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**Modelling of utility-scale PV systems
and effects of solar irradiance variations
on voltage levels**

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This work is dedicated to my mother, Elvia, and my sisters, Marggy and Majo.

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“The good life is one inspired by love and guided by knowledge.”

Bertrand Russell

Resumo

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Este trabalho apresenta um modelo dinâmico de sistemas fotovoltaicos de grande escala. O modelo é baseado em uma topologia de conversor centralizado, que usa um conversor de fonte de tensão (VSC) para facilitar a troca de energia entre os geradores fotovoltaicos e a rede elétrica. O sistema de controle relacionado regula a energia ativa e reativa injetada pelo sistema fotovoltaico, com base em uma estratégia de controle de corrente. Além disso, o modelo inclui um sistema de rastreamento de ponto de potência máxima (MPPT), implementado com o método da condutância incremental. O dimensionamento do modelo é apresentado, bem como vários casos de simulação para validar o seu desempenho. Posteriormente, o modelo foi utilizado para analisar o efeito das variações na radiação solar sobre uma rede de teste com uma elevada penetração de geração fotovoltaica. Os resultados mostraram que sem uma adequada compensação de energia reativa, as variações na radiação solar podem causar flutuações de tensão fora dos limites permitidos. Assim, a fim de mitigar estas flutuações, estratégias de controle local foram implementadas para permitir a troca de potência reativa entre os sistemas fotovoltaicos e a rede. As simulações mostraram que as estratégias propostas podem mitigar as flutuações de tensão no ponto de acoplamento comum, melhorando a regulação de tensão na rede.

Palavras-chave: Sistemas fotovoltaicos de grande escala. Perturbações na irradiação solar. Flutuações de tensão. Controle de potência reativa.

Abstract

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This work presents a dynamic model for utility-scale PV systems. The model is based on a centralized converter topology, which uses a voltage-sourced converter (VSC) to facilitate the exchange of energy between PV generators and the utility grid. The related control system regulates active and reactive power injected by the PV system, based on a current control strategy. Moreover, the model includes a Maximum Power Point Tracking (MPPT) scheme, implemented with the incremental conductance method. Dimensioning of the model is presented as well as simulation cases to validate its performance. Subsequently, the model was used to analyze the effect of variations in solar radiation on a test network with high penetration of photovoltaic generation. Results showed that without proper compensation of reactive power, variations in solar radiation can cause voltage fluctuations outside allowable limits. Thus, in order to mitigate these fluctuations, local control strategies were implemented to allow the exchange of reactive power between the solar farm and the utility grid. Simulations showed that the proposed strategies can mitigate voltage fluctuations at the point of common coupling, improving voltage regulation in the network.

Keywords: Utility-scale PV systems. Perturbations in solar irradiance. Voltage fluctuations. Reactive power control.

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Acronyms

ANEEL *Agência Nacional de Energia Elétrica*

AC *Alternating Current*

DC *Direct Current*

EPE *Empresa de Pesquisa Energética*

FiTs *Feed-in Tariffs*

IEA *International Energy Agency*

IRENA *The International Renewable Energy Agency*

IEI *International Energy Initiative*

IGBT *Insulated-Gate Bipolar Transistor*

MME *Ministério de Minas e Energia*

MPP *Maximum Power Point*

MPPT *Maximum Power Point Tracker*

OLTC *On-Load Tap-Changing*

PLL *Phase-Locked Loop*

PWM *Pulse-Width Modulation*

PCC *Point of Common Coupling*

PV *Photovoltaic Generation*

PRODIST *Procedimentos de Distribuição de Energia Elétrica no Sistema Elétrico Nacional*

SVC *Static Var Compensator*

STATCOM *Synchronous Static Compensator*

VSC *Voltage-Sourced Converter*

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Introduction

Renewable energy technologies have emerged as a response to challenges in climate change. Among these challenges are the need to reduce environmental impacts caused by fossil fuels, mainly greenhouse gases; the increasing electricity consumption due to population and industrial growth; and the substitution of finite sources of electricity.

Within the main renewable technologies, *Photovoltaic Generation* (PV) gained notoriety in the last decade, driven mainly by political incentives that accelerated its growth. Benefits of solar PV include the use of the sun as energy source and the generation of electricity without greenhouse gas emissions. With such an abundant source, solar PV can be used in remote geographic locations as well as in urban areas, making it an attractive technology for both off-grid and grid-tied facilities. On the other hand, high installation costs and the intermittency and unpredictability of solar radiation are major disadvantages of photovoltaic generation. Recently, researchers have been focused on these issues in order to make solar PV become a source of electrical energy on a large scale basis.

This master thesis is focused on the area of research that examines the interaction between photovoltaic generation and power systems regarding voltage fluctuations, as well as PV system modelling.

1.1 Solar PV in the World

During the last decade, solar PV global installed capacity has increased exponentially driven mainly by Europe, as shown in Figure 1. By the end of 2014, the global cumulative capacity of solar power was approximately 178 GW with forecasts between 396 GW and 540 GW by 2019 (REKINGER et al., 2015). Moreover, Germany was the country with the largest installed capacity, 38 GW, which represents 22% of the global cumulative, followed by China (16%), Japan (13%), Italy (11%), and USA (10%) (IEA, 2015a).

The trend of growth between regions has changed in the last years. Since 2011, the drop in the number of new installations in Germany (from 7.48 GW in 2011 to 1.9 GW in 2014) and Italy (from 9.28 GW in 2011 to 0.4 GW in 2014) has affected significantly the

Figure 1 – Evolution of PV global cumulative capacity 2000-2014.

APAC: Asia Pacific; MEA: Middle East and Africa; RoW: Rest of the World.

Source: Rekinger et al. (2015)

European results (REKINGER et al., 2015). Nonetheless, the rapid growth in China, APAC and the Americas allowed the exponential global trend to continue (Figure 1). According to IEA (2015a) and Fraunhofer ISE (2015), the decline in the number of new facilities in Europe is a direct consequence of the reduction in *Feed-in Tariffs* (FiTs)¹. In this regard, others authors refer to FiTs as a key factor for the deployment of solar PV in the world (NREL, 2010; IEA, 2015b). In the coming years, the Asian market will lead the growth, with China on the top reaching 114 GW by 2019 (REKINGER et al., 2015).

Another key element in the accelerated growth of PV is the reduction in installation costs. As reported by IRENA (2015), from 2010 to 2014 the total installed costs of utility-scale² PV systems have fallen from 29% to 65%, depending on the world region. In this context, the USA launched in 2011 *The SunShot Initiative*, a plan intended to reduce costs in PV technology with a target of 1 USD/W by 2020 for unsubsidized utility-scale PV systems. It is attributed to this plan a considerable share in the growth of photovoltaics in the USA that went from 1.2 GW in 2008 to 19 GW in 2014 (U.S. DEPARTMENT OF ENERGY, 2014; REKINGER et al., 2015). Figure 2 shows the behavior of averaged installed costs of solar PV from 2009 to 2014.

In Brazil, the development of photovoltaics has not followed the international trend. According to the *Agência Nacional de Energia Elétrica* (ANEEL), by February 2016 the

¹Feed-in Tariffs (FiTs): Political incentives implemented to accelerate the growth of renewable technologies characterised by the offer of long-term contracts to renewable energy producers.

²Utility-scale refers to solar photovoltaic plants with an output capacity greater than 4 MVA and connected to the grid.

Figure 2 – Estimated global average installed costs for utility-scale and residential solar PV systems and the range of country averages from 2009 to 2014.

Source: IRENA (2015)

energy matrix of the country had around 26.9 MW of solar PV in operation (ANEEL, 2016). The small penetration of solar PV in Brazil is attributed to the fact that most part of the electricity generation in the country comes from renewable sources. As stated in the *Brazilian Energy Balance 2015*, renewable technologies represented the 74.5% of the total domestic supply of electricity in 2014, with 65.2% coming from hydropower (MME, 2015). In this scenario, Brazil has not had to make major changes in its energy system to satisfy environmental needs as others countries.

However, there are signs of growth in the market of photovoltaics in Brazil. This has been determined by the international scenario of falling prices, and severe droughts that have affected the electricity generation in last years highlighting the importance of the diversification in the energy matrix.

The first sign is the ANEEL Normative Resolutions n°481 and n°482 of 2012. These resolutions are intended to stablish the general conditions for the access of distributed microgeneration and minigeneration to power distribution systems and to provide discounts for solar generation projects (ANEEL, 2012a; ANEEL, 2012b).

Secondly, the largest photovoltaic plant in Brazil was connected to the grid in 2014. Located in Tubarão, Santa Catarina, *Cidade Azul* (3 MVA) is intended to serve for research purposes having three different PV cell technologies (amorphous silicon, CIGS³ and multicrystalline silicon).

Finally, it was announce in November 2014 by the *Empresa de Pesquisa Energética*

³CIGS: Copper Indium Gallium Selenide.

(EPE) the construction of 31 solar farms with a total capacity of 889.6 MW. These projects will be mainly concentrated in the states of Bahia (14) and São Paulo (9). Furthermore, 29 of them are projected with a capacity of 30 MVA (EPE, 2015).

1.2 Motivation of the Study

A fact that accompanies the substantial increase in the number of PV systems around the world is that solar plants are being connected to the existing grids, which were not originally designed to have this generation. Thus, as a result of a large penetration of solar PV different problems may arise in the power systems. In this regard, as stated by Appen et al. (2013), the three main problems can be classified as:

1. *Reverse power flows in the distribution system*

These flows may appear when PV generation exceeds the local load of a distribution network.

2. *Additional power flows in the transmission system*

They may occur as a consequence of reverse power flows in the distribution system.

3. *Grid stability problems*

Issues that are related to the behaviour of voltage and frequency in the presence of high PV penetration.

One example of these issues is the so-called "50.2 Hz risk". It was perceived on November 4, 2006, when an unscheduled event caused the isolation of some areas of the German power system. At that time in Germany, PV systems were required to have a fixed cut-off frequency of 50.2 Hz. Besides, some of the isolated regions had high penetrations of photovoltaic generation with respect to local loads. Then, as a result of the mentioned event, frequency values varied from region to region -being larger in the areas with high penetration of photovoltaics- and, in some cases, exceed the cut-off frequency. This, in turn, caused the loss of PV capacity (APPEN et al., 2013).

To avoid this problem, some measures were adopted by the German Government. Among these measures is the requirement for the power inverters associated to PV systems to reduce their output during over-frequency periods or to avoid abrupt shutdowns (DELTA, 2014).

In Brazil, although it has not been reached a high penetration of solar power, some works have been developed in this regard. As an example, J.A. Paludo (2014) discussed some impacts of high penetration of distributed PV in the steady-state condition. This research found some effects such as voltage rises at the connection points of the PV systems to the grid, which may be detrimental to network's voltage regulation.

These examples provide a contextualization of the problems that emerge with high penetrations of photovoltaics. They show the importance of analysing solutions that have already been implemented in other countries, and research in this field based on the growth that is projected in Brazil for the coming years.

1.3 Objectives

As previously discussed, there are ongoing projects of utility-scale PV systems intended to expand photovoltaic capacity in Brazil. This brings the need to understand the impacts of connecting large amounts of photovoltaic energy to the grid. Moreover, it is not easy to find models of solar farms with rated powers in the megawatt order in commercial software programs. Thus, based on the above, the objectives of this work are:

1. *To implement a dynamic model of an utility-scale PV system.*

A solar farm was modeled with a capacity of 30 MWp in correspondence with the nominal power of ongoing projects in Brazil. The model was implemented based on works found in the literature.

2. *To analyse the effects of variations in solar radiation on voltage levels.*

Among the various analyzes that can be made of electrical systems with high penetration of photovoltaic generation, this work focused on variations of solar radiation, using the implemented model of a solar farm. This analysis addressed numerals 1 and 3 of Section 1.2.

3. *To study alternatives to mitigate the negative effects of variations in solar radiation on voltage levels.*

The alternatives considered are local control strategies that regulate the reactive power provided by the solar farm to the grid.

1.4 Overview of the Dissertation

This dissertation consists of five chapters. Chapter 2 describes the model of the photovoltaic system. It discusses some characteristics of photovoltaic generation, the topology of the model, and describes in detail its components. Chapter 3 discusses the dimensioning and testing of the photovoltaic system. It presents in detail the considerations taken into account to implement the system. Sizing of components, selection of control compensators, and simulation software are discussed. The chapter ends presenting the results of several simulation cases carried out to validate the performance of the model. In Chapter 4 is discussed the effect of variations in solar irradiance on voltage levels in a test grid with high penetration of photovoltaic generation. For this purpose, a solar farm of 30

MWp based on the model presented in chapters 2 and 3 was implemented. Moreover, the chapter presents an analysis of voltage increases caused by reverse power flows appearing during peak hours of photovoltaic generation. Furthermore, local control strategies that enable photovoltaic systems to provide reactive power support were implemented in order to mitigate the negative effects of solar irradiance variations on voltage levels. Chapter 5 presents the conclusions of the work and describes topics for future work.

PV System Modelling

This chapter describes the PV system model implemented in this work. The model is based on Yazdani et al. (2011), which was chosen for three reasons. First, because it is a collection of works carried out by its authors. Second, because there are examples of implementation of this work in the literature (MAHMOOD; VANFRETTI; HOOSHYAR, 2014). And third, because it was done by an IEEE Task Force¹, giving relevance to the work. The general diagram of the model is illustrated in Figure 3.

Figure 3 – Diagram of a single-stage PV system.

Source: Author

The system of Figure 3 converts solar radiation into electricity in the form of DC current by means of a *PV generator*. This electricity is then converted into AC three-phase current through a *Voltage-Sourced Converter* (VSC). The model of Figure 3 is referred as *single-stage PV system* (also called *centralized-converter topology*) because it has just one stage of electricity conversion -from DC to AC- that allows the transfer of active power from the PV generator to the grid. Moreover, the system is connected to

¹It refers to the IEEE Task Force on Modelling and Analysis of Electronically-Coupled Distributed Resources.

the utility grid at the *Point of Common Coupling* (PCC). All components of the model are described in the following sections.

2.1 PV Generator

Photovoltaic cells (PV cells) are the fundamental component of PV systems since they convert solar radiation into electricity. A *PV generator* is composed by these cells, and depending on their amount and topology several characteristics of the system are established (e.g. generated power or DC-voltage level). The equivalent circuit of a PV cell is shown in Figure 4.

Figure 4 – Single-diode equivalent circuit of a PV cell.

Source: Author

The circuit is composed by the current source I_g (modelling the electric current generated by the photovoltaic effect), a diode (modelling the p-n junction of the semiconductor materials of the PV cell), the resistor R_p (modelling the leakage currents of the p-n junction), and the resistor R_s (modelling the internal resistance of the cell). The equation that describes this circuit is obtained from Kirchhoff's law as follows:

$$\begin{aligned}
 I_{pv} &= I_i - I_p \\
 I_{pv} &= I_g - I_d - I_p \\
 I_{pv} &= I_g - I_0 \left[\exp \left(\frac{\beta \cdot (V + R_s \cdot I_{pv})}{\alpha} - 1 \right) \right] - \frac{V_{pv} + R_s \cdot I_{pv}}{R_p}
 \end{aligned} \tag{1}$$

where V_{pv} and I_{pv} are the voltage and current at the terminals of the PV cell and the current I_d is determined by the Shockley diode equation with β being the inverse thermal voltage, I_0 the diode reverse saturation current, and α an ideality diode factor. β is defined by the following equation:

$$\beta = \frac{q}{kT} \tag{2}$$

where q is the electron charge ($1.60217646 \times 10^{-19} \text{C}$), T is the operating temperature of the cell in Kelvin and k is the Boltzmann's constant ($1.3806503 \times 10^{-23} \text{J/K}$).

The I-V curve of a PV cell is shown in Figure 5. Operating points 1 and 3 in the figure represent the cell short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}). Moreover, the rectangular area under the I-V curve is equal to the output power, which is maximized at point 2. Because of that, this point is known as the *Maximum Power Point* (MPP).

Figure 5 – I-V curve of a PV cell.

Source: Author

Load, solar radiation and temperature determine the values of Figure 5. Assuming constant values of solar radiation and temperature, the operating point moves from 1 to 3 as the load increases from zero (short-circuit at $(0, I_{sc})$) to infinity (open-circuit at $(V_{oc}, 0)$).

In addition, the effect of solar radiation and temperature on PV cell current (I_{pv}) and diode reverse saturation current (I_0) is determined by the following equations (YAZDANI et al., 2011):

$$I_{pv} = (I_n + K_I \cdot \Delta_T) \cdot \frac{G}{G_n} \quad (3)$$

$$I_0 = \frac{I_{sc,n} + K_I \cdot \Delta_T}{\exp[(V_{oc,n} + K_V \cdot \Delta_T) \cdot \beta/\alpha] - 1} \quad (4)$$

where:

I_n : nominal cell current (A)

K_I : current temperature coefficient (A/K)

K_V : voltage temperature coefficient (V/K)

Δ_T : difference between nominal temperature (25 °C) and operating temperature

G : solar irradiance reaching the cell (W/m^2)

G_n : nominal solar irradiance ($1000 W/m^2$)

$I_{sc,n}$: nominal short-circuit current (A)

$V_{oc,n}$: nominal open-circuit voltage (V)

According to equations (3) and (4), variations in solar irradiance and temperature affect the output power of a photovoltaic cell by changing the magnitude of current I_{pv} . This is shown in Figure 6, where it is illustrated the direct relationship between irradiance and PV power (Figure 6-a), and the inverse relationship between temperature and power (Figure 6-b).

Figure 6 – P-V characteristic curve of a PV cell. a) Effect of irradiance with constant temperature at 25 °C. b) Effect of temperature with constant irradiance at $1000 W/m^2$.

Source: MathWorks (2015)

Commercially, PV cells are combined into larger units called *PV modules*. These modules have between 50 and 100 cells and output capacities in the range of 50 to 200 W (MITSUBISHI ELECTRIC, 2015). In practice, arrangements of PV modules connected in series or parallel form a PV generator. The equation that model these arrangements, assuming that all of them are equal, is a modified version of (1) (VILLALVA, 2010):

$$I_{pv} = I_g \cdot N_p - I_0 \cdot N_p \left[\exp \left(\frac{\beta \cdot \left(V_{pv} + \frac{R_s \cdot N_s}{N_p} \cdot I_{pv} \right)}{\alpha N_s} - 1 \right) \right] - \left(V_{pv} + \frac{R_s \cdot N_s}{N_p} \cdot I_{pv} \right) \cdot \left(\frac{N_p}{R_s \cdot N_s} \right) \quad (5)$$

where N_p and N_s are the amount of PV modules connected in parallel and series, respectively.

In the present work, the features of the module *Kyocera KD205GX-LP* were used to perform all simulations and can be found in Appendix A.1 (KYOCERA, 2014).

2.2 Topology of the PV System

As stated in Islam, Guo e Zhu (2014), there are two main topologies for PV systems. They are the *centralized-converter* topology and the *string-converter* topology, shown in Figure 7.

The centralized topology is characterized by having one DC/AC converter connected directly to the array of PV modules (Figure 7-a). By contrast, the string topology has an additional DC/DC converter per each string of modules (Figure 7-b), that boosts the voltage of the strings. The advantage of this scheme over the centralized topology is the possibility to control every string individually, reducing the voltage mismatch that can appear between them as a consequence of non-uniform solar irradiance distributions. This, in turn, may improve the efficiency of the system. However, given that the centralized topology utilizes just one converter, it is simpler and has lower costs. In addition, the centralized topology is a common choice between manufacturers of converters for large-scale PV systems (ABB, 2015). For these reasons, the centralized topology was adopted in the present work.

Figure 7 – PV system topologies. a) Centralized topology. b) String topology.

Source: Islam, Guo e Zhu (2014)

2.3 Voltage-Sourced Converter (VSC)

The main function of the VSC is to convert the DC current delivered by the PV generator into AC three-phase current. VSCs can also operate as reactive power sources that provide voltage support in distribution networks, or increase power transfer capability in transmission systems (VARMA; RAHMAN; VANDERHEIDE, 2015; LI et al., 2012).

VSCs are composed of semiconductor switches -e.g. IGBTs- arranged in several schemes, among which the most common is the two-level converter with *Pulse-Width Modulation* (PWM) (MOHAN; UNDELAND; ROBBINS, 2007).

Several models of VSC have been proposed in the literature. Some of them have detailed representations of the semiconductor elements, allowing the analysis of events that include the high-frequency components generated in the modulation process (QI; WOODRUFF; STEURER, 2007). Others, as the *topological model*, consider semiconductors as common switches (YAZDANI et al., 2011). As stated in Chiniforoosh et al. (2010) and Yazdani e Iravani (2010), for studies that do not require high-frequency details -as the current dissertation-, the VSC can be represented with an *averaged model*. In this model, switches are ignored and the relation between voltages and currents at both sides of the VSC relies on the principle of energy conservation. Thus, if converter losses are neglected, the power balance between the two sides of the VSC can be written as:

$$P_{dc} = P_t$$

$$V_{pv} \cdot I_{pv} = v_{ta} \cdot i_a + v_{tb} \cdot i_b + v_{tc} \cdot i_c \quad (6)$$

where P_{dc}, V_{pv}, I_{pv} represent the power, voltage and current at the DC side of the VSC and P_t, v_{tabc}, i_{abc} are their counterparts at the AC side. Furthermore, to obtain a simplified structure of the related controllers, Yazdani e Iravani (2010) encourage to work this equations in a d-q frame:

$$P_t = \frac{3}{2} \cdot (V_{td} \cdot i_d + V_{tq} \cdot i_q)$$

$$V_{pv} \cdot I_{pv} = \frac{3}{2} \cdot (V_{td} \cdot i_d + V_{tq} \cdot i_q)$$

$$I_{pv} = \frac{3}{2} \cdot \left(\frac{V_{td} \cdot i_d + V_{tq} \cdot i_q}{V_{pv}} \right) \quad (7)$$

where V_{td}, i_d, V_{tq} and i_q are the voltages and currents at the AC side in d-q coordinates. Figure 8 shows the block diagram of the averaged model. In the diagram, I_{dc} is calculated using Eq. (7) and included in the power circuit with a controlled current source. The synchronization scheme -discussed in the next section- provides the angle ρ to the *dq-abc* blocks. The model of Figure 8 assumes PWM operation with modulation signals m_d and m_q . The constant K_{vdc} is the amplification gain that relates voltage magnitudes on both sides of the converter, as expressed in equations (8) and (9). The value of this gain

depends on the modulation strategy; for the case of PWM, K_{vdc} is equal to 0.5 (MOHAN; UNDELAND; ROBBINS, 2007; YAZDANI; IRAVANI, 2010).

$$V_{td}(t) = K_{vdc} \cdot V_{pv} \cdot m_d(t) \quad (8)$$

$$V_{tq}(t) = K_{vdc} \cdot V_{pv} \cdot m_q(t) \quad (9)$$

Figure 8 – VSC averaged-model diagram.

Source: Yazdani et al. (2011)

2.4 Synchronization Scheme (PLL)

The function of the *Phase-Locked Loop* (PLL) is to provide the angular position (ρ) of the grid voltage at the *Point of Common Coupling* (PCC). This is used to synchronize the PV system with the utility network. As Figure 9 illustrates, the angular position is calculated by referring grid voltage (v_{abc}) to a d-q rotating frame. Then, the quadrature component (V_q) is introduced into a PI controller that adjust the angular speed (ω_s) until V_q becomes zero. In this condition, the direct axis of the d-q frame is align with v_{abc} , and, then, ρ is equal to the angular position of the grid voltage.

Figure 9 – Block diagram of the PLL.

Source: Author

2.5 Control System

The control system relies on a real-and-reactive-power controller implemented with a current mode strategy, and in a rotating d-q frame. References of this controller come from the VAR/Vac controller, that either regulates reactive power or AC-voltage at the PCC; and the DC-link voltage controller, which receives its reference from the *Maximum Power Point Tracker* (MPPT) scheme (Figure 10). The control system provides modulation signals md and mq to the VSC. Its components are presented in the following subsections.

Figure 10 – General diagram of the PV system control.

Source: Author

2.5.1 Real and reactive power Control

This control regulates the real and reactive power supplied by the PV system, by controlling the AC-side current of the VSC. According to (KAZMIERKOWSKI; MALESANI, 1998), this strategy of control provides fast responses, high accuracy and high-level of

performance under dynamic conditions. Moreover, current control schemes are expected to protect VSCs against over-current events (YAZDANI; IRAVANI, 2010).

The first step to analyse this scheme of control is to establish the relationship between power and current on the AC side of the VSC. Thus, the active and reactive power supplied by the PV system at the *Point of Common Coupling* (PCC) are defined as:

$$P_s = \frac{3}{2} \cdot (V_d \cdot i_d + V_q \cdot i_q) \quad (10)$$

$$Q_s = \frac{3}{2} \cdot (-V_d \cdot i_d + V_q \cdot i_q) \quad (11)$$

where V_d, i_d, V_q and i_q are the voltages and currents at the PCC in a d-q frame, and P_s and Q_s are the active and reactive power injected by the PV system to the grid at the PCC. Furthermore, given that the PLL scheme ensures $V_q = 0$, from (10) and (11):

$$P_s = \frac{3}{2} \cdot (V_d \cdot i_d) \quad (12)$$

$$Q_s = -\frac{3}{2} \cdot (V_d \cdot i_d) \quad (13)$$

It is noted from equations (12) and (13) that P_s and Q_s can be controlled by regulating currents i_d and i_q . That is, the power supplied by the photovoltaic system to the grid can be regulated with a current controller. To further investigate this, it is proposed the simplified diagram of a PV system shown in Figure 11. In the diagram, the VSC is modelled in a d-q reference frame as an ideal element, receiving modulation signals md and mq from the control system. The utility grid is represented by an ideal balanced voltage source with frequency ω_o , and PV generator is represented by V_{pv} and I_{pv} . The PV system is connected to the utility grid through a RL branch, modelling the interface reactor and interconnection transformer (Tr) of Figure 3.

From Kirchhoff's laws, a set of equations that describes the AC-side dynamics of Figure 11 can be written as:

$$L \cdot \frac{di_a}{dt} = -R \cdot i_a + v_{ta} - v_a \quad (14)$$

$$L \cdot \frac{di_b}{dt} = -R \cdot i_b + v_{tb} - v_b \quad (15)$$

$$L \cdot \frac{di_c}{dt} = -R \cdot i_c + v_{tc} - v_c \quad (16)$$

Figure 11 – Simplified diagram of a PV system.

Source: Author

Then, referring equations (14)-(16) to a d-q frame (YAZDANI; IRAVANI, 2010), it is obtained:

$$L \cdot \frac{di_d}{dt} = L \cdot \omega(t) \cdot i_q - R \cdot i_d + V_{td} - V_d \quad (17)$$

$$L \cdot \frac{di_q}{dt} = -L \cdot \omega(t) \cdot i_d - R \cdot i_q + V_{tq} - V_q \quad (18)$$

$$\frac{d\rho}{dt} = \omega(t) \quad (19)$$

As discussed in Section 2.4, ρ must be equal to the angular position of grid voltage to ensure synchronization between PV system and utility grid. Moreover, as mentioned above, the grid is represented by a voltage source with frequency ω_o . Therefore, the angular position of grid voltage can be written as $\rho = \omega_o t + \theta_0$, where θ_0 is an initial phase angle.

Thus, replacing ρ in equation (19) and substituting in (17) and (18):

$$L \cdot \frac{di_d}{dt} = L \cdot \omega_o \cdot i_q - R \cdot i_d + V_{td} - V_d \quad (20)$$

$$L \cdot \frac{di_q}{dt} = -L \cdot \omega_o \cdot i_d - R \cdot i_q + V_{tq} - V_q \quad (21)$$

Equations (20) and (21) represent a system where i_d and i_q are state variables, V_{td} and V_{tq} are control inputs, and V_d and V_q are disturbance inputs. Moreover, i_d and i_q are coupled by the term $L \cdot \omega_o$.

To decouple i_d and i_q , Yazdani e Iravani (2010) calculates modulation signals m_d and m_q as follows:

$$m_d = \frac{2}{V_{dc}} \cdot (u_d - L \cdot \omega_o \cdot i_q + V_d) \quad (22)$$

$$m_q = \frac{2}{V_{dc}} \cdot (u_q + L \cdot \omega_o \cdot i_d + V_q) \quad (23)$$

where u_d and u_q are outputs of the controller. Moreover, from equations (8)-(9):

$$V_{td}(t) = 0.5 \cdot V_{dc} \cdot m_d(t) \quad (24)$$

$$V_{tq}(t) = 0.5 \cdot V_{dc} \cdot m_q(t) \quad (25)$$

Thus, replacing (22)-(23) in (24)-(25) and the resultant into (20)-(21), it is deduced:

$$L \frac{di_d}{dt} = -R \cdot i_d + u_d \quad (26)$$

$$L \frac{di_q}{dt} = -R \cdot i_q + u_q \quad (27)$$

Equations (26) and (27) represent two decoupled linear systems in which the state variables, i_d and i_q , can be controlled separately by u_d and u_q , respectively. The diagram of the current controller is shown in Figure 12.

In Figure 12, u_d and u_q are obtained by computing current errors ($i_{dref} - i_d$ and $i_{qref} - i_q$) through PI compensators $K_i(s)$. These compensators can be the same because, as shown in the figure, the two control plants - controlling i_d and i_q - are identical. The plant equivalent (RL branch) is shown in green, and includes the coupling $L \cdot \omega_o$ deduced in equations (20) and (21); moreover, m_d and m_q are obtained according to equations (22) and (23).

2.5.2 Maximum Power Point Tracking (MPPT)

As discussed in Section 2.1, the *Maximum Power Point* (MPP) of a PV generator varies with changes in solar irradiance and temperature (Figure 6). During the course of the day, cloud coverage and the daily-cycle of sunlight cause variations in the irradiance received by photovoltaic cells. Therefore, the maximum-power-point is continually changing. The MPPT scheme locates this point, which is described by coordinates (V_{MPP}, P_{MPP}) in the P-V curve, and delivers the value of V_{MPP} to the control system. This value is taken as reference by the DC-Link voltage controller, which set the voltage at terminals of the

Figure 12 – Current controller diagram.

Source: Adapted from Yazdani e Iravani (2010)

PV generator (DC-side of the VSC). This ensures that the PV generator operates at the maximum-power-point.

To achieve this objective, various strategies have been proposed in the literature. In Dolara, Faranda e Leva (2009) seven of these techniques are compared in terms of efficiency performance. It concluded that *Perturb and Observed Method (P&Ob)* and *Incremental Conductance Method (IC)* have highest efficiency between the tested methods. In addition, the *Incremental Conductance Method* has better responses to rapid changes in irradiance. Then, given that the present work contemplates the analysis of changing irradiance conditions, the *IC* method was implemented along with the PV system model.

Figure 13 illustrates the P-V curve of a PV generator. As can be inferred from the figure, at the maximum-power-point (MPP), the derivative of power with respect to voltage is zero. Then, the maximum-power-point is obtained when:

$$\frac{dP_{pv}}{dV_{pv}} = 0 \quad (28)$$

Moreover, given that $P_{pv} = V_{pv} \cdot I_{pv}$, it is deduced from (28):

$$\frac{dP_{pv}}{dV_{pv}} = \frac{dI_{pv}}{dV_{pv}} + \frac{I_{pv}}{V_{pv}} = 0 \quad (29)$$

where P_{pv} , V_{pv} and I_{pv} are the power, voltage and current of the PV generator.

Figure 13 – P-V curve of a PV generator.

Source: Author

Then, the incremental conductance method operated by altering the value of the DC-voltage reference according to the following conditions, which follow from equation (29):

1. If: $\frac{dI_{pv}}{dV_{pv}} + \frac{I_{pv}}{V_{pv}} = 0 \rightarrow$ Then: the reference is unchanged
2. If: $\frac{dI_{pv}}{dV_{pv}} + \frac{I_{pv}}{V_{pv}} > 0 \rightarrow$ Then: the reference is increased by D
3. If: $\frac{dI_{pv}}{dV_{pv}} + \frac{I_{pv}}{V_{pv}} < 0 \rightarrow$ Then: the reference is decreased by D

The first condition represents the operating point in which the PV generator is working at the MPP. In the second, the operation point is at the left side of the MPP, that is, the derivative dP_{pv}/dV_{pv} is positive. Therefore, a step D is added to the reference DC-voltage in order to reach the maximum power point. In the third condition, the operational point is at the right of the MPP and a step D is subtracted.

The value of the step D could be fixed or dynamically adjusted. According to Yan et al. (2008), an adjustable step gives faster and more accurate responses. Thus, D is calculated as:

$$D = N \cdot \left| \frac{dP_{pv}}{dV_{pv}} \right| \quad (30)$$

where N is a constant obtained by trial and error. Moreover, the step D must have a maximum limit to prevent the condition in which dV_{pv} is zero.

The algorithm of the *IC* method is shown in Figure 14. Some clarifications regarding the diagram are necessary. First, an error ε is added to equation (29) to improve the response of the algorithm, taking into account residual values. Second, the algorithm has an additional pair of conditions that consider variations in PV current (I_{pv}), and are

included to increase the robustness of the scheme. In these conditions, voltage reference is modified in accordance with the I-V curve of the PV generator (Figure 5). If $dI_{pv} < 0$, the operation point is at the left of the MPP and a step is added to the reference. On the other hand, if $dI_{pv} > 0$, an step is subtracted.

Figure 14 – Diagram of the maximum power point tracking controller.

Source: Author

2.5.3 DC-Link Voltage Control

This scheme of control regulates the DC-side voltage (V_{pv}), based on the reference provided by the *Maximum Power Point Tracker* (MPPT). To analyze this control, the power balance on both sides of the VSC is obtained as:

$$P_{pv} - \frac{d}{dt} \left(\frac{1}{2} C V_{pv}^2 \right) = P_s + P \quad (31)$$

where P_{pv} is the power supplied by the PV generator, P_s is the active power at the PCC,

the differential term represents the power in the DC bus capacitor, and P is the power loss in the interface reactor and transformer of Figure 3.

According to Yazdani e Dash (2009), the model can be simplified by omitting the power loss in the interface reactor and transformer. Thus, equation (31) becomes:

$$P_{pv} - \frac{d}{dt} \left(\frac{1}{2} C V_{pv}^2 \right) = P_s \quad (32)$$

Equation (32) represents a control plant where V_{pv}^2 is the output and the state variable, P_s is the input and P_{pv} is a disturbance.

Additionally, from equation (12) it follows that:

$$P_s = \frac{3}{2} \cdot (V_d \cdot i_d) \quad (33)$$

Thus, rewriting equation (32):

$$\frac{C}{2} \frac{dV_{pv}^2}{dt} = P_{pv} - \frac{3}{2} \cdot V_d \cdot i_{dref} \quad (34)$$

Equation (34) assumes that the current controller operates satisfactorily, maintaining $i_d = i_{dref}$. Moreover, this equation is nonlinear due to the presence of V_{pv}^2 and P_{pv} . The reason for the nonlinearity of the photovoltaic power P_{pv} is attributed to its dependence on solar irradiance and temperature, and to the characteristics of the P-V curve of a PV generator.

To mitigate the effect of nonlinearity, Yazdani e Dash (2009) proposes to obtain i_{dref} as:

$$i_{dref} = u_v + \frac{2}{3} \frac{P_{pv}}{V_d} \quad (35)$$

where u_v is a control input.

Thus, replacing (35) in (34):

$$\frac{C}{2} \frac{dV_{pv}^2}{dt} = -\frac{3}{2} \cdot V_d \cdot u_v \quad (36)$$

Then, it is deduced from equation (36) that V_{pv}^2 can be controlled by regulating u_v . The diagram of the control scheme is shown in Figure 15.

In Figure 15, u_v is obtained by multiplying the error $V_{pvref}^2 - V_{pv}^2$ by a PI compensator $K_v(s)$. Then, a feed-forward signal of P_{pv} is added, as established in equation (35). This

Figure 15 – Diagram of the DC-Link voltage controller.

Source: Adapted from Yazdani e Iravani (2010)

generates the reference current i_{dref} , which is the input of block G_i . This block represents the transfer function in closed loop of the current controller discussed in Section 2.5.1. Moreover, the DC bus is modelled with the transfer function $\frac{-2}{sC}$, which follows from equation (32).

2.5.4 VAr/Vac Control

As discussed in Section 2.3, VSCs can operate as reactive power sources that provide voltage support to the utility network. Then, two different control schemes were implemented to achieve this objective.

The first of them directly regulates the voltage at *Point of Common Coupling* (PCC); its diagram is illustrated in Figure 16. The voltage at the PCC, represented by its component in the direct axis (V_d), is controlled by regulating the reactive power supplied by the photovoltaic system. A compensator $K_{vac}(s)$ computes the error $V_{dref} - V_d$ to generate the reactive power reference Q_{sref} . Then, the current reference in the quadrature axis (i_{qref}) is calculated with equation (13). This reference is the input of the block G_i that represents the transfer function in closed loop of the current controller. According to Yazdani e Iravani (2010), the utility grid can be simplified using the term $L_g \cdot \omega_o$, where L_g is the equivalent inductance of the utility grid at the PCC, and ω_o is the nominal angular frequency of the system. Finally, the control scheme has a 5% voltage droop that allows V_d to vary slightly from the reference V_{dref} . This prevents an oscillatory behaviour of the system and facilitates the parallel operation of multiple PV system (HINGORANI; GYUGYI, 2000).

The second control scheme maintains a constant power factor at the PCC. To achieve the targeted power factor, the reference for the quadrature current i_q is calculated as shown in Figure 17.

Figure 16 – Block diagram of the Vac controller.

Source: Adapted from Yazdani e Iravani (2010)

Figure 17 – Calculation of i_{qref} for constant power factor control.

Source: Author

2.6 Utility Elements

This section introduces the characteristics of the isolation transformer (Tr) and the interface reactor that connect the photovoltaic system to the utility grid (see Figure 3).

Regarding the transformer, it increases the AC voltage delivered by the VSC to the value required at the *Point of Common Coupling* (PCC). The type of connection may vary depending on the characteristics of the network in which the PV system is installed. According to Arritt e Dugan (2008), the Yg- Δ connection has some features that are beneficial for this type of application. The first advantage is that the delta connection -located on the photovoltaic system side- blocks third-order harmonics that may be generated by the switching process of the VSC. Furthermore, this delta configuration isolates the PV system from zero sequence components of fault currents that may occur in the utility grid. Although neither the implemented PV model include harmonic generation (because of the average model adopted for the VSC), nor the scope of work includes the study of network faults, this configuration was chosen because it is a common choice for this type of application (YAZDANI et al., 2011).

On the other hand, the function of the interface reactor is to provide sufficient impedance to connect the photovoltaic system to the network. Some schemes include an additional capacitive filter, but such filter is out of the scope of this work.

PV System Dimensioning and Testing

This chapter is divided into two parts. The first part presents recommendations for dimensioning the components of the photovoltaic system model presented in the previous chapter. The second part shows the results of simulations conducted to validate the performance of the model.

3.1 DC-Link

The DC-link voltage is selected according to equation (YAZDANI; IRAVANI, 2010):

$$V_{pv} \geq 2 \cdot V_t \quad (37)$$

where V_{pv} is the DC-Link voltage and V_t is the peak phase voltage on the AC side of the VSC. Equation (37) assumes that VSC operates with PWM modulation. V_t is calculated assuming a critical operating scenario in terms of sudden variation of the power fed into the grid by the photovoltaic system. For this purpose, the components in a dq reference frame of V_t are calculated as:

$$V_{td} = V_{sd} + \left(\frac{2 \cdot L \cdot \omega_0}{3 \cdot V_{sd}} \right) \cdot Q_{s0} + \left(\frac{2 \cdot L}{3 \cdot \tau_i \cdot V_{sd}} \right) \Delta P_s \quad (38)$$

$$V_{tq} = \left(\frac{2 \cdot L \cdot \omega_0}{3 \cdot V_{sd}} \right) \cdot P_{s0} - \left(\frac{2 \cdot L}{3 \cdot \tau_i \cdot V_{sd}} \right) \Delta Q_s \quad (39)$$

where V_{sd} is the direct axis voltage at the PCC; L is the sum of the interface reactor and isolation transformer inductances; ω_0 is network frequency; P_{s0} and Q_{s0} are the active and reactive power injected by the PV system on steady state condition; ΔP_s and ΔQ_s are variations of the power injected by the PV system, selected by design; and τ_i is the time constant of the closed-loop transfer function of the real and reactive power controller.

After calculating V_{td} and V_{tq} , V_t is obtained with the equation:

$$V_t = \sqrt{V_{td}^2 + V_{tq}^2} \quad (40)$$

Then, V_t is replaced in equation (37) to obtain the minimum value of V_{pv} . The magnitude of V_{pv} is adjusted with the number of modules connected in series (Ns) in the photovoltaic generator (Section 2.1).

DC Capacitor

Voltage variations in the DC-link are mainly due to the operation of the MPPT scheme. As discussed in Section 2.5.2, the MPPT finds the maximum power point by varying the DC voltage reference in a step D. Therefore, if a stable operation is assumed in the network, the DC voltage ripple is determined by the magnitude of D. According to Chen, Chang e Wu (2009), the value of the capacitor can be selected using the equation:

$$C \geq \frac{2 \cdot \Delta P}{(2 \cdot V_{pv} + \Delta V_{pv}) \cdot \Delta V_{pv} \cdot \omega_o} \quad (41)$$

where V_{pv} is the nominal voltage of the DC-link, ΔV_{pv} is the maximum expected peak-peak ripple in steady state operation (usually less than 3%), and ω_0 is the frequency of the network. ΔP_{pv} represents the variation in the power supplied by the photovoltaic generator caused by MPPT operation. This value is obtained from the P-V curve of the photovoltaic generator, using the maximum allowed value for the step D (D_{max}). Thus, ΔP_{pv} is obtained as:

$$\Delta P = P_{mpp} - P'' \quad (42)$$

where P_{mpp} is the power at the MPP, and P'' is the power corresponding to the voltage $V_{mpp} + D_{max}$, where V_{mpp} is the voltage at the maximum power point.

3.2 Control System

This section presents recommendations for sizing the components of the control schemes presented in Section 2.5.

3.2.1 Real and Reactive Power Controller

According to Yazdani e Iravani (2010), the closed-loop transfer function of this controller can be written as:

$$G_i = \frac{1}{\tau_i \cdot s + 1} \quad (43)$$

where τ_i is the closed-loop time constant of the controller. Moreover, this controller uses a PI compensator $K_i(s)$ with the form:

$$K_i(s) = \frac{k_p \cdot s + k_i}{s} \quad (44)$$

where k_p and k_i are the proportional and integral gains. The values of these gains are obtained with the equations:

$$k_p = \frac{L}{\tau_i} \quad (45)$$

$$k_i = \frac{R}{\tau_i} \quad (46)$$

where L and R are the inductance and resistance of the sum between the interface reactor and the isolation transformer Tr . Typical values of τ_i are between 0.5 and 5 *ms*.

3.2.2 MPPT Scheme

The incremental conductance algorithm was implemented with Matlab code, using the block *MATLAB Function Block* from the library *User-Defined Functions*. The scheme starts at 0.5 seconds. Before that, it delivers a constant reference voltage equal to 0.8 times the open circuit voltage of the photovoltaic generator. The same reference is provided when solar radiation is zero (night hours).

As discussed in Section 2.5.2, the value of the step D -which is added or subtracted to the reference voltage to reach maximum power point- is proportional to the derivative dP_{pv}/dV_{pv} . As shown in Figure 18, the magnitude of this derivative is different at both sides of the maximum power point. Therefore, adding a different scaling factor for D at each side of the MPP improves the performance of the algorithm. Table 5 (Appendix A.1) summarizes the parameters of the scheme. The code can be consulted in Appendix A.3.

3.2.3 DC-Link Voltage Controller

This controller uses a PI compensator $K_v(s)$ defined as:

$$K_v(s) = k_p \cdot \frac{1 + T_i \cdot s}{T_i \cdot s} \quad (47)$$

From the block diagram of Figure 15, the open loop transfer function $l(s)$ of this control is:

$$l(s) = -K_v(s) \cdot G_i(s) \cdot \left(\frac{3}{2}\right) \cdot \left(\frac{-2}{s \cdot C}\right) \quad (48)$$

Figure 18 – Behaviour of derivative dP/dV in a PV generator.

Source: Author

where $G_i(s)$ is the closed-loop transfer function of the real and reactive power controller, and C is the value of the DC-Link capacitor. Then, substituting from equations (43) and (47):

$$l(s) = -k_p \cdot \left(\frac{1 + T_i \cdot s}{T_i \cdot s} \right) \cdot \left(\frac{1}{\tau_i \cdot s + 1} \right) \cdot \left(\frac{3}{2} \right) \cdot \left(\frac{-2}{s \cdot C} \right)$$

$$l(s) = 3 \cdot k_p \cdot \left(\frac{1 + T_i \cdot s}{T_i \cdot s} \right) \cdot \left(\frac{1}{\tau_i \cdot s + 1} \right) \cdot \left(\frac{1}{s \cdot C} \right) \quad (49)$$

According to Leonhard (2001), for an open loop transfer function with the form of (49), parameters k_p and T_i of the compensator can be obtained with the *symmetrical optimum method*, using the following equations:

$$T_i = a^2 \cdot \tau_i \quad (50)$$

$$a = \frac{1}{\omega_d \cdot \tau_i} \quad (51)$$

$$k_p = \left(\frac{1}{3 \cdot a} \right) \cdot \left(\frac{C}{\tau_i} \right) \quad (52)$$

where a is a design parameter usually in the range $2 \leq a \leq 4$, and ω_d is the cross-over frequency of the open loop, selected to maximize the phase margin.

Moreover, Teodorescu, Liserre e Rodriguez (2011) recommends to add a lag term to the reference signal in order to reduce the overshoot caused by the lead term of the PI compensator. Such lag term is defined by

$$H_v(s) = \frac{1}{1 + T_i \cdot s} \quad (53)$$

3.2.4 VAr/Vac Controller

The compensator K_{vac} of this controller has the form:

$$K_{vac} = \frac{K}{s} \quad (54)$$

where K is a constant gain. This controller was tuned using the graphical tool for control design SISOTOOL from Matlab. Moreover, the equivalent inductance of the grid, required in the block diagram of Figure 16, was calculated with the approximation:

$$L_g = \frac{U^2}{S_k} \quad (55)$$

where U is the line-to-line rms voltage at the PCC and S_k is the short-circuit power of the utility grid.

3.3 Utility elements

The interface reactor was chosen according to the recommendation given in Yazdani et al. (2011), which establishes a value between 0.1 and 0.25 p.u. (with respect to the nominal power of the converter). In this case, it was chosen a value of 0.1 p.u. with a quality factor of 38. On the other hand, data of the isolation transformer Tr is presented in Table 4, Appendix A.1.

3.4 Testing

This section presents simulations to evaluate the performance of the PV system model. For this purpose, a photovoltaic system of 1.5 MWp was dimensioned according to the recommendations presented in this chapter. Its parameters can be consulted in Appendix A.1. The size of the photovoltaic system was chosen according to rated values of commercial converters, which can reach 2 MW (ABB, 2015). Simulations were performed using the libraries of *SimPowerSystems*, from *Matlab-Simulink*. Simulation parameters are summarized in Table 2, Appendix A.1.

3.4.1 Test System

The test network is an adaptation of the grid used in Salles (2004), and is shown in Figure 19. Data of the network can be found in Appendix A.2. The network has a 30 MWp solar farm that is composed by twenty identical PV systems with individual capacity of 1.5 MWp. Each PV system has its own independent control and VSC, and is connected to the *Point of Common Coupling* (PCC) using an isolation transformer Tr ,

as shown in Figure 3. The solar farm is connected to bus 6 of a distribution grid of 33 kV through an interconnection transformer of 33/12.47 kV and Yg/Yg connection.

Figure 19 – Single-line diagram of the test network.

Source: Author

The distribution grid has four load buses (B2, B3, B4 and B5) connected to a sub-transmission system of 132 kV and short-circuit capacity of 1500 MVA via two Δ/Y_g transformers of 132/33 kV. Loads were modelled with the exponential load model:

$$P = P_o \left(\frac{V}{V_o} \right)^{np} \quad (56)$$

$$Q = Q_o \left(\frac{V}{V_o} \right)^{nq} \quad (57)$$

where

P : active power consumed by the load (W)

P_o : active power consumed by the load at rated voltage (W)

Q : reactive power consumed by the load (VAr)

Q_o : reactive power consumed by load at rated voltage (VAr)

V : nodal load voltage (V)

V_o : rated voltage of the load (V)

np and nq : exponents controlling the nature of the load

Furthermore, following the recommendation given in Price et al. (1993), active power components were modelled with a constant current characteristic ($np = 1$), while reactive power components were modelled with a constant impedance characteristic ($nq = 2$). The implementation of the load model was carried out using the block *Three-Phase dynamic Load* of Simpowersystems.

3.4.2 Results

The results are divided into two parts. First, the results for an individual 1.5 MWp PV system are discussed. Subsequently, the simulations for the complete solar farm are presented.

1.5 MWp PV system

Figure 20 shows the step response of currents i_d and i_q . Both currents have a settling time of about 0.2 seconds. i_q has an overshoot of about 3.5%.

Figure 20 – Response of currents i_d and i_q

Figure 21 shows the response of the PV system with a change of active power reference at $t = 1.2$ s (from 0 to 1100 kW), and a step of the reactive power reference at $t = 1.3$ s (from 0 to 800 kVAr). Figure 21-c shows the voltage and current of phase-a at the point of common coupling. From 1.2 to 1.3 seconds, current and voltage are in phase. At $t = 1.3$ s reactive power increases and current passed to lead voltage.

Figure 22 shows the response of the DC-Link voltage to a reference step at 0.5 seconds. The response has a voltage overshoot of 10.4 V.

Figure 21 – Response to changes in power references

Figure 22 – DC-Link voltage response to a step change in the reference

Figure 23 shows the response of the PV system when operating with constant power factor control. Figure 23-a illustrates the behaviour of the power factor subjected to step changes. Figure 23-b shows the corresponding active and reactive powers at the PCC.

Solar farm

In the first place, the test network is subjected to the following sequence of events. Until $t=5$ s, the solar irradiance reaching the solar farm is zero. From 5 to 10 seconds, the irradiance increases linearly to reach 1000 W/m^2 . From 10 to 14 second, the irradiance

Figure 23 – Power factor control

remains constant at 1000 W/m^2 . From 14 to 17 seconds, the irradiance decreases to 400 W/m^2 . The reference of reactive power of the twenty PV systems of the solar farm is subjected to a step change from 0 to -800 kVAr at $t = 25 \text{ s}$.

Figure 24 shows the time response of the solar farm. Figures 24-b and 24-c illustrate the currents in the direct and quadrature axis (i_d and i_q) of one of the twenty PV systems. The i_d current follows the shape of the solar irradiance. The i_q current follows the shape of the reactive power reference (not shown in the figure). Figure 24-d shows the voltage in the direct axis at the point of common coupling. The voltage fluctuates according to the active power generated by the solar farm (Figure 24-f). At $t = 25 \text{ s}$, the voltage has a step increase due to the change in the reactive power injected by the solar farm (Figure 24-d). Figure 24-e illustrates the DC-link voltage of one of the twenty PV systems. Until $t = 5 \text{ s}$, solar irradiance is zero and the MPPT scheme delivers a reference voltage equal to 0.8 times the open circuit voltage of the PV generator. At $t = 5 \text{ s}$, the MPPT begins to track the voltage as the irradiance changes, this generates a ripple in the voltage. A similar behaviour occurs from 14 to 17 seconds. The voltage is tracked to 1009.6 V at $t = 10$, and 1021.4 V at $t = 17 \text{ s}$. These values correspond with the maximum power points of each operating condition, 1010.8 V and 1021.22 V respectively.

In the second simulation, the twenty systems that comprise the solar farm are divided

Figure 24 – Overall response of the solar farm subjected to an uniform curve of solar irradiance and a step change of the reactive power reference.

into two equal groups. The same irradiance curve of Figure 24 is applied to the first group. A similar curve, with a delay of 5 seconds, is applied to the second. The reference of reactive power of the twenty photovoltaic systems is subjected to a step change from 0 to -800 kVAR at $t = 25$ s.

Figure 25-b illustrates the direct axis currents obtained in the PV systems of each group. Such currents follow the shape of the associated irradiance. DC voltages have a similar behaviour than Figure 24, with the delay of 5 seconds for the second group. The shapes of the voltage at point of common coupling and the active power generated by the solar farm are affected by the irradiance curves. The step change in reactive power increases voltage at the PCC.

Finally, all PV systems of the solar farm were enabled with the voltage control scheme

Figure 25 – Overall response of the solar farm subjected to a non-uniform distribution of solar irradiance and a step change of the reactive power reference.

of Figure 16. Solar irradiance was set at 600 W/m^2 . The step response of voltage at bus 6 (phase-a) is shown in Figure 26-a. Figure 26-b illustrates the corresponding active and reactive power provided by the solar farm.

Figure 26 – Voltage control

Effects of Solar Irradiance Variations on Voltage Levels

The previous chapters introduced the model of the PV system and the characteristics of photovoltaic cells. Section 2.1 discussed that power generated by a photovoltaic cell varies depending on solar radiation and operating temperature. Moreover, cloud coverage and the diurnal cycle¹ affect solar radiation reaching a photovoltaic system, causing variations in its magnitude. Therefore, power generated by PV systems has fluctuations throughout the day that affect power flows in the network. Moreover, this impact is greater as photovoltaic penetration increases.

This chapter studies the impacts caused by variations in solar radiation on a network with high penetration of photovoltaic generation. Results focus on the effects of power fluctuations on voltage levels. Moreover, the chapter presents alternatives to mitigate negative effects based on the capability of photovoltaic systems to provide reactive power support.

4.1 Background

This section presents some background for the simulations conducted in the chapter. Requirements of voltage levels of Brazilian standards are discussed, as well as the basics of reverse power flows and reactive power support by photovoltaic systems.

4.1.1 Voltage Requirements

Electric utilities must ensure that networks operate with voltage levels within defined limits. This is necessary because equipments connected to the grid are designed to operate at rated voltages. If networks operate outside those limits, malfunctioning or damages may occur in the equipment. For the Brazilian case, these limits are de-

¹It refers to the 24 hours cycle caused by the rotation of the Earth with respect to the Sun.

defined in the *Procedimentos de Distribuição de Energia Elétrica no Sistema Elétrico Nacional* (PRODIST) (ANEEL, 2010). PRODIST defines three ranges for the steady state operation, based on the difference between measured and reference voltages. These ranges are referred as *appropriate*, *precarious* and *critical*, and are shown in Table 1 for the case of voltage levels between 1 kV and 69 kV². In this chapter, the values under the *appropriate* classification were used as target limits.

Table 1 – PRODIST-8 Connection points in nominal voltage greater than 1 kV and lower than 69 kV

Classification	Variation Range of Utilization Voltage (UV) in relation to the Reference Voltage (RV)
Appropriate	$0.93RV \leq UV \leq 1.05RV$
Precarious	$0.90RV \leq UV \leq 0.93RV$
Critical	$UV < 0.90RV$ or $UV > 1.05RV$

4.1.2 Reverse Power Flows

Reverse power flows occur when power generated by a PV system (or, in a general sense, a source of distributed generation) is greater than local load of a distribution network, generating power flows in opposite direction than usual. The effect of reverse power flows on voltage levels is analysed with the simplified circuit of a network shown in Figure 27-a, where v is the utility voltage, Z_{line} is the line impedance, and Z_{load} represents the load. Thus, load voltage is given by

$$v_{load} = v - Z_{line} \cdot i_1 \quad (58)$$

Now, a photovoltaic system represented by the current source i_{pv} is connected to the load side of the network (Figure 27-b). If it is assumed that photovoltaic power is greater than load requirements, a current i_2 with opposite direction to i_1 will appear in the circuit, and v_{load} will be expressed by

$$v_{load} = v + Z_{line} \cdot i_2 \quad (59)$$

Thus, comparing equations (58) and (59) it is deduced that reverse power flows may cause a rise in load voltage, which is determined by the value of current i_2 , that is, by the capacity of the photovoltaic source, and by the magnitude of the line impedance.

²As it is discussed in Section 3.4.1, the voltage level of interest in this work is 33 kV.

Figure 27 – Simplified circuits representing reverse power flows

Source: Author

4.1.3 Voltage Control and Reactive Power Support

The control of voltage levels in an electrical network is achieved by regulating the reactive power flows of the system (KUNDUR; BALU; LAUBY, 1994). Reactive power flows can be controlled by generation units, which inject reactive power to maintain their terminal voltages within allowable limits. Regulation of reactive power flows can also be accomplished using capacitors or reactors connected in series or parallel; *On-Load Tap-Changing* (OLTC) transformers; *Static Var Compensators* (SVCs); or *Synchronous Static Compensators* (STATCOMs), which use Voltage-Sourced Converters (VSCs) to act as sources or sinks of reactive power. As discussed in Chapter 2, the *Voltage-Sourced Converter* (VSC) is one of the components of PV systems. Therefore, PV systems can be used as STATCOM to provide voltage support to the network. This type of application is referred as PV-STATCOM in the literature (VARMA; RAHMAN; VANDERHEIDE, 2015), and it is implemented in this work with the control schemes of Section 2.5.4.

The capability of a photovoltaic system to provide reactive power is limited by the capacity of its converter. If the rated power of the converter is equal to the maximum photovoltaic production, the system will not be able to inject or absorb reactive power during periods of maximum PV generation. In this regard, Figure 28 shows that increasing by 10% the size of the converter results in an additional capacity of 46% to provide reactive power. Moreover, during night hours when solar radiation is zero, the full capacity of converter can be used to provide reactive power support to the network.

4.2 Research Approach

The study conducted in this chapter comprises the following procedure:

1. Implement a 30 MWp solar farm on a test network.
2. Conduct simulations of various scenarios, including variations in solar irradiance due to the daily cycle of sunlight and passing clouds.

Figure 28 – Reactive power support capability of the VSC

Source: Author

3. Review active and reactive power curves and voltage profiles.
4. Implement control schemes of Section 2.5.4 to include reactive power support provided by the solar farm.
5. Repeat point 3 and compare results.

4.2.1 Test System and Assumptions

The test system used in this chapter is the same as that presented in Section 3.4.1. Moreover, simulations were performed with the following assumptions:

- ❑ Operating temperature of PV generators was set at 25 °C in all cases.
- ❑ Size of Voltage-Sourced Converters (VSCs) was assumed as 110 % of the rated value of PV systems.

4.2.2 Variations in Solar Irradiance

Figure 29 shows a daily curve of solar irradiance obtained on a cloudy day with a sampling period of one minute (NREL, 2015, April 10). Based on the information contained in this figure, variations in solar irradiance can be classified into two types. The first type, defined in this work as *daily variation*, is caused by the daily cycle of sunlight. Because of this cycle, solar radiation is zero during night hours and has a shape similar to a parabola during the day, with maximum at noon. Moreover, given that this variation is caused by the daily cycle of sunlight, it has a deterministic behaviour, i.e., irradiance is consistently higher (or lower) at certain times of day, varying predictably between seasons.

The second type of variation is caused by clouds. In Figure 29 these variations can be seen as distortions in the overall layout of the daily curve (distortions in the parabolic shape). Contrary to the daily cycle of sunlight, clouds are a stochastic phenomenon and, therefore, this type of variation is characterized by its randomness during the day, both in duration and magnitude.

Variations of solar radiation are further discussed in the following sections.

Figure 29 – Daily curve of solar irradiance

Source: NREL (2015, April 10)

4.2.2.1 Daily Variation

Figure 30 shows a curve of solar irradiance obtained in a region of the United States³ on March 22, 2012. The information was collected on a sunny day, with a sample period of one hour. Due to weather conditions in the day of the measurement and sampling time, this curve isolates the effect of the daily cycle of sunlight, excluding the effect of clouds. In the figure, solar irradiance is zero in the night hours, and begins to grow from dawn (7 hours). Then, it reaches its peak at noon (13 hours), and thereafter decreases to zero at sunset (20 hours). This curve illustrates the behavior of the solar irradiance reaching a PV system during the day. Thus, the impacts of this type variation were analyzed by setting Figure 30 as input to the whole solar farm.

Figure 30 – Solar irradiance in a sunny day.

Source: SolarAnywhere (2012, March 22)

³Coordinates: 31.35, -103.75

4.2.2.2 Passing Clouds

As shown in Figure 29, clouds cause disturbances in the daily layout of solar irradiance. According to measurements carried out in Gulachenski et al. (1990), these variations have rates between 60 and $150 \text{ W/m}^2/\text{s}$. On the other hand, the largest perturbation in Figure 29 occurs at about 13 hours, with an approximate magnitude of 600 W/m^2 . Thus, this information was used to construct the curve of Figure 31, which simulates a passing cloud. This curve has slopes of $150 \text{ W/m}^2/\text{s}$ and a sag of 600 W/m^2 . In addition, it is assumed that in the precondition to the passage of the cloud solar irradiance is equal to 1000 W/m^2 , which corresponds to the maximum value of Figure 29. Similarly, it is assumed that the period of lowest radiation (400 W/m^2) lasts 5 seconds.

Figure 31 – Curve used to simulate the effect of a cloud.

Source: Author

The impacts of passing clouds were studied in two scenarios. In the first case study, the cloud of Figure 31 covers uniformly the twenty PV systems that make up the solar farm. On the other hand, the second scenario studied a non-uniform distribution of solar irradiance. For this purpose, the twenty PV systems of the solar farm were divided into five equal groups (Figure 32), and the curves of Figure 33 were applied to them. This case simulates the condition in which the cloud of Figure 22 moves from left to right in Figure 32.

4.2.3 Daily Load Profiles

Profiles of Figure 34 were used to model load in the analysis of daily variations of solar irradiance. These profiles represent residential, commercial and industrial loads, and were obtained from measurements carried out in Jardini et al. (2000). Moreover, both active and reactive power components of the loads were modelled with these profiles.

Figure 32 – Groups of PV systems.

Source: Author

Figure 33 – Curves used to simulate the effect of a cloud with non-uniform distribution.

Source: Author

4.3 Results and Discussion

This section presents the results of the simulations conducted to study the effect of variations in solar radiation on voltage levels. In addition, it is presented a discussion about the joint operation between PV systems and OLTCs, regarding reactive power flows.

4.3.1 Daily Variation

Figure 35 shows the results of simulating an operating day of the solar farm, with an industrial load in the network. Figure 35-a illustrates the curves of active and reactive power of network load -sum of loads in buses 2, 3, 4 and 5; and the active power generated by the solar farm, multiplied by -1 to facilitate the visualization. Power values in Figure 35-a are in per unit (p.u.), with a base power equal to the nominal capacity of the solar farm, 30 MVA. The same base is used in all results of this chapter. Moreover, it is assumed that maximum active power of the load is equal to 1.5 p.u., and maximum reactive power is 0.3 p.u. Figure 35-b shows the voltage profiles of the network for the case where there

Figure 34 – Daily load profiles. a) Residential. b) Commercial. c) Industrial.

Source: Jardini et al. (2000)

is no photovoltaic generation connected to the grid. In turn, Figure 35-c shows these profiles when the solar farm is connected to bus 6, and working with unity power factor.

The first observation about Figure 35 is that photovoltaic power follows the shape of the daily curve of solar radiation (Figure 30), peaking at noon and with null values at night. Moreover, a comparison between Figures 35-b and 35-c indicates that the inclusion of photovoltaic generation increases the magnitude of network voltages. Figure 35-c also shows that the largest increase occurs in the connection bus of the solar farm (bus 6). Moreover, maximum voltages coincide with the period of the day in which photovoltaic generation is greater than the load, i.e., 12 to 13 hours approx. In this period, as noted in Section 4.1.2, reverse power flows appear in the network.

Figure 36 shows a comparison between residential, commercial and industrial loads, with the power generated by the solar farm during the day. In all three cases, maximum active power of the load is 1.5 p.u., and maximum reactive power is 0.3 p.u.

As shown in Figure 36, the behaviour of load with respect to photovoltaic power is different in each simulated profile. In the residential case, for example, PV power is greater than load from 10 to 16 hours, which coincides with the peak hours of photovoltaic generation. On the other hand, commercial load is greater than photovoltaic power throughout the day. These differences between profiles affect the behaviour of network voltages. This is illustrated in the bar graph in Figure 37, which summarizes the maximum voltages

Figure 35 – Operating day with industrial load. a) Curves of active and reactive power of the load, and active power generated by the solar farm. b) Voltage profiles without PV generation. c) Voltage profiles with PV generation.

obtained in the network for the load profiles of Figure 36. The bar graph shows that maximum voltage increases occur in the case of residential load. In addition, confirming the observations of Figure 35, the largest increase occurs at bus 6, with 6.3%. Moreover, in residential and industrial loads -where reverse power flows take place-, voltage values exceed the maximum limit on at least one bus. This shows that in operating conditions with reverse power flows, greater voltage rises occur. To further investigate this issue, the scenarios of Figure 38 are analysed.

Figure 38-a shows the curves of active power of four residential profiles, and the power generated by the solar farm. Each profile is identified by the ratio between the maximum active power of the load, and the rated power of the solar farm. Figure 38-b shows the maximum voltages reached in the network for each profile.

In Figure 38-b, the largest rises in voltage occur in scenarios with reverse power flows -profiles with ratios 1.5 and 2. Moreover, increases in voltage are lower in the buses nearest to the sub transmission system. These two facts are congruent with equation (59) of Section 4.1.2. Thus, in the buses nearest to the sub-transmission network, e.g. bus 2, the magnitude of the current coming from the solar farm is diminished due to the

Figure 36 – Comparison between daily load profiles and PV power a) Residential load. b) Commercial load. c) Industrial load.

Figure 37 – Summary of the maximum voltages for three load profiles. a) Residential load. b) Commercial load. c) Industrial load.

consumption of network loads, and therefore, the voltage increase indicated in equation (59) is smaller.

Results of Figure 38 suggest that the connection point of the solar farm -with respect to the sub-transmission network- affects the magnitude of voltage rises that are produced by photovoltaic generation. In this regard, Figure 39 shows the maximum voltages reached in the network when the connection point is varied between the buses of the system. Results show that connecting the solar farm to bus 2 -the closest to the sub-transmission

Figure 38 – Effect of reverse power flows on voltage regulation. a) Load profiles and PV power. b) Maximum voltages for each profile.

system- has no effect on voltage levels, compared with the condition with no photovoltaic generation. In contrast, as the connection point moves away from the sub-transmission system, increases in voltage are greater.

Figure 39 – Maximum voltages obtained by varying the point of connection of solar farm between the bars of the network.

Reactive Power Support

The capability of the solar plant to provide reactive power support is enabled with the control schemes of Section 2.5.4. First, the operation with constant power factor is discussed. Figure 40 shows four voltage profiles at bus 6, obtained with the solar farm working with different power factors, and a residential load on the network. The first point to note about Figure 40 is that capacitive power factors worsen voltage regulation, since they further increase voltage magnitude -as it might be expected. Moreover, all profiles in Figure 40 are equal in the night hours. This is a limitation of this control scheme, since when PV power is zero (night hours), the calculated reference of reactive power is also zero (see Figure 17). In other words, no reactive power support is provided with this control scheme at night. Furthermore, inductive power factors in the figure reduce voltage magnitudes to values within allowable limits.

Figure 40 – Daily voltage profile at bus 6 with the solar farm working at different power factors.

A comparison between constant power factor and voltage regulation control schemes is shown in Figure 41. Figure 41-a illustrates the reactive power injected by the solar farm, considering inductive power factors of 0.9 and 0.95. Figure 41-b shows the corresponding voltage profiles at bus 6. It is noted that voltage regulation control provides reactive support during all day, including night hours, changing from inductive to capacitive power according to voltage requirements. This is a difference with respect to the constant power factor scheme that results in a more regular voltage profile at the bus. Moreover, since all of the VSC capacity is available to provide reactive power support at night, voltage fluctuations caused by load variations during night could be attenuated with this strategy.

Figure 41 – Comparison between constant power factor and voltage regulation schemes. a) Reactive power injected by the solar farm. b) Voltage profiles at bus 6.

4.3.2 Passing Clouds

Figure 42 shows the impact of a cloud uniformly covers the entire solar farm while photovoltaic systems are working with unity power factor. Figure 42-a shows the curve of solar irradiance produced by the cloud, as defined in Section 4.2.2.1. The active power

generated by the solar farm is shown in Figure 42-b, while voltages at buses 4, 5 and 6 are illustrated in Figure 42-c. It is observed in figures 42-b and 42-c that the photovoltaic power and the voltage at buses 4, 5 and 6 vary following the shape of solar radiation. PV power is reduced to 0.4 p.u. when solar irradiation is minimum (400 W/m^2), while voltage at bus 6 is reduced by 4.48%. The cloud affects the voltages at the other nodes in the network, but to a lesser extent the bus 6.

Figure 42 – Impact of an uniform cloud on PV power and voltages a) Solar irradiance b) Active power generated by the solar farm c) Voltages at buses 4, 5 and 6

Similarly, Figure 43 illustrates the effect of a non-uniform cloud on the network (Section 4.2.2.2). In this scenario, reductions in PV power and voltage are lower than in the uniform case. The minimum PV power is now 0.76 p.u., while voltage at bus 6 decreases by 1.5%. This is because not all photovoltaic systems of the solar farm are covered by the cloud at the same time. Then, this leads to smaller reductions in generated power and voltage values. The ripple in the curves is due to the nature of solar irradiation used for simulations.

Reactive Power Support

As previously discussed, the uniform case is the most critical of the proposed scenarios of passing clouds. Therefore, only the results for a uniform cloud are presented in this section. Figure 44-a shows the voltage at bus 6, obtained with two strategies for reactive

Figure 43 – Impact of an non-uniform cloud on PV power and voltage levels. a) Solar irradiance. b) PV power. c) Voltages at buses 4, 5 and 6.

power support. In the first strategy, solar farm works with constant power factor of 0.95 inductive. In the second, the solar farm operates with the voltage regulation scheme. In addition, the results for a unity power factor are presented for comparison. Figure 44-b shows the reactive power supplied with each strategy, as well as the maximum allowable reactive power, which is defined by the capacity of VSCs as discussed in Section 4.1.3.

As shown in Figure 44-a, both control strategies attenuate the effect of the cloud, maintaining voltage within permitted limits and reducing the sag produced by the variation of solar radiation. Furthermore, Figure 44-b shows that in both cases the reactive power supplied by the solar farm is less than the maximum allowed.

4.3.3 Combined Effect

After analyzing separately the effects of the daily cycle of solar radiation and clouds, Figure 45 presents the results for a curve of solar radiation containing the two types of variation. The results are consistent with observations made in the previous sections. The active and reactive power injected by the solar farm, and the voltages of the network follow the shape of solar radiation; the largest voltage rise occurs in the connecting point of the solar farm (bus 6); and the control strategies operate satisfactorily, mitigating voltage

Figure 44 – Impact of the reactive power support by the solar farm facing a passing cloud a) Voltage at bus 6 with different control strategies b) Reactive power injected by the solar farm

fluctuations. A point to note is that the greater voltage drop caused by the passage of a cloud (which occurs approximately 13 hours), is compensated by the elevation in voltage generated by the photovoltaic generation at peak hours.

4.3.4 Reactive Power Support and OLTCs

Until now it has been considered that reactive power support in the distribution network comes solely from the solar farm (besides the one coming from the sub-transmission network). However, as discussed in Section 4.1.3, various equipment can be used for controlling reactive power flows in the network. Then, it is reasonable to consider that reactive power coming from a solar farm must be coordinated with the operation of other equipment. This section briefly discusses this aspect, studying the joint operation of OLTCs with the solar farm. This is approached with two case studies. In them, the solar farm operates with the voltage regulation strategy, load is maintained constant, and solar irradiance is kept at 800 W/m^2 . Voltage profiles as well as active and reactive power flows on steady-state operation are plotted for analysis.

The first case is a baseline configuration that does not consider the operation of OLTCs. Figure 46-a shows the voltage profile of the distribution network. Figure 46-b illustrates the corresponding active and reactive power flows. As observed, all voltages are maintained within the limits. Moreover, the solar farm is injecting active power at bus 6, which is consumed by the load of each bus, reducing its magnitude as it moves from bus 6 to bus 2. PV power is greater than local load, thus, some power transfer from distribution to sub-transmission network occurs. This is represented by the negative value of active power at bus 2. On the other hand, the solar farm and the bus loads are consuming reactive power. This power is provided by the sub-transmission system to the distribution network (positive value of reactive power at bus 2).

Figure 45 – Operation day with residential load. a) Solar irradiance b) Active power generated by the solar farm and active power of the load. c) Voltages at buses 4, 5 and 6 if solar farm works at unity power factor. d) Voltage at bus 6 for different reactive support strategies. e) Reactive power injected by the solar farm for different control strategies.

In the second case the operation of OLTCs is included. This is achieved by manually changing the ratios of distribution transformers T1, T2 by -2.5 % and T3 by -10 % (Figure 23). All other system parameters remain the same as in the previous case. The results show that including OLTC capability does not have any effect on active power flows and, although voltages values are different, they continue within the limits (Figure 47). However, reactive power flows are drastically changed. Now the solar farm injects capacitive power to the network, and, therefore, reactive power coming from the sub-transmission system is reduced -from 1 p.u. to 0.3 p.u. approximately.

Figure 46 – Voltage profile and active - reactive power flows without OLTCs in steady state operation

Figure 47 – Voltage profile and active - reactive power flows with OLTCs in steady state operation

Conclusions and Recommendations

This work presented a dynamic model for utility-scale PV systems. The model was implemented using Matlab/Simulink and the SimPowerSystems toolbox. However, the results are applicable to other software programs. The model is based on a centralized converter topology, which uses a voltage-sourced converter (VSC) to facilitate the exchange energy between PV systems and utility grid. The related control system regulates active and reactive power injected by the PV system, based on a current control strategy. Moreover, the model includes a Maximum Power Point Tracking (MPPT) scheme, implemented with the incremental conductance method. Recommendations for the dimensioning of the system and simulations to validate its performance were presented. Results showed the effectiveness of the model to operate during conditions that include variations in solar radiation, and changes in the reference values of the controllers.

Subsequently, a 30 MWp solar farm was implemented to study the effect of variations in solar radiation on the voltage levels of a test network. Two types of variation were considered. The first type is caused by the daily cycle of sunlight. The second is related to passing clouds. Results showed that without adequate compensation of reactive power, variations in solar radiation can cause voltage fluctuations outside allowable limits. On one hand, the daily cycle of sunlight causes voltage increases that are more significant in the peak hours of PV generation, and in the presence of reverse power flows. On the other, passing clouds cause momentary reductions in PV power, generating voltage drops in the network.

In order to mitigate these fluctuations, two local control strategies were implemented to allow the exchange of reactive power between PV systems and utility grid. The implemented controls allow the solar farm to i) work with constant power factor and ii) regulate the voltage at the point of common coupling (PCC). Results showed the effectiveness of these controls to reduce voltage fluctuations. However, the voltage regulation strategy showed a better performance given its flexibility to change between inductive and capacitive power and the capability to provide reactive support during night hours.

Finally, some scenarios of joint operation between the solar farm -working as reactive

power source- and OLTCs were studied. The results showed that the inclusion of OLTCs drastically change the power flows in the network as well as the orientation of the reactive power supplied by the solar farm. These results showed the importance of coordinating solar farms with other reactive support equipment to optimize the reactive power consumption in the network. An appropriate coordination could also represent a reduction in reactive power flows at the sub-transmission level, a reduction of losses in transmission lines, and, depending on the characteristic of the network, the solar farm may be able to provide reactive power to sub-transmission systems.

Based on the analysis conducted in this dissertation, recommendations for future work in this field are:

- ❑ Investigate centralized control strategies for coordinating the operation of solar farms with other equipment for reactive power support, such as *On-Load Tap-Changes* (OLTCs), *Synchronous Static Compensators* (STATCOMs) or *Static Var Compensators* (SVCs).
- ❑ Propose an effective methodology for tuning MPPT schemes.
- ❑ Analyse voltage stability under dynamic conditions associated with network perturbations -such as three-phase faults or load changes-, in networks with high penetration of photovoltaic generation.

Bibliography

ABB. ASEA Brown Boveri. **ABB Solar inverters for photovoltaic systems**. Brochure BCB.00076 Rev. A. Available in: <<https://www.abb.com>>. Accessed: February 20. 2015.

ANEEL. Agência Nacional de Energia Elétrica. **Procedimentos de Distribuição de Energia Elétrica no Sistema Elétrico Nacional-PRODIST. Módulo 8, Qualidade da Energia Elétrica**. Available in: <<https://www.aneel.gov.br>>. 2010.

ANEEL. Agência Nacional de Energia Elétrica. **Resolução normativa nº481**. Available in: <<https://www.aneel.gov.br>>. 2012.

ANEEL. Agência Nacional de Energia Elétrica. **Resolução normativa nº482**. Available in: <<https://www.aneel.gov.br>>. 2012.

ANEEL. Agência Nacional de Energia Elétrica. **Banco de Informações de Geração. Capacidade de Geração do Brasil**. Available in: <<https://www.aneel.gov.br>>. Accessed: February 2. 2016.

APPEN, J.; BRAUN, M.; STETZ, T.; DIWOLD, K.; GEIBEL, D. Time in the sun: the challenge of high pv penetration in the german electric grid. **IEEE Power and Energy Magazine**, IEEE, v. 11, n. 2, p. 55–64, 2013.

ARRITT, R.; DUGAN, R. Distributed generation interconnection transformer and grounding selection. In: **IEEE Power and Energy Society General Meeting- Conversion and Delivery of Electrical Energy in the 21st Century**. Pittsburgh, PA: IEEE, 2008. p. 1–7.

CHEN, Y.-M.; CHANG, C.-H.; WU, H.-C. Dc-link capacitor selections for the single-phase grid-connected pv system. In: IEEE. **International Conference on Power Electronics and Drive Systems (PEDS)**. Taipei, 2009. p. 72–77.

CHINIFOROOSH, S.; JATSKEVICH, J.; YAZDANI, A.; SOOD, V.; DINAHAHI, V.; MARTINEZ, J.; RAMIREZ, A. Definitions and applications of dynamic average models for analysis of power systems. **IEEE Transactions on Power Delivery**, IEEE, v. 25, n. 4, p. 2655–2669, 2010.

DELTA. **Retrofit of PV plants in Germany for 50.2 Hz issue**. Available in: <<http://www.solar-inverter.com/en-GB/797.htm>>. Accessed: November 18. 2014.

DOLARA, A.; FARANDA, R.; LEVA, S. Energy comparison of seven mppt techniques for pv systems. **Journal of Electromagnetic Analysis and Applications**, Scientific Research Publishing, v. 3, p. 152–162, 2009.

EPE. Empresa de Pesquisa Energética. **Leilão de Energia de Reserva 2014 atrai investimentos de R\$ 7,1 bilhões**. Available in: <www.epe.gov.br> Accessed: January 20. 2015.

FRAUNHOFER ISE. **Recent Facts about Photovoltaics in Germany**. Available in: <www.ise.fraunhofer.de>. Accessed: March 20. 2015.

GULACHENSKI, E.; KERN, E.; FEERO, W.; EMANUEL, A. Photovoltaie generation effects on distribution feeders, volume i: Description of the gardner, massachusetts, twenty-first century pv community and research program. **EPRI report EL-6754, Tech. Rep**, 1990.

HINGORANI, N. G.; GYUGYI, L. **Understanding FACTS, Concepts and Technology of Flexible AC Transmission Systems**. [S.l.]: IEEE press, 2000.

IEA. **Trends 2015 in Photovoltaic Application**. International Energy Agency. Report IEA-PVPS T1-27. Available in: <<http://www.iea.org/>>. 2015.

IEA. **Tracking Clean Energy Progress**. International Energy Agency, report, 2015. Available in: <www.iea.org>.

IRENA. **Renewable Power Generation Costs in 2014**. The International Renewable Energy Agency, report, 2015. Available in: <www.irena.org>.

ISLAM, M. R.; GUO, Y.; ZHU, J. **Power converters for medium voltage networks**. [S.l.]: Springer, 2014. 38-40 p.

J.A. PALUDO. **Avaliação dos Impactos de Elevados Níveis de Penetração da Geração Fotovoltaica no Desempenho de Sistemas de Distribuição de Energia Elétrica em Regime Permanente**. Dissertação (Mestrado) — Universidade de São Paulo, 2014.

JARDINI, J. A.; TAHAN, C.; GOUVEA, M.; AHN, S. U.; FIGUEIREDO, F. Daily load profiles for residential, commercial and industrial low voltage consumers. **IEEE Transactions on Power Delivery**, IEEE, v. 15, n. 1, p. 375–380, 2000.

KAZMIERKOWSKI, M. P.; MALESANI, L. Current control techniques for three-phase voltage-source pwm converters: a survey. **IEEE Transactions on Industrial Electronics**, IEEE, v. 45, n. 5, p. 691–703, 1998.

KUNDUR, P.; BALU, N. J.; LAUBY, M. G. **Power system stability and control**. [S.l.]: McGraw-hill New York, 1994. v. 7.

KYOCERA. **KD205GX-LP: Módulo Fotovoltaico Policristalino de Alta Eficiencia**. Available in: <<http://www.kyocerasolar.com/assets/001/5201.pdf>>. Accessed: June 8. 2014.

LEONHARD, W. **Control of electrical drives**. [S.l.]: Springer Science & Business Media, 2001. 85–87 p.

- LI, H.; XU, Y.; ADHIKARI, S.; RIZY, D. T.; LI, F.; IRMINGER, P. Real and reactive power control of a three-phase single-stage pv system and pv voltage stability. In: IEEE. **IEEE Power and Energy Society General Meeting**. San Diego, CA, 2012. p. 1–8.
- MAHMOOD, F.; VANFRETTI, L.; HOOSHYAR, H. Modeling of a detailed photovoltaic generation system for emt-type simulation. In: IEEE. **Energy Conference (ENERGYCON), 2014 IEEE International**. Cavtat, 2014. p. 916–921.
- MATHWORKS. **PV array block**. Matlab Simulink v. 2015a. 2015.
- MITSUBISHI ELECTRIC. **Mitsubishi Electric Photovoltaic Module UD5 Series**. Available in: <www.u-renew.com>. 2015.
- MME. **Brazilian Energy Balance**. Ministério de Minas e Energia. Available in: <ben.epe.gov.br>. 2015.
- MOHAN, N.; UNDELAND, T.; ROBBINS, W. **Power electronics: converters, applications, and design**. 3. ed. [S.l.]: John Wiley & Sons, 2007. 201-210 p.
- NREL. **A Policymaker's Guide to Feed-in Tariff Policy Design**. National Renewable Energy Laboratory. Available in: <http://www.nrel.gov>. 2010.
- NREL. **MIDC Research Stations**. National Renewable Energy Laboratory. Available in: <http://www.nrel.gov>. 2015, April 10.
- PRICE, W.; CHIANG, H.-D.; CLARK, H.; CONCORDIA, C.; LEE, D.; HSU, J.; IHARA, S.; KING, C.; LIN, C.; MANSOUR, Y. et al. Load representation for dynamic performance analysis. **IEEE Transactions on Power Systems**, IEEE, v. 8, n. 2, p. 472–482, 1993.
- QI, L.; WOODRUFF, S.; STEURER, M. Study of power loss of small time-step vsc model in rtds. In: IEEE. **IEEE Power Engineering Society General Meeting**. Tampa, FL, 2007. p. 1–7.
- REKINGER, M.; THIES, F.; EUROPE, S. P.; MASSON, G.; ORLANDI, S.; INSTITUTE, B. **Global market outlook for solar power 2015-2019**. [S.l.], 2015.
- SALLES, M. **Análise do desempenho dinâmico de geradores eólicos conectados em redes de distribuição de energia elétrica**. Dissertação (Mestrado) — Universidade Estadual de Campinas, 2004.
- SOLARANYWHERE. **Irradiance and weather data**. 2012, March 22. Available in: <https://www.solaranywhere.com>.
- TEODORESCU, R.; LISERRE, M.; RODRIGUEZ, P. **Grid converters for photovoltaic and wind power systems**. [S.l.]: John Wiley & Sons, 2011. v. 29. 217 p.
- U.S. DEPARTMENT OF ENERGY. **SunShot Initiative Portfolio Book**. Available in: <http://energy.gov/>. 2014.
- VARMA, R. K.; RAHMAN, S. A.; VANDERHEIDE, T. New control of pv solar farm as statcom (pv-statcom) for increasing grid power transmission limits during night and day. **IEEE Transactions on Power Delivery**, IEEE, v. 30, n. 2, p. 755–763, 2015.

VILLALVA, M. **Conversor Eletrônico de Potência Trifásico para Sistema Fotovoltaico Conectado à Rede Elétrica**. Tese (Doutorado) — UNICAMP, p. 54, 2010.

YAN, Z.; FEI, L.; JINJUN, Y.; SHANXU, D. Study on realizing mppt by improved incremental conductance method with variable step-size. In: IEEE. **3rd IEEE Conference on Industrial Electronics and Applications**. Singapore, 2008. p. 547–550.

YAZDANI, A.; DASH, P. P. A control methodology and characterization of dynamics for a photovoltaic (pv) system interfaced with a distribution network. **IEEE Transactions on Power Delivery**, IEEE, v. 24, n. 3, p. 1538–1551, 2009.

YAZDANI, A.; FAZIO, A. R. D.; GHODDAMI, H.; RUSSO, M.; KAZERANI, M.; JATSKEVICH, J.; STRUNZ, K.; LEVA, S.; MARTINEZ, J. A. Modeling guidelines and a benchmark for power system simulation studies of three-phase single-stage photovoltaic systems. **IEEE Transactions on Power Delivery**, IEEE, v. 26, n. 2, p. 1247–1264, 2011.

YAZDANI, A.; IRAVANI, R. **Voltage-sourced converters in power systems: modeling, control, and applications**. [S.l.]: John Wiley & Sons, 2010.

Appendices

APPENDIX **A**

System Parameters

A.1 Simulation Parameters

Table 2 – Simulation parameters

Simulation Type	Discrete
Solver type	Tustin
Step	Fixed
Power sample time	50 μs
Control sample time	100 μs

Table 3 – Parameter of the PV generator

Parameter	Value
Number of cells per module	54
Number of series-connected modules per string (Ns)	38
Number of parallel strings (Nr)	193
Maximum power per module (W)	205.09
Open circuit voltage Voc (V)	33.1999
Short-circuit current Isc (A)	8.3596
Voltage at maximum power point Vmp (V)	26.6
Current at maximum power point Imp (A)	7.7096
Temperature coefficient of Voc (V/°C)	-0.12
Temperature coefficient of Isc (A/°C)	0.005016
Diode Quality factor	1.5

Table 4 – Parameter of the PV system

Parameter	Value
C (μF)	9343
L (μH)	100
R ($\text{m}\Omega$)	1
Voltage ratio of Tr (kV)	12.47/0.48
Rating of Tr (MVA)	1.5
Inductance of Tr (p.u.)	0.1

Table 5 – Parameters of the MPPT scheme

Parameter	Value	Comment
Error (ϵ)	0.001	
Vinit	1261.6 x 0.8	Initial voltage (V)
Enable	0.5	Start time (s)
N1	0.09	Left side of MPP
N2	0.045	Right side of MPP
Dmax	20	Max limit of voltage step (V)
Sample time	50	μs

Table 6 – Parameters of the controllers

Real and reactive power	Value	Comment
τ_i	1	ms
k_p	0.127	
k_i	1	
DC-Link		
k_p	2.29	
T_i	0.0018	s
a	1.4	
Vac		
K	800	

A.2 Parameters of the Test network

Table 7 – Parameters of the transformers

Transf.	Sn (MVA)	V1 (kV)	R1 (p.u.)	L1 (p.u.)	V2 (kV)	R2 (p.u.)	L2 (p.u.)	Rm (p.u.)	Lm (p.u.)
T1	100	132	0.00	0.02	33	0.00	0.02	500	500
T2	100	132	0.00	0.02	33	0.00	0.02	500	500
T3	50	33	0.00	0.01	12.47	0.00	0.01	500	500

Figure 48 – I-V and P-V curves of the 1.5 MWp photovoltaic generator with constant irradiance at $1000 \frac{W}{m^2}$

Source: MathWorks (2015)

Source: MathWorks (2015)

Table 8 – Parameters of the transmission lines

Line	R (Ω)	L (mH)
2-4	2.34	9.9
2-3	0.486	5.54
3-4	2.6	12.0
4-5	1.3	6.0
5-6	1.04	4.8

Table 9 – Nominal load values

Bus	P (MW)	Q (MVar)
2	50.0	12.0
3	6.0	2.0
4	24.0	5.0
5	12.0	3.0

Figure 49 – I-V and P-V curves of the 1.5 MWp photovoltaic generator with constant temperature at 25°C

Source: MathWorks (2015)

A.3 Code of the MPPT-Incremental Conductance Method

```
function Vr = Increm(V, I, Enable, ir)
persistent Vold Iold Irold;
dataType = 'double';

%Initialization of voltage, current and radiation
vectors
if isempty(Vold)
    Vold = 0;
    Iold = 0;
    Irold = 0;
end

%Calculating initial voltage as 0.8 times open circuit
voltage
Vinit=1262*0.8;

%Setting error
error=0.001;

%Previous calculations
dV = V - Vold;
dI = I - Iold;
dIr = ir -Irold;
dVabs = abs(dV);
dIabs = abs(dI);
dP = (V*I)-(Vold*Iold);
c=dP/dV;
y=dI/dV+I/V;
x = abs(y);
N = 0.09;

%D step calculations:
%1)left side of the mppt
d1 = N*abs(c);

%2)right side of the mppt
d2=0.5*d1;

%Max limit to the step voltage change
if dIr>=0
    if d2<24
```

```

        d=d2;
    else
        d=24;
    end
else
    if d1<24
        d=d1;
    else
        d=24;
    end
end

%Incremental conductance algorithm.
if Enable > 0
    if ((dVabs < error) && (dIabs < error))
        Vr = V;
    elseif ((dVabs < error) && (dI > 0))
        Vr = V + d;
    elseif ((dVabs < error) && (dI < 0))
        Vr = V - d;
    elseif ((dVabs >= error) && (x < error))
        Vr = V;
    elseif ((dVabs >= error) && (x >= error) && (y > 0))
        Vr = V + d;
    elseif ((dVabs >= error) && (x >= error) && (y < 0))
        Vr = V - d;
    else
        Vr = V;
    end
else
    Vr = Vinit;
end

%Saving the (k-1) voltage and current.
Vold = V;
Iold = I;
Irold = ir;

```

APPENDIX **B**

Publications

MONTENEGRO, C. F. T.; SALLES, M. B. C; MONARO, R. M. Análise do desempenho dinâmico de redes de distribuição/subtransmissão com alta penetração de geração fotovoltaica. In: 10^o Congresso sobre Geração Distribuída e Energia no Meio Rural, AGRENER GD 2015, São Paulo, Brazil, 2015.

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MONTENEGRO, C. F. T.; LOURENÇO, L. F. N.; SALLES, M. B. C; MONARO, R. M. Control strategies for mitigating the effect of solar irradiance changes on voltage regulation for a utility-scale PV system. In: ICRERA 2016 : 18th International Conference on Renewable Energy Resources and Applications, Paris, France, June 20-21, 2016.