UNIVERSIDADE DE SÃO PAULO–USP
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**Technical cost of operating a PV
installation as a STATCOM during
nighttime**

São Paulo
2017

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Dissertação de mestrado apresentada à Escola Politécnica para a obtenção do título de Mestre em Ciências.

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This work is dedicated to my parents.

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“May you live in interesting times.”
(Chinese curse)

Resumo

O suporte de potência reativa por fazendas solares fotovoltaicas está sob discussão em diversos países. Este tipo de operação foi proposta pois o conversor das fazendas solares é um equipamento de custo elevado que é usualmente utilizado abaixo de sua potência nominal. Este trabalho propõe uma metodologia para estimar a capacidade de suporte de reativos e o custo técnico associado na operação de uma fazenda solar fotovoltaica como um STATCOM durante o período da noite. O custo técnico desta operação está associado à necessidade da compra de potência ativa da rede elétrica para suprir as perdas de energia para compensar as perdas nos equipamentos. Uma estimativa precisa deste custo técnico é de interesse tanto dos empreendedores que possuem fazendas fotovoltaicas como dos operadores da rede elétrica para que se avalie a viabilidade econômica deste tipo de operação. Para ilustrar a metodologia proposta, uma fazenda solar fotovoltaica de 1.5 MWp é considerada. Através da avaliação das perdas em cada componente (conversor, reator, filtro e transformador), um mapa de capacidade de suporte de potência reativa é obtido integrando os custos técnicos para cada ponto de operação. A análise realizada neste trabalho destaca os pontos chave para a operação noturna de uma fazenda solar como STATCOM: o sistema deve incluir um diodo de bloqueio, o mapa de capacidade é assimétrico, a operação com tensão do circuito CC é desejável e resulta em economia de energia de 8.9 % em comparação com operação com a operação em tensão nominal fixa do circuito CC.

Palavras-chave: Fazenda solar fotovoltaica. STATCOM. Perdas de energia.

Abstract

Reactive power support by photovoltaic farms has been under discussion in several countries. This kind of operation has been proposed because the photovoltaic farm converter is an expensive asset that is often used well below its power rating. This paper proposes a methodology for estimating the reactive power support capability and the associated technical cost of operating a photovoltaic installation as a STATCOM at nighttime. The technical cost is related to the need to buy active power from the grid to compensate for power losses. A precise estimation of this cost is of interest for both photovoltaic farm owners and grid operators to be able to evaluate the economic feasibility of this kind of operation. In order to illustrate the proposed methodology, a 1.5 MWp photovoltaic farm is considered. By evaluating the losses of each component (converter, tie reactor, filter and transformer), a reactive power support capability map integrating the technical cost for each point of operation is obtained. The analysis outlines key points to operate a PV farm as a STATCOM at nighttime: the system must include a blocking diode, the capability map is asymmetric, an operation with variable DC-link voltage is desirable and can lead to savings of up to 8.9 % in comparison with operation at fixed nominal DC-link voltage.

Keywords: Photovoltaic solar farms. STATCOM. Power losses.

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List of acronyms

AC alternate current

DC direct current

MPP maximum power point

MPPT maximum power point tracker

PV photovoltaic

VSC voltage source converter

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Introduction

This work aims at evaluating the technical cost of operating a photovoltaic (PV) installation as a static var compensator (PV-STATCOM) at nighttime and to demonstrate that this cost can be reduced by variable direct current (DC) circuit voltage operation. To do so, a methodology for evaluating power losses by electromagnetic transient simulations is proposed. The main contributions of this work are: the systematic methodology for evaluating power losses of PV-STATCOM operation relying entirely in simulations; a reactive power support capability map that summarizes power losses and reactive power support capability in function of DC link voltage; the demonstration that variable DC voltage operation is able to reduce the amount of power that must be bought from the grid for PV-STATCOM nighttime operation. Moreover, a precise estimation of the technical cost is of interest for both PV farm owners and grid operators to be able to evaluate the financial gain of this kind of operation, and to bid accordingly in future markets for ancillary services.

This chapter is structured as follows: in section 1.1 the motivation of the present study is discussed; section 1.2 presents the objectives of this work; section 1.3 presents the materials and methods used in this work; section 1.4 presents this text overview; finally section 1.5 summarizes the publications done by the author during the masters period.

1.1 Motivation

With the continued growth of renewable energy, grid operators are facing the challenge of integrating large amounts of distributed and variable generation [1, 2] while maintaining system stability, continued operation and power quality. grid codes for the grid connection of renewable energy power plants are being developed [3]. Desired power plants characteristics to fulfill this goals can be achieved through grid codes [3].

Grid codes are technical requirements for grid interconnection of power plants that ensures power system stability, reliability and safe operation. Power system operators

are responsible for such specifications and must keep in sight current trends to accurately estimate growth in new technologies to avoid costly retrofitting and legal problems due to requirement change after power plants are commissioned [1, 4].

The first grid codes for the grid connection of small-scale PV systems, such as IEEE 1547 [5] and EN 50160 [6], prevented them from offering voltage/reactive power support [1, 3]. In 2008, a grid code [7] was adopted in Germany that required reactive power support from utility scale PV systems. This grid code is expected to become a reference in Europe [3].

Today, reactive power support by PV farms is under discussion in several countries [4]. This can be explained by two facts. First, the cumulated utility scale installed PV power is estimated to reach 290 GW by 2019 [3, 8] and therefore PV farms could have a strong impact in the operation of the grid. Second, most of large-scale PV systems are connected to the grid using a voltage source converter (VSC) that can be used as a STATCOM [9]. This converter is an expensive asset that is used most of the time well below its power rating during daytime, and is inactive during nighttime.

A PV farm converter being used to provide reactive power support is then referred to as "PV-STATCOM". The PV-STATCOM was first discussed by Varma *et al.* [10] for nighttime. This application is particularly attractive as a way for the PV farm operator to increase his revenues at a time when the PV farm is inactive. In [10] was shown that PV farm VSC can be used as a STATCOM during nighttime and it prevents the point of common coupling to arise beyond constraints due to increased nighttime wind power production.

Following work from the same authors [11, 12] extended the study to daytime operation. In that case, the power converter transfers both active and reactive power to the grid. In reference [11], the PV-STATCOM concept was applied to supply the necessary reactive power for an asynchronous motor (heat pump) for both steady-state and transient operation. In reference [12], it was demonstrated that a PV-STATCOM can increase the power transfer limits of a transmission system. Reactive power support by one-phase and three-phase single-stage PV systems was also discussed by [13, 14, 15] focusing on control strategies to keep the converter within its operating limits. However, none of those works discussed the technical cost of operating a PV farm as a STATCOM.

1.2 Objective

The three main objectives of this work are: evaluate the technical cost of operating a PV-STATCOM during nighttime; demonstrate that variable DC link voltage operation is able to reduce losses in the PV-STATCOM operation; the proposition of a methodology that relies entirely in electromagnetic transient simulations for evaluating the losses.

In comparison to previous works, the originality of the proposed approach is to be

systematic and to include all the components of a PV-STATCOM. Indeed, many works are dealing with the power losses of the switches of VSC [16, 17, 18, 19, 20, 21], the power losses of the interface reactor, that is required for the good operation and control of the VSC, are either simply neglected [22, 23], or roughly included using a percentage of the active power [24]. Similarly the losses of the transformer and filter are usually not included.

1.3 Materials and methods

To achieved these objectives the following steps were conducted: first, the modeling, dimensioning and control of a PV farm and the PV-STATCOM were studied. These studies allowed the understanding of the main source of power losses during nighttime operation of a PV installation as a STATCOM and the proposal of a test system for a case study. Then, a literature survey was conducted on how to calculate losses from these components. This procedure was necessary to put together all the elements of the proposed methodology for evaluating power losses.

