] M. Datta, T. Senjyu, A. Yona, T. Funabashi, and Chul-Hwan Kim, "A Frequency-Control Approach by Photovoltaic Generator in a PV–Diesel Hybrid Power System," *IEEE Transactions on Energy Conversion*, vol. 26, pp. 559–571, jun 2011.

[20] S. Shivashankar, S. Mekhilef, H. Mokhlis, and M. Karimi, "Mitigating methods of power fluctuation of photovoltaic (PV) sources," *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 1170–1184, jun 2016.

[21] R. Van Haaren, M. Morjaria, and V. Fthenakis, "Utility scale PV plant variability and energy storage for ramp rate control," pp. 973–979, 2013.

[22] D. I. Doukas, K. Papastergiou, P. Bakas, and A. Marinopoulos, "Energy storage sizing for large scale PV power plants base-load operation - Comparative study & results," *Conference Record of the IEEE Photovoltaic Specialists Conference*, pp. 570–574, 2012.

[23] B. Dunn, H. Kamath, and J.-M. Tarascon, "Electrical Energy Storage for the Grid: A Battery of Choices," *Science*, vol. 334, no. 6058, pp. 928–935, 2011.

[24] H. Ul Banna, A. Luna, P. Rodriguez, A. Cabrera, H. Ghorbani, and S. Ying, "Performance analysis of conventional PSS and fuzzy controller for damping power system oscillations," *3rd International Conference on Renewable Energy Research and Applications, ICRERA 2014*, pp. 229–234, 2014.

[25] C. Rahmann, V. Vittal, J. Ascui, and J. Haas, "Mitigation Control Against Partial Shading Effects in Large-Scale PV Power Plants," vol. 7, no. 1, pp. 173–180, 2016.

[26] A. Ahmed, L. Ran, S. Moon, and J. H. Park, "A fast PV power tracking control algorithm with reduced power mode," *IEEE Transactions on Energy Conversion*, vol. 28, no. 3, pp. 565–575, 2013.

[27] Y. Yang, F. Blaabjerg, and H. Wang, "Constant power generation of photovoltaic systems considering the distributed grid capacity," *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, pp. 379–385, 2014.

[28] S. Ghosh, S. Rahman, and M. Pipattanasomporn, "Distribution Voltage Regulation through Active Power Curtailment with PV Inverters and Solar Generation Forecasts," *IEEE Transactions on Sustainable Energy*, vol. 3029, no. c, pp. 1–1, 2016.

[29] S. Chalise, H. R. Atia, B. Poudel, and R. Tonkoski, "Impact of Active Power Curtailment of Wind Turbines Connected to Residential Feeders for Overvoltage Prevention," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 2, pp. 471–479, 2016.

[30] D. Version and E. Technology, "Grid Support in Large scale PV Power Plants using Active Power Reserves By," 2014.

[31] E. Muljadi, M. Singh, and V. Gevorgian, "PSCAD Modules Representing PV Generator PSCAD Modules Representing PV Generator," no. August, 2013.

[32] T. Markvart, *Solar electricity*. Wiley, 2000.

[33] A. Kashyap, "Small-signal Stability Analysis and Power System Stabilizer Design for Grid-Connected Photovoltaic Generation System

Affairs in partial fulfillment of the requirements for the degree of Master of Applied Science," 2014.

[34] A. Egea-Alvarez, A. Junyent-Ferre, and O. Gomis Bellmunt, "Active and reactive power control of grid connected distributed generation systems," pp. 1–35, 2000.

[35] T. Markvart and L. Castañer, "Practical Handbook of Photovoltaics: Fundamentals and Applications: Fundamentals and Applications," p. 1015, 2003.

[36] A. Cabrera-tobar, "Dynamic response of a PV generator considering its capabilities curves," no. 1, pp. 1–7, 2015.

[37] L. Hassaine, "Implementación de un Control Digital de Potencia Activa y Reactiva para Inversores . Aplicación a Sistemas Fotovoltaicos Conectados a Red," pp. 1–288, 2010.

[38] R. Teodorescu, M. Liserre, and P. Rodríguez, *GRID CONVERTERS FOR PHOTOVOLTAIC AND WIND POWER SYSTEMS Grid Converters for Photovoltaic and Wind Power Systems GRID CONVERTERS FOR PHOTOVOLTAIC AND WIND POWER SYSTEMS*. 2010.

[39] L. Hassaine, E. Olias, J. Quintero, and V. Salas, "Overview of power inverter topologies and control structures for grid connected photovoltaic systems," *Renewable and Sustainable Energy Reviews*, vol. 30, pp. 796–807, 2014.

[40] D. L. M, J. D. C, and C. G. L, "Pulse Width Modulation (PWM) aplicadas a inversores trifásicos," pp. 145–176.

[41] M. A. Eltawil and Z. Zhao, "MPPT techniques for photovoltaic applications," *Renewable and Sustainable Energy Reviews*, vol. 25, pp. 793–813, 2013.

[42] N. S. D'Souza, L. A. C. Lopes, and X. J. Liu, "An intelligent maximum power point tracker using peak current control," *PESC Record - IEEE Annual Power Electronics Specialists Conference*, vol. 2005, pp. 172–177, 2005.

[43] D. P. Hohm and M. E. Ropp, "Comparative study of maximum power point tracking algorithms," *Progress in Photovoltaics: Research and Applications*, vol. 11, no. 1, pp. 47–62, 2003.

[44] I. Houssamo, F. Locment, and M. Sechilariu, "Maximum power tracking for photovoltaic power system: Development and experimental comparison of two algorithms," *Renewable Energy*, vol. 35, no. 10, pp. 2381–2387, 2010.

[45] W. W. W. Wu, N. Pongratananukul, W. Q. W. Qiu, K. Rustom, T. Kasparis, and I. Batarseh, "DSP-based multiple peak power tracking for expandable power system," *Eighteenth Annual IEEE Applied Power Electronics Conference and Exposition, 2003. APEC '03.*, vol. 1, no. C, pp. 525–530, 2003.

[46] S. Yuvarajan and S. X. S. Xu, "Photo-voltaic power converter with a simple maximum-power-point-tracker," *Proceedings of the 2003 International Symposium on Circuits and Systems, 2003. ISCAS '03.*, vol. 3, pp. 399–402, 2003.

[47] F. Bignucolo, R. Caldon, M. Coppo, F. Pasut, and M. Pettinà, "Integration of Lithium-Ion Battery Storage Systems in Hydroelectric Plants for Supplying Primary Control Reserve," *Energies*, vol. 10, no. 1, pp. 1–22, 2017.

[48] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Applied Energy*, vol. 137, pp. 511–536, 2015.