The proposed test system for a case study and the methodology for evaluating power losses were then implemented in Matlab/Simulink toolbox *SimPowerSystems*. Obtaining a reactive power support capability map with good resolution requires a large number of simulations of a grid connected PV farm. Therefore, the materials needed for the execution of this work were a Matlab/Simulink toolbox *SimPowerSystems* license and adequate computational resources.

1.4 Text overview

Chapter 2 presents the modeling and dimensioning of a single stage PV farm connected to the electric grid. A simple PV panel model is presented and discussed. The main components of the PV farm, namely the tranformer, the tie reactor and the DC circuit are presented along with guidelines for their dimensioning.

Chapter 3 presents the PV farm control system and the tuning of the controllers. Previously from tuning the controllers the modeling of the alternate current (AC) and DC circuits is presented and a detailed derivation of the AC circuit current and DC circuit voltage plants transfer function is shown. Then, the controllers tuning guidelines are presented. Finally, the test system parameters values are listed and a step test of the controllers is shown.

Chapter 4 presents the PV farm operation for both day time and nighttime. The day time scenario considered that only active power is injected into the grid. For nighttime operation two scenarios were considered: a constant DC voltage and a constant reactive power support. These three scenarios allowed the evaluation of the reference tracking and

the disturbance rejection of the controllers. It was concluded that the same controllers are keen to achieve the requirements for both day time and nighttime operation.

Chapter 5 presents how power losses were calculated and the methodology for evaluating the technical cost of operating a PV-STATCOM during nighttime. VSC losses are decomposed in switching and conduction losses and how their estimation by look-up tables is discussed. Transformer and tie reactor losses are also presented.

Chapter 6 presents the results from this research. Power losses estimated according to the proposed methodology of each PV-STATCOM components are presented. Overall PV-STATCOM losses are then presented and from them, a reactive power support capability map in function of DC voltage is presented. The map is applied to optimize a reactive power dispatch demonstrating that variable DC voltage operation during nighttime results in significant savings for the PV farm operator if compared to fixed nominal DC voltage operation.

Finally, chapter 7 presents the conclusions.

1.5 Awards and publications

The published works during the Masters period are summarized below.

Publication in national conference:

1. LOURENÇO, L. F. N.; SALLES, M. B. C. . Análise de Sensibilidade da Produção de Energia de Turbinas Eólicas Modernas no Brasil. In: AGRENER, 2015, São Paulo. 10º Congresso sobre Geração Distribuída e Energia no Meio Rural, 2015.

Publications in international conferences:

1. MONTENEGRO, C. T. ; LOURENÇO, L. F. N. ; SALLES, M. B. C. ; MONARO, R. M. . Dynamic Performance Analysis of Distribution/ Sub-Transmission Networks with High Penetration of PV Generation. In: ICRERA 2016: International Conference on Renewable Energy Resources and Applications, 2016, Paris. International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering, 2016. v. 10. p. 742-476.
2. NAKATA, B.H.; LOURENÇO, L.F.N.; SALLES, M.B.C. ; Voltage Control Analysis for Integrating Wind Generation in Distribution/Sub-Transmission Grids. In: International Conference on. CLEAN ELECTRICAL POWER Renewable Energy Resources Impact (ICCEP 2017), 2017, Alghero. anais, 2017.

Awards from conferences:

1. Best paper award from the 18th ICRERA: International Conference on Renewable Energy Resources and Applications, 2016, Paris.

1.6 Chapter remarks

This chapter presented an introduction to this work. The motivation, objectives, materials and methods and the dissertation structure were presented. Furthermore, a list of publications done by the author during the Masters period is shown.

Next chapter presents PV farm modeling and dimensioning.

PV farm modeling and dimensioning

This chapter aims at presenting the modeling and dimensioning of a single stage PV farm connected to grid through a VSC. The PV farm model and its components are presented. Then, the modeling and dimensioning of each individual component is presented as well. This model serves as base of the test system implemented in chapter 3 and was developed in partnership with the Group of electrical engineering, Paris (GeePs) from CentraleSupélec.

This chapter is structured as follows: section 2.1 presents the system modeling; section 2.2 presents the PV panel model; section 2.3 presents the VSC and discusses the need for a detailed converter model; section 2.4 presents the tie reactor dimensioning and modeling; section 2.5 presents the voltage filter and its dimensioning; section 2.6 presents the transformer features and its dimensioning; section 2.7 presents the DC circuit voltage and the capacitor dimensioning; finally, section 2.8 presents this chapter remarks.

2.1 PV farm model

The PV farm modeled in this work is a single-stage PV farm whose topology is presented in Fig. 1. A PV module is connected to a VSC through a DC circuit. The VSC converts the DC current generated by the PV panel into AC current. A tie reactor is connected at the output of the VSC. The reactor output is connected to the step-up transformer that elevates the voltage generated by the converter into grid voltage levels.

The model was implemented in Matlab *SimPowerSystems* and was developed in partnership with the Group of electrical engineering, Paris (GeePs) from CentraleSupélec. In Fig. 1 main components from the PV farm can be seen: the PV panels, DC circuit capacitor, the tie reactor, the filter and the transformer alongside with signal conventions for power transfer. In the following sections, each of the mentioned components are presented in detail.

Figure 1 – Grid connected PV farm scheme.

Source: Author.

2.2 PV panel

The PV panel is the device responsible for converting the energy from inciding sunlight photons into electrical energy. The basic element from the PV panels are the PV cells that are associated in series to form PV strings [25]. From the PV strings series and parallel associations, PV panels with different powers can obtained [25].

An ideal PV panel can be modeled as a current source in parallel with a Shockley diode as shown in Fig. 2 [26].

Figure 2 – Ideal PV panel model.

Source: Author.

The PV panel current I can be written as [26]:

$$I = I_{pv} - I_d \quad (1)$$

where I is the PV panel output current, I_{pv} the current generated from converting the fotons energy and I_d the diode current. In (1), I_{pv} value depends only on the solar irradiation and the panel p - n junction temperature.

The diode current I_d is calculated as [25]:

$$I_d = I_o[e^{\frac{qV}{akT}} - 1] \quad (2)$$

where I_o is the reverse saturation current from the diode, q is the elementary electron charge, a is the diode ideality factor, k is the Boltzmann constant and T the temperature (in kelvin) from the PV cell p - n junction.

Assuming a constant operating temperature from the PV panel one can present a plot of (1) by parts as in Fig. 3 [25]. The current I_{pv} depends exclusively from the solar irradiance, however I_d is dependent on the voltage V applied to the PV panel. From the subtracion of this parts, the PV panel IxV curve can be obtained.

Figure 3 – Ideal PV panel equation plot by parts.

Source: Author.

The PV panel IxV curve was obtained in Fig. 3 for specific irradiance and temperature conditions known as standard test conditions (STC). The STC are the conditions for which the manufacturers present the PV panels properties. The STC are 1.000 W/m² for solar irradiance and 25°C for temperature.

However, the PV panel will rarely operate in practice in the STC. Hence, the PV panel performance in different operating conditions is shown in Fig. 4. In Fig. 4(a), the IxV curve was obtained for a 1.000 W/m² constant solar irradiance and temperatures from 25°C to 100°C. In Fig. 4(b), the IxV curve was obtained for a 25°C temperature and solar irradiances from 250 W/m² to 1.000 W/m².

From the curves presented in Fig. 4, two noticeable points can be seen. The first one is the PV short circuit current. The short circuit current is defined as the output PV panel current when its terminals are short circuited [26]. The second one is the open circuit voltage. The open circuit voltage is defined as the voltage that results in a null PV panel current output.

Another curve of interest is the curve that relates the power converted by the PV panel in function of the voltage applied to the PV panel. To obtain this curve, one must

Figure 4 – PV panel $I \times V$ curve for different operating conditions.

Source: Author.

multiply the I and V values presented in Fig. 4. The resulting $P \times V$ curve is presented in Fig. 5. From this figure, one can note that the voltage applied to the PV panel has influence over its output power. So, to guarantee the maximum power production from the PV farm a maximum power point tracking (MPPT) scheme is required to generate the reference for the DC circuit voltage.

Figure 5 – PV panel $P \times V$ curve for different operating conditions.

Source: Author.

2.3 Voltage source converter

The VSC is responsible for converting the direct voltage at the DC circuit into alternate voltage to be delivered to the grid. There are two class of models that can be chosen for the VSC: the averaged model and the detailed model [27].

The converter averaged model does not take into account the semiconductor switches and, to represent DC/AC conversion, it employs three controlled voltage sources (one for each phase). However, the use of an averaged model reduces the simulation time. These voltage sources are controlled by the modulation index generated by a chosen modulation technique [28]. Hence, the averaged model for the VSC cannot be used in studies where high frequency phenomena is being investigated nor when details of switching are required [28, 27].

Therefore, a detailed model is required to evaluate the power losses from the VSC. The detailed model considers the semiconductor switches in the DC/AC conversion process. In this work, an insulated gate bipolar transistor (IGBT) based VSC was considered. The detailed switch model for this type of VSC consists in an IGBT with an anti-parallel diode [29]. There is a disadvantage in employing a detailed converter model because simulation times are increased due to the need of simulation steps in the order of micro-seconds to accurately evaluate switching transients [20].

2.4 Tie reactor

The tie reactor (or interface reactor) is an important device in the modeling of PV farm because it is responsible for the interconnection of the VSC with the electric grid. In this work a RL tie reactor was implemented due to its simple dimensioning and because controller tuning relationships can be directly applied for systems that adopt this reactor topology [30, 31, 32].

The tie reactor can be dimensioned as [27]:

$$L_r = 0.1 L_{base} \quad (3)$$

where L_r is the interface reactor inductance and L_{base} is the base inductance.

2.5 Filter

The filter is responsible for filtering frequencies above the modulation frequency. A single tuned filter was chosen for this work [33]. It is composed of a capacitor (C_f) in series with an inductance (L_f). The R_f resistor show in Fig. 1 corresponds to the parasitic resistance of the inductor. The dimensioning presented below is based on [33].

The dimensioning of the filter is carried based on its cut-off frequency ω_f , which is chosen as:

$$\omega_f = 2\pi f_{PWM} \quad (4)$$

where f_{PWM} is the converter switching frequency.

For a LC series filter, the cut-off frequency can be calculated as:

$$\omega_f = \frac{1}{\sqrt{L_f C_f}} \quad (5)$$

The inductor is chosen based on its quality factor. Typical values for the quality factor are in the range of $50 < q_f < 100$ with q_f defined as [33]:

$$q_f = \frac{\omega_f L_f}{R_f} \quad (6)$$

Hence, the capacitor C_f can be chosen as:

$$C_f = \frac{1}{L_f \omega_f^2} \quad (7)$$

2.6 Transformer

The transformer function is to elevate VSC voltage levels to voltage levels compatible with the electric grid. The transformer windings are usually connected in delta in the low voltage side (PV farm side) and the high voltage winding is connected in star. This sort of winding connection is desired to avoid distortion in the voltage waveform and also to provide the PV farm insulation from zero sequence faults that might occur in the electric grid side [27].

Figure 6 – Single phase transformer model.

Source: Author.

The transformer can be modeled as three single phase transformers as the one depicted in Fig. 6. In this figure, V_h and V_l are the line-to-line voltages applied to the high

and low voltage windings respectively, r denotes the winding resistency and L the dispersion inductance with subscripts h and l indicating the high and low voltage windings respectively. Finally, the parameter R_p models core losses and the parameter L_m is the transformer magnetizing inductance.

2.7 DC circuit

The DC voltage level and the chosen modulation have influence over the maximum AC voltage that can be generated by the converter [34]. For a given modulation technique, a minimum DC voltage level must be respected. Below $v_{dc \min}$ the VSC operates as a diode rectifier and neither the DC side nor the AC side can be controlled [34]. To avoid converter operation as a diode rectifier for a 2-level sinusoidal PWM $v_{dc \min}$ is given by [30]:

$$v_{dc \min} = x \frac{2\sqrt{2}}{\sqrt{3}} v_{LL \Delta} \quad (8)$$

where x is taken as 1.15 for medium voltage applications [34], $v_{LL \Delta}$ is the line-to-line RMS voltage of the low voltage side of the transformer.

For a PV farm, $v_{dc \max}$ is the maximum photovoltaic module open circuit voltage v_{oc} . It is generally taken as the open circuit voltage for the maximum irradiance at -10°C [35]. In this work, as local irradiance is not known, $v_{dc \max}$ was obtained to an irradiance of 1000 W/m^2 and -10°C .

The DC circuit capacitor is responsible to provide the DC circuit with energy storage and filter the DC current ripple. The DC capacitor is an important component of the system and its dimensioning affects the overall dynamic of the DC circuit [36]. Moreover, its dimensioning is a trade-off between lifetime, voltage ripple and fast dynamic of the DC circuit [30]. Its value can be chosen as [37]:

$$C = \frac{S}{4\pi f_{\min} v_{dc \min} \Delta v_{dc}} \quad (9)$$

where S is the converter apparent power, f is the AC side frequency and Δv_{dc} is the allowable peak-to-peak ripple in the DC circuit.

2.8 Chapter remarks

This chapter presented the modeling and dimensioning of a single-stage PV farm connected to the electric grid. Its main components such as the PV panel, VSC, tie reactor, voltage filter, transformer and DC circuit capacitor were presented and dimensioned along with their main characteristics. Moreover, the need for adequate DC circuit voltage levels for correct converter operation were discussed.

In the next chapter, the control structure of the PV farm and the modeling of AC and DC circuits are presented.

PV farm control

This chapter presents the PV farm control system and the controller tuning. The AC and DC circuits are modeled and a detailed derivation of current and voltage transfer functions is shown. The controllers are tuned according to the symmetrical optimum method. This tuning method has the advantages of good disturbance rejection and well established tuning rules.

The chapter is structured as follows: section 3.1 presents the overall PV farm control system; section 3.2 presents the AC circuit modeling and the current loop tuning; section 3.3 presents the DC circuit modeling and the DC voltage controller tuning; section 3.4 presents the reactive power controller; section 3.5 discusses the maximum power point tracker; section 3.6 presents the test system used throughout this work; finally, section 3.7 presents the chapter remarks.

3.1 PV farm control system

The control system of a PV farm is composed of four main controllers: current and DC voltage controller, reactive power controller and maximum power point tracker (MPPT) as shown in Fig. 7.

Current controller is the inner loop of the control system responsible for controlling the current across the tie reactor [38]. It receives its reference values from the outer DC voltage controller and the outer reactive power controller. The DC voltage controller during day time operation receives $v_{dc \text{ ref}}$ from the MPPT [27]. The MPPT is an iterative algorithm whose objective is to seek the DC voltage corresponding to the maximum power point based on DC voltage and DC current measurements. During nighttime operation, $v_{dc \text{ ref}}$ can be set manually by PV farm operator.

The PLL shown in Fig. 7 is responsible for tracking grid frequency and phase angle and it is necessary for implementing control in the $dq0$ frame [31]. The formulation of the control in the $dq0$ frame was chosen because AC quantities in the abc frame become DC quantities in the $dq0$ frame.

Figure 7 – Grid connected PV farm and its control system.

Source: Author.

There is a blocking diode between the PV modules and the converter. This is necessary to prevent reverse power flow into the panels during nighttime operation.

3.2 Current controller

The current controller is the inner loop of the control system interconnecting the outer control loops. To present the current controller first the modeling of the AC side circuit is presented. A detailed derivation of the current plant transfer function is carried. Then, the current controller is tuned according to the symmetrical optimum method.

3.2.1 AC circuit modeling

As current measurement was taken between the transformer and the grid, the equivalent AC circuit must be obtained by referring voltage and current measurements and component values to the transformer low voltage side. The filter current is not taken into account for the AC circuit modeling. This is because, for the grid fundamental frequency, the filter impedance is high and, therefore, the filter currents are too low to be considered.

The equivalent AC side circuit is presented in Fig. 8. In this figure, $v_{c\ x}$ denotes the converter voltage of phase x , i_x the current of phase x and $v_{g\ x}$ denotes the grid voltage of phase x referred to the transformer low voltage side.

Figure 8 – AC side equivalent circuit referred to transformers low voltage side.

Source: Author.

The equivalent resistance and inductance (r_{eq} and L_{eq}) are obtained by:

$$r_{eq} = r_r + r_l + r'_h \quad (10)$$

$$L_{eq} = L_r + L_l + L'_h \quad (11)$$

where r_l and L_l are the low voltage winding parameters of the transformer and r'_h and L'_h are the high voltage winding parameters referred to the low voltage side.

By applying Kirchhoff voltage law to the AC side circuit:

$$L_{eq} \frac{di_a}{dt} + r_{eq} i_a = v_{c\ a} - v_{g\ a} \quad (12)$$

$$L_{eq} \frac{di_b}{dt} + r_{eq} i_b = v_{c\ b} - v_{g\ b} \quad (13)$$

$$L_{eq} \frac{di_c}{dt} + r_{eq} i_c = v_{c\ c} - v_{g\ c} \quad (14)$$

Isolating the derivative term (12 - 14) become:

$$\frac{di_a}{dt} = -\frac{r_{eq}}{L_{eq}} i_a + \frac{1}{L_{eq}} (v_{c\ a} - v_{g\ a}) \quad (15)$$

$$\frac{di_b}{dt} = -\frac{r_{eq}}{L_{eq}} i_b + \frac{1}{L_{eq}} (v_{c\ b} - v_{g\ b}) \quad (16)$$

$$\frac{di_c}{dt} = -\frac{r_{eq}}{L_{eq}} i_c + \frac{1}{L_{eq}} (v_{c\ c} - v_{g\ c}) \quad (17)$$

The derived AC side equations (15-17) are in the abc frame. To obtain AC side equations in the $dq0$ frame, the voltage invariant Park transform (18) must be applied [39].

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (18)$$

Applying the Park transform and assuming a balanced three-phase voltage, AC side equations can be expressed in a synchronous $dq0$ frame as [39]:

$$\frac{di_d}{dt} = -\frac{r_{eq}}{L_{eq}}i_d + \omega i_q + \frac{1}{L_{eq}}(v_{c\ d} - v_{g\ d}) \quad (19)$$

$$\frac{di_q}{dt} = -\frac{r_{eq}}{L_{eq}}i_q - \omega i_d + \frac{1}{L_{eq}}(v_{c\ q} - v_{g\ q}) \quad (20)$$

where ω is the AC grid angular frequency.

A cross-coupling between i_d and i_q exists which can be removed by adding the feed forward variables Δv_d and Δv_q [30]:

$$\Delta v_d = v_{c\ d} - v_{g\ d} + \omega L_{eq}i_q \quad (21)$$

$$\Delta v_q = v_{c\ q} - v_{g\ q} - \omega L_{eq}i_d \quad (22)$$

Substituting (21) and (22) into (19) and (20) respectively:

$$\frac{di_d}{dt} = -\frac{r_{eq}}{L_{eq}}i_d + \frac{1}{L_{eq}}\Delta v_d \quad (23)$$

$$\frac{di_q}{dt} = -\frac{r_{eq}}{L_{eq}}i_q + \frac{1}{L_{eq}}\Delta v_q \quad (24)$$

The current loop transfer function $G_p(s)$ can be obtained by applying the Laplace transform to (23) and (24) as:

$$G_p(s) = \frac{i_d(s)}{\Delta v_d(s)} = \frac{i_q(s)}{\Delta v_q(s)} = \frac{1}{r_{eq} + L_{eq}s} \quad (25)$$

Active and reactive power can be calculated in the $dq0$ frame as:

$$P = \frac{3}{2}(v_{g\ d}i_d + v_{g\ q}i_q) \quad (26)$$

$$Q = \frac{3}{2}(v_{g\ q}i_d - v_{g\ d}i_q) \quad (27)$$

By synchronizing the d -axis with phase a , (26), (27) become:

$$P = \frac{3}{2}v_{g\ d}i_d \quad (28)$$

$$Q = -\frac{3}{2}v_{g\ d}i_q \quad (29)$$

Therefore, active and reactive power can be controlled independently by manipulating i_d and i_q .

3.2.2 Controller tuning

The current control block diagram is shown in Fig. 9. In this figure, $G_c(s)$, $G_a(s)$ and $G_p(s)$ are the controller, the delay imposed by the converter switching and the current loop transfer functions respectively.

Figure 9 – Block diagram for current controller.

Source: Author.

The delay imposed by converter switching can be modeled as (30) [39][32].

$$G_a(s) = \frac{1}{1 + T_a s} \quad (30)$$

where T_a is given by $1/f_{PWM}$, the 2-level pulse width modulation frequency.

The open-loop transfer function without the controller can be written as (31).

$$G_{p \text{ OL}}(s) = G_a(s)G_p(s) = \frac{\frac{1}{r_{eq}}}{(1 + T_a s)(1 + \frac{L_{eq}}{r_{eq}} s)} \quad (31)$$

As system model was carried in the $dq0$ frame, AC quantities in the abc frame become DC quantities in the $dq0$ frame. Therefore, the use of proportional-integral (PI) controllers guarantee zero steady-state error for current reference tracking [32]. A PI controller transfer function is given by (32).

$$G_c(s) = k_p \left(\frac{1 + T_i s}{T_i s} \right) \quad (32)$$

where k_p and T_i are the controller parameters to be tuned.

Current PI controllers were tuned according to the symmetrical optimal method proposed for plant transfer functions in the form shown by (33) [40]. The symmetrical optimal method has the practical advantage that its tuning relations are well established [40] and it has a good disturbance rejection [41]. The notation used in this work for controller tuning is the same as [30].

$$G(s) = \frac{k}{s(1 + Ts)} \quad (33)$$

The transfer function $G_{p \text{ OL}}(s)$ can be approximated into the form of (33) as $L_{eq}/r_{eq} \gg T_a$ [41] resulting in (34).

$$G_{p \text{ OL}}(s) \approx \frac{1/L_{eq}}{s(1 + T_a s)} \quad (34)$$

With (25) approximated as (34) the current controller can be tuned. The controller tuning using the symmetrical optimum method can be done in two ways: by specifying system open-loop crossover frequency ω_c or by setting a design parameter a . For current controller tuning ω_c is chosen as $2\pi f_{PWM}/10$ to avoid noise [30][31]. Finally, the PI controller can be tuned as (35) [30].

$$\{a, k_p, T_i\} = \left\{ \frac{1}{\omega_c T_a}, \frac{L_{eq}}{a T_a}, a^2 T_a \right\} \quad (35)$$

3.3 DC voltage controller

The DC voltage controller is one of the outer loops of the control system. Its main function is to track the optimum DC voltage reference provided by the MPPT during day time and to track the DC voltage reference manually set by the PV farm operator during nighttime. Hence, the DC controller is important both during day time and nighttime to maximize PV farm incomes. To present the DC voltage controller first the modeling of the DC side circuit is presented. A detailed derivation of the DC voltage plant transfer function is carried. Then, the current controller is tuned according to the symmetrical optimum method.

3.3.1 DC circuit modeling

The DC circuit is shown in Fig. 10.

Figure 10 – DC circuit current diagram.

Source: Author.

From instantaneous power balance [30] between AC and DC sides:

$$v_{dc} i_{dc} = \frac{3}{2} v_g d i_d \quad (36)$$

By using sinusoidal PWM modulation, $v_g d$ in (36) can be substituted by [32]:

$$v_g d = \frac{v_{dc}}{2} \quad (37)$$

resulting in:

$$i_{dc} = \frac{3}{4}i_d \quad (38)$$

Applying Kirchhoff current law in Fig. 10:

$$i_{pv} = i_C + i_{dc} \quad (39)$$

Hence, the capacitor current can be obtained as:

$$i_C = -i_{dc} - i_{pv} \quad (40)$$

The capacitor current is calculated by:

$$i_C = C \frac{dv_{dc}}{dt} \quad (41)$$

Substituting (38) and (41) in (40):

$$C \frac{dv_{dc}}{dt} = -\frac{3}{4}i_d - i_{pv} \quad (42)$$

By applying the Laplace transform to (42) and by considering the PV panel current as a disturbance, the DC voltage transfer function is obtained as:

$$G_v(s) = \frac{i_d \text{ ref}(s)}{v_{dc}(s)} = -\frac{3}{4C} \frac{1}{s} \quad (43)$$

3.3.2 DC voltage controller tuning

Block diagram for the DC voltage control is presented in Fig. 11. In this figure, $G_v(s)$ is the transfer function that models DC circuit dynamics presented in 43. $G_{eq}(s)$ is a first order transfer function with equivalent 10 % settling time to the closed-loop current transfer function 10 % settling time. $G_c(s)$ is the PI controller transfer function with the same structure presented in (32).

Figure 11 – Block diagram for the DC voltage controller.

Source: Author.

The equivalent transfer function has the structure presented in (44). The parameter T_{eq} is obtained dividing the 10 % settling time of the closed current loop step response ($t_{s, 10\%}$) by 2.3 [30].

$$G_{eq}(s) = \frac{1}{1 + T_{eq}s} \quad (44)$$

with

$$T_{eq} = \frac{t_{s, 10\%}}{2.3} \quad (45)$$

The DC voltage open loop transfer function $G_{v\ OL}(s)$ is given by (46). Equation (46) is already in the form of (33). Therefore, symmetrical optimum method tuning relations can be promptly applied.

$$G_{v\ OL}(s) = \frac{-\frac{3}{4C}}{s(1 + T_{eq}s)} \quad (46)$$

For tuning the DC voltage PI controller the tuning relations shown in (47). For DC voltage controller tuning the design parameter a has been specified as 3 [32].

$$\{k_p, T_i\} = \left\{ -\frac{4C}{3aT_{eq}}, a^2T_{eq} \right\} \quad (47)$$

3.4 Reactive power controller

Reactive power controller is one of the outer loops of the control system. It is responsible for generating $i_{q\ ref}$ for the inner current controller. Locking the d -axis into phase a , reactive power reference value can be calculated as (27) [27, 31] resulting in:

$$Q_{ref} = -\frac{3}{2}v_{g\ d}i_{q\ ref} \quad (48)$$

Therefore reactive power controller calculates $i_{q\ ref}$ as (49).

$$i_{q\ ref} = -\frac{2}{3}\frac{Q_{ref}}{v_{g\ d}} \quad (49)$$

3.5 Maximum power point tracker

As seen in Fig. 5 by regulating DC link voltage it is possible to extract maximum power from the PV panels. During daytime operation, the maximum power point tracker (MPPT) scheme is responsible for generating the DC link voltage reference value to achieve this goal. During nighttime operation, as there is no solar irradiance, there is no need for a MPPT scheme as no active power is being produced.

The MPPT can be implemented by methods such as the incremental conductance [28, 27], perturb and observe (P&O) [27, 42] and fuzzy logic [43]. In practice, the incremental conductance and perturb and observe methods are widely applied [27]. The incremental conductance method was implemented by [28]. This work adopted the P&O method due to its simplicity and to extend the algorithms implemented by the research group. The main drawback of this method is that the operating voltage point oscillates around the maximum power point (MPP) [42].

The P&O method consist in periodic disturbances of fixed magnitude ΔV in the voltage applied to the PV panel and evaluating its consequence on power output. First, voltage and current (v_{pv}, i_{pv}) in the PV panel are measured. Then, the power being produced by the PV panel is calculated as:

$$P_{pv}(t) = v_{pv}(t)i_{pv}(t) \quad (50)$$

To locate where the operating point is located the power calculated by (50) is subtracted from the power calculated in the previous simulation step. The result of this operation is divided by the subtraction of voltage levels from the actual and previous simulation step as (51) shows.

$$\frac{P_{pv}(t) - P_{pv}(t - T_S)}{v_{pv}(t) - v_{pv}(t - T_S)} \quad (51)$$

If (51) is greater than zero then the operating point is located at the left hand side of the MPP. Therefore, voltage must be increased of ΔV . If (51) is lesser than zero then the operating point is located at the right hand side of the MPP and therefore voltage must be decreased of ΔV . A flow chart summarizing the P&O method is shown in Fig. 12

Figure 12 – Flow chart of perturb and observe MPPT method.

Source: Author.

Tuning and improvements in the MPPT scheme are outside of the scope of this work. For a detailed discussion on MPPT, reader is referred to [27, 42].

3.6 Test system

The test system is a 1.5 MWp single stage PV farm based on [27] whose control system is shown in Fig. 7.

The converter is a 2-level voltage source converter (VSC). A detailed model has been adopted to model the VSC. This is necessary because the average model does not consider the switches and freewheeling diodes and therefore cannot be used for the evaluation of the converter losses. The converter switches were considered as two ABB 5SNA 1600N170100 IGBT modules in parallel with maximum collector-emitter voltage of 1700 V and maximum DC collector current of 1600 A. To perform the simulation Matlab/Simulink *SimPowerSystems* toolbox has been used.

The tie reactor inductance was chosen as (3) and its resistance (r_r) was chosen as 1 m Ω as [28, 27]. The quality factor of the filter inductor is chosen as 50 and with parasitic resistance R_f of 0.5 Ω . The filter capacitor is then chosen by applying (7). The transformer parameters shown in Fig. 6 were dimensioned as follows: transformer winding resistances were chosen as 0.003 p.u. and winding inductances were chosen as 0.1 p.u. as in [27]. For the other transformer model parameters, a transformer was designed and magnetizing inductance L_m was chosen as 500 p.u. and R_p was obtained as 750 p.u.. The test system parameters are summarized in Table 1.

Table 1 – Test system parameters

Parameter	Value	Unit	Parameter	Value	Unit
C	9343	μF	r_r	1	m Ω
$v_{dc \min}$	900	V	L_r	49	μH
$v_{dc \max}$	1400	V	f_{PWM}	10	kHz
Grid frequency	50	Hz	R_p	750	p.u.
L_m	500	p.u.	R_f	0.5	Ω
L_f	400	μH	C_f	0.64	μF
$v_{LL \Delta}$	480	V	$v_{LL} Y_g$	12.37	kV

Current and DC voltage controllers were tuned according to the symmetrical optimum method presented in this chapter. The controller parameters and step response characteristics are summarized in Table 2. Closed loop step responses from current controller and DC voltage controller are shown in Figs. 13 and 14 respectively.

Table 2 – Controller parameters

Control loop	K_p	T_i	t_s 10%	<i>Overshoot</i>
Current	0.4608	0.0010	1.8 ms	22.6%
DC voltage	-5.4389	0.0069	14.5 ms	17.4%

Figure 13 – Current controller closed loop step response.

Source: Author.

Figure 14 – DC voltage controller closed loop step response.

Source: Author.

3.7 Chapter remarks

This chapter presented PV farm control scheme and controller tuning. First, overall control system was presented. Then AC circuit modeling was presented to derive AC current plant transfer functions and the current controllers were presented along with its tuning by the symmetrical optimum method. It also presented the DC circuit modeling and the derivation of DC voltage controller along with its tuning relations. A simple reactive power controller was also presented.

Next chapter presents the operation of the test system during day time and nighttime.

PV farm operation

This chapter presents the operation of the PV farm during both day time and nighttime operation. To demonstrate the performance of the controllers developed in chapter 3, it was considered that during day time there is no reactive power support. For nighttime operation two scenarios were considered: a fixed DC voltage scenario with a ± 1 p.u. step in reactive power reference and a constant reactive power scenario with a ± 50 V step applied to the DC voltage reference.

This chapter is structured as follows: section 4.1 presents day time operation; section 4.2 presents the nighttime operation with fixed DC voltage; section 4.3 presents the nighttime operation with fixed reactive power support; finally, section 4.4 presents the chapter remarks.

4.1 Day time operation

During day time operation, the PV-STATCOM main goal is to generate active power. The remaining inverter capacity might be used to provide reactive power support [12]. To demonstrate day time operation of the PV farm it was considered that the PV farm does not provide reactive power support during this period. This test evaluates the performance of the DC voltage controller and the current controller in tracking their respective values and how the PV farm behaves during changes in solar irradiance levels regarding active power generation. To verify the PV farm day time operation the irradiance sequence from Fig. 15 was used in this work [28].

The resulting DC voltage, active power and reactive power are shown in Figs. 16, 17 and 18 respectively. In Fig. 16 the performance of DC voltage control can be evaluated. The control is keen to track the reference values generated by the MPPT. The measured DC voltage oscillates around the maximum power point voltage as expected given the structure of the P&O scheme implemented and due to the use of a detailed converter model.

Figure 15 – Irradiance sequence for day time operation of PV farm [28].

Source: Author.

Figure 16 – Day time operation DC voltage of PV farm.

Source: Author.

In Fig. 17(a), the performance of the current controller in tracking a reference signal can be evaluated. The i_d component follow the irradiance curve shape, showing the capability of the tuned controllers to follow the reference signal. In Fig. 17(b) active power P does not have a reference value as by controlling DC voltage we guarantee that

all power being injected in the DC link injected into the electric grid.

Figure 17 – Day time operation active power of PV farm.

Source: Author.

Figure 18 – Day time operation reactive power of PV farm.

Source: Author.

In Fig. 18(a), the performance of the current controller to reject disturbances can be evaluated. In Fig. 18(b), as the PV farm does not provide reactive support in this

scenario, Q_{ref} is set to zero and therefore the i_q component was regulated at zero as well.

4.2 Nighttime operation with fixed DC voltage

During nighttime operation, the entire inverter capacity can be used for reactive power support as active power is not produced at night [10, 12]. To verify the PV farm nighttime operation, the irradiance was kept null and two scenarios were considered: constant DC voltage and constant reactive power support. This section discusses the constant DC voltage variable reactive power support.

The constant DC voltage variable reactive power support aims at evaluating the reference tracking for the current controller and the disturbance rejection by the DC voltage controller in nighttime operation.

Fig. 19 shows the i_q component and reactive power tracking for a ± 1 p.u. step test in Q . As the reactive power controller is a simple $i_{q\ ref}$ calculator, all responsibility of reference tracking falls to the current controller. From Fig. 19 it can be seen that the current controller is capable of tracking references for i_q .

Figure 19 – Reactive power for constant DC voltage nighttime operation of PV farm.

Source: Author.

The disturbance rejection of DC controller can be seen in Fig. 20. In the time instants when a step was applied to the reactive power, a disturbance arise in the DC voltage controller and is quickly suppressed by the controller. This disturbance is due to the change in $i_{q\ ref}$ and the reference tracking of the current controller. With the increase in the i_q component shown in Fig. 19(a), total AC current increases, therefore, joule effect

Figure 20 – Constant DC voltage nighttime operation of PV farm.

Source: Author.

power losses increase in the transformer windings and in the tie reactor. To supply this power losses, active power need to be bought from the grid as can be seen in Fig. 21.

Figure 21 – Active power for constant DC voltage nighttime operation of PV farm.

Source: Author.

Fig. 21 shows the i_d and active power response for the ± 1 p.u. step test in Q . During

the time which Q_{ref} is different from zero, both the i_d component and P are negative meaning that there is a transfer of active power from the grid to the PV farm.

4.3 Nighttime operation with fixed reactive power support

This section evaluates the nighttime operation for a fixed reactive power support and variable DC voltage. Differently from the day time operation when the DC voltage reference was varying quickly due to the MPPT, this test allows the evaluation of the DC voltage controller response to a ± 50 V step. Moreover, it is possible to evaluate the disturbance rejection of the current controller for the i_q component as the DC voltage step has influence on i_q because of the cross coupling terms of the current plant.

Fig. 22 shows the reference tracking of the DC voltage controller. It can be seen that the DC voltage controller is also able to track high value steps in addition to the quick mid value changes of the DC voltage reference provided by the MPPT during day time operation. Fig. 23 shows the i_d component and the P response for the applied DC voltage steps.

Figure 22 – DC voltage for constant reactive power support for nighttime operation of PV farm.

Source: Author.

From Fig. 23 it can be seen that the i_d component has some peaks that could be mistaken as disturbances. However, they are the quick responses of the cascade of DC voltage and i_d component control to charging/discharging of the capacitor to keep track

of the DC voltage level. The first and the last peaks are due to energy bought from the grid (negative i_d) to charge the capacitor. The second and third peaks are due to energy injected into the grid (positive i_d) to discharge the capacitors following the DC voltage step.

Figure 23 – Active power for constant reactive power support for nighttime operation of PV farm.

Source: Author.

Finally, Fig. 24 shows the disturbance rejection of the i_q component controller. As there is no significant variation in the i_d component no significant disturbance is seen in the i_q component. Therefore, i_q and Q are kept at their steady state values.

4.4 Chapter remarks

This chapter presented the test system operation for both day time and nighttime. During day time operation it was considered that the PV farm does not provide reactive power support to verify its performance for irradiance changes and the DC voltage controller tracking of the maximum power point voltage and the disturbance rejection for the current controller. For nighttime operation two scenarios were presented: constant DC voltage to evaluate the performance of the reactive power controller and the disturbance rejection of the DC voltage controller; and constant reactive power support to evaluate DC controller reference tracking during nighttime operation. The controllers demonstrated that they are keen to provide good reference tracking and disturbance rejection during both day time and nighttime operation meaning that the same controller tuning can be used for both day time and nighttime operation.

Figure 24 – Reactive power for constant reactive power support for nighttime operation of PV farm.

Source: Author.

Next chapter presents the proposed methodology for evaluating power losses.

Power losses evaluation

This chapter presents the methodology for power losses evaluation proposed in this work and how power losses were calculated. The methodology hereby presented is a systematic approach based on electromagnetic transient simulations that includes power losses from all key components of the PV farm. During nighttime operation, the sources of power losses in operating a PV-STATCOM are converter losses, transformer losses, tie reactor losses and filter losses. Power losses for each component are presented alongside with a description of the main parameter that have influence over them.

This chapter is structured as follows: section 5.1 presents converter losses and how they are calculated; section 5.2 presents transformer losses; section 5.3 presents reactor losses; section 5.4 presents reactor losses; section 5.5 presents the methodology proposed in this work; finally, section 5.6 presents the chapter remarks.

5.1 Converter losses

The converter losses can be divided into switching losses and conduction losses [20]. Conduction losses are a function of the IGBT current and temperature. Switching losses are a function of IGBT blocking voltage, current and junction temperature [17]. In this work the temperature effect has been neglected: the IGBT junction temperature is assumed to be equal to 125°C which is the maximum recommended operation temperature and it is also the worst case scenario for power losses evaluation.

For converter losses evaluation in an electromagnetic transient analysis the use of detailed switch model proves to be infeasible due to the need of simulation time steps in the order of nanoseconds. So, alternative models have been proposed in the literature. Curve fitting models for calculating power losses were proposed by [16, 17, 18, 19] with focus on VSCs. An electrothermal model has been proposed by [20] for evaluation of heat generation by VSC and performance evaluation of heat sinks. A look-up table for power losses estimation was proposed by [21] and results were used for thermal performance evaluation as well.

The technique described in [21] consists in evaluating power losses in the IGBTs and diodes using look-up tables filled used data from the IGBT datasheet as well as experimental data. A simplification of [21] is adopted in this work and only data from datasheet are required. The datasheet provides only the data for a given voltage. Assuming no loss at zero current/zero voltage, a linear interpolation is made to estimate the losses for other voltages and small currents [33].

With this simplified approach the proposed methodology can also be used in the planning stage of a PV farm when measured data is available. The power loss data of ABB 5SNA 1600N170100 IGBT module was retrieved from the datasheet [44] and was reproduced in Figs. 25 and 26. Also, estimated power losses for 1400 V DC voltage level are shown.

For the IGBTs, the look-up tables for switching losses stores information of the turn on energy (E_{on}) and the turn off energy (E_{off}) in function of the collector current and the DC voltage level. The conduction losses look-up table stores the collector-emitter voltage in function of the collector current.

For the free-wheeling diode only the turn off losses due to reverse recovery (E_{rr}) are considered as they account for 99 % of diode losses [20]. The switching losses look-up table stores E_{rr} in function of the DC voltage and the diode current. The conduction losses look-up table stores the forward voltage in function of the diode current. For full detail on how to assemble the look-up tables readers are referred to [21].

Figure 25 – IGBT switching energy losses and collector-emitter voltage in function of collector current [44].

Source: Author.

For evaluating VSC switching on losses, in each simulation step the IGBTs current $I(t)$ must be measured. If the current $I(t)$ is greater than zero, then the switch is on. The

Figure 26 – Diode switching energy losses and forward voltage in function of diode current [44].

Source: Author.

switch was turned on if the previous simulation step current $I(t - T_S)$ is equal to zero. The actual value of switch current is then used to search the respective $E_{on}(I_{ce})$ value in the look-up table. To adjust energy losses to the actual step DC voltage level a linear relation is used assuming that for 0 V there are no energy losses. Energy losses are finally converted into power losses by dividing the adjusted energy loss value by the simulation time step.

As for evaluating VSC switching off losses the process is similar. Both IGBT and diode actual step currents are compared to their previous step value. If their previous value was different from zero and the actual value is zero then a turn off occurred. The previous step current value is then used to search in the respective look-up table for $E_{off}(I_{ce})$ or $E_{rr}(I_f)$ values. The same linear adjustment is applied to convert energy losses to the corresponding DC voltage level. The energy losses value are finally converted to power losses by dividing respective diode and IGBT energy losses by the simulation time step.

A flow chart summarizing the process for evaluating switching losses described in the last two paragraphs is shown in Fig. 27.

For evaluating VSC conduction losses in each simulation step it is checked whether IGBTs and diodes currents are greater than zero. If they are, then the respective switch element is conducting. For IGBTs the current value is used to search the corresponding collector-emitter voltage (v_{ce}). To obtain the IGBTs conduction power losses the step current is multiplied by the corresponding collector-emitter voltage.

For diodes the current value is used to search the corresponding forward voltage (v_f). To obtain the diode conduction power losses the current is multiplied by the corresponding forward voltage.

Figure 27 – Flow chart for switching losses evaluation.

Source: Author.

A flow chart summarizing the process for evaluating conduction losses is shown in Fig. 28.

5.2 Transformer losses

Transformers have two sources of losses: core and winding losses. Core losses are due to Eddy current losses and hysteresis losses. As for winding losses, they are due Joule effect. Hence, transformer power losses ($P_{transformer}$) can be calculated as:

$$P_{transformer} = P_{core} + P_{windings} \quad (52)$$

where core losses are a function of the applied voltage in the high voltage winding:

$$P_{core} = 3 \frac{V_g^2}{R_p} \quad (53)$$

Figure 28 – Flow chart for conduction losses evaluation.

Source: Author.

with R_p being the resistance that models transformer core losses [45] and V_g the line-to-neutral true RMS value of the voltage applied to the high voltage winding.

Winding losses can be calculated by:

$$P_{windings} = 3r_h I_h^2 + 3r_l I_l^2 \quad (54)$$

where r indicates winding resistance and I is the true RMS value of winding current. The subscripts h and l indicates high and low voltage sides respectively.

For transformer losses, it can be seen that neither core losses nor winding losses depend on DC voltage level.

5.3 Tie reactor losses

For air core tie reactors, power losses are due Joule effect only:

$$P_{reactor\ losses} = 3r_r I^2 \quad (55)$$

where r_r is the reactor resistance and I is the true RMS value of reactor current. It can be seen that tie reactor power losses do not depend on the DC voltage level.

5.4 Filter losses

For the filter, power losses are due Joule effect only:

$$P_{filter\ losses} = 3R_f I_f^2 \quad (56)$$

where R_f is the filter resistance and I_f is the true RMS value of filter current.

5.5 Methodology

The aim of the proposed methodology is to evaluate the reactive power support capability of a PV-STATCOM in nighttime operation and the related technical cost for each point of operation. A flow chart for the proposed methodology is shown in Fig. 29. There are two loops: an outer loop and an inner loop.

The outer loop is responsible for sweeping the DC voltage reference $v_{dc\ ref}$ from the minimum DC voltage $v_{dc\ min}$ up to the maximum DC voltage $v_{dc\ max}$. This is necessary because, the DC voltage level has an influence over the reactive power support capability [36] as well as over the power losses [16]. The inner loop is responsible for sweeping the reactive power reference Q_{ref} from Q_{min} to Q_{max} .

For each operating point $(v_{dc\ ref}, Q_{ref})$, the current and DC voltage controls are checked to assure that the converter is operating correctly. If yes, the operating point is inside the capability area and the system power losses are evaluated. If the DC voltage or current control is lost, the operating point is outside the capability area because the VSC is incapable of delivering Q_{ref} .

5.6 Chapter remarks

This chapter presented sources of power losses in PV-STATCOM operation during nighttime and how they were estimated in this work. First, converter losses were presented and its components (switching and conduction losses) were discussed. Next, transformer and tie reactor losses were presented and they independance from DC voltage level could be verified. Also, voltage filter losses were presented. Finally, a methodology was presented for overall PV-STATCOM power losses evaluation during nighttime operation. This methodology is a systematic approach based on electromagnetic transient simulation that includes power losses from all key compoenets of the system.

The results of applying the afore mentioned methodology to the test system described in chapter 3 are presented in the next chapter.

Figure 29 – Proposed methodology for evaluating power losses flow chart.

Source: Author.

Results and discussions

This chapter presents the evaluation of technical cost in operating a PV installation as a STATCOM. The methodology presented in the previous chapter is applied to the test system and power losses from each component of the PV farm are obtained. Then overall PV-STATCOM power losses are obtained. By evaluating power losses for a wide range of operating points, a reactive power capability support map is presented. A optimization of the reactive power dispatch is made based on the operation map.

This chapter is structured as follows: 6.1 presents the evaluated reactor power losses; 6.2 presents the evaluated transformer power losses; 6.3 presents the evaluated filter power losses section 6.4 presents the evaluated converter losses; 6.5 presents overall PV-STATCOM operation power losses; 6.6 presents the reactive power support capability map; 6.7 presents the reactive power dispatch optimization. Finally, the chapter remarks are presented in section 6.8.

6.1 Reactor losses

Reactor power losses estimate according to the proposed methodology are shown in Fig. 30. The reactor power losses do not depend on the DC voltage level and are symmetrical with respect to Q_{ref} . They depend exclusively on current levels as (49) shows. Therefore reactor power losses increase with reactive power reference values.

6.2 Transformer losses

Transformer power losses estimated according to the proposed methodology are shown in Fig. 31. As reactor losses, transformer losses do not depend on the DC voltage level and are symmetrical with respect to Q_{ref} . For 0 p.u. one can note that power losses are significantly different from zero. This happens because transformer core losses are present whenever a voltage is applied to the transformer windings. Winding losses are

Figure 30 – Tie reactor power losses in PV-STATCOM operation.

Source: Author.

also present due to the active power flow from the grid to the PV farm to supply power losses.

Figure 31 – Transformer power losses in PV-STATCOM operation.

Source: Author.

6.3 Filter losses

The filter losses estimated according to the proposed methodology are shown in Fig. 32. It shows that filter losses are dependent on DC voltage levels. For a fixed DC voltage, the modulation index must increase in order to generate higher voltages at the VSC output to enable the delivery of Q_{ref} . Therefore, the harmonic content increases with the increase of Q_{ref} , resulting in higher power losses. Moreover, for a fixed Q_{ref} the increase in DC voltage results in a decrease of the modulation index for generating the same voltage at the VSC output. Hence, for an increase in DC voltage the harmonic content decreases and so do the power losses.

Figure 32 – Voltage filter losses in PV-STATCOM operation.

Source: Author.

6.4 Converter losses

As explained in section 5.1 converter losses may be divided into two categories: switching and conduction losses. Conduction losses depend only on the current level that flows through the switches and are shown in Fig. 33. As for switching losses, they depend on DC voltage level and are shown in Fig. 34. Therefore converter losses depend on the DC voltage level.

Results from converter power losses evaluation are shown in Fig. 35. Curves presented in Fig. 35 reflect the reactive power capability as for lower voltage levels there is an upper limit for Q_{ref} .

Figure 33 – VSC conduction losses in PV-STATCOM operation.

Source: Author.

Figure 34 – VSC switching losses in PV-STATCOM operation.

Source: Author.

One can note that converter losses are different from zero for $Q_{ref} = 0$ p.u.. This happens because the VSC must generate a voltage waveform with same phase angle as the grid in stand-by operation. This effort requires switching of the VSC when no reactive power is being injected into the grid.

Figure 35 – VSC losses in PV-STATCOM operation.

Source: Author.

6.5 PV-STATCOM losses

Finally, power losses evaluation in PV-STATCOM operation are shown in Fig. 36. Results reflect the effect that the DC voltage has over PV-STATCOM power losses.

Figure 36 – Overall power losses in PV-STATCOM operation.

Source: Author.

For Q_{ref} at 0.3 p.u. operating at 900 V results in consumption of 28.8 kW of electrical power that must be bought from the grid to supply power losses. This technical cost is increased by 7.0 %, 14.2 %, 21.5 %, 29.0 % and 36.4 % when operating at 1000 V, 1100 V, 1200 V, 1300 V and 1400 V respectively.

6.6 Reactive power support capability

There are three quantities that limit reactive power support capability: maximal admissible AC converter current, maximal converter voltage on the AC side and the maximal DC current [36].

Figure 37 – Theoretical reactive power support capability.

Source: Author.

Maximal admissible AC converter current sets the first superior limit to reactive power support. This limit is a circle of radius equal to the converter rated apparent power. As for the second limit, the maximum converter voltage on the AC side depends on the DC side voltage level. These theoretical limits are shown in Fig. 37. Finally, the third limit does not have an impact in this work as during nighttime there is no significant DC current. From Fig. 37, it is clear that the reactive power support capability increases

with the increase of v_{dc} and to be asymmetrical in respect to positive and negative reactive power injection.

An operation map for each point (v_{dc}, Q_{ref}) is presented in Fig. 38. The presented map summarizes overall power losses and reactive power support capability of the PV-STATCOM. The operation map shows the influence of v_{dc} over reactive power support capability and summarizes the overall system technical costs: operating at variable v_{dc} during nighttime has advantages over any constant v_{dc} operation by minimizing the energy that must be bought from the grid to supply power losses. In the worst case scenario ($Q_{ref} = \pm 1$ p.u., $v_{dc} = 1400$ V), overall system power losses over rated power ratio is 7.7 %.

Figure 38 – Reactive power support capability area.

Source: Author.

6.7 Optimization of the dispatch

From the results two possible operation modes can be considered for a PV-STATCOM. One of them consists in setting v_{dc} to a fixed value and the other in a variable v_{dc} operation that sets the DC voltage to a value that guarantee minimal power losses for that particular Q_{ref} .

A nighttime reactive power dispatch for the PV farm has also been considered. The dispatch data was obtained from [46] and its presented in Fig. 39.

Three operation scenarios were considered: a variable DC voltage which sets $v_{dc \text{ ref}}$ to the minimum DC voltage level that enables Q_{ref} injection/consumption, a constant v_{dc} that supports the maximum Q_{ref} for the given dispatch and constant at the DC level 1030 V. The constant DC value of 1030 V was chosen because this is the minimal DC voltage level calculated by the proposed methodology capable of injecting 1 p.u. of reactive power.

Figure 39 – Dispatch of Q_{ref} from [46] and $v_{dc \text{ ref}}$ set by the PV farm.

Source: Author.

Power losses for the three scenarios for reactive power dispatch are shown in Fig. 40. Results shown that dynamic v_{dc} operation consumes 1.9 % less energy than operating at constant DC voltage of 940 V and 8.7 % less energy than operating at constant v_{dc} of 1030 V. Extrapolating this to the VSC lifespan, it is clear that operating by setting the proper v_{dc} level during nighttime results in significant money savings for the PV farm owner.

Therefore, the proposed methodology supplies essential information for PV farms owners and operators regarding economic viability of operating a PV-STATCOM at night.

Figure 40 – Power losses for nighttime reactive power dispatch.

Source: Author.

With this results and a risk analysis of reactive power supply, owners might bid properly into specific auctions for reactive power in developing markets for ancillary services. In case these markets do not develop, PV farm owners can evaluate if the price suggested by system operator are adequate and rewarding before compromising to provide the service in long term.

6.8 Chapter remarks

This chapter presents the results from the proposed methodology for technical cost evaluation of a PV installation operating as a STATCOM during nighttime. Power losses from all key components (tie reactor, transformer, filter and VSC) were shown. Overall system power losses were presented in the sequence. Technical costs were estimated from overall system power losses. Then, a reactive power support capability operation map was presented. The operation map confirmed that variable DC voltage operation is desirable for minimizing power losses. Finally, a PV farm reactive power dispatch was optimized with variable DC voltage and 8.7 % energy was saved in comparison to fixed DC voltage

operation.

Next chapter presents the conclusions and future work suggestions.

Conclusions and future work

This work proposed a methodology for evaluating the technical cost of operating a PV-STATCOM at nighttime using electromagnetic transient simulations. This methodology was applied to a 1.5 MWp PV farm to obtain its reactive power support capability map and associated technical cost. The capability map is asymmetrical and overall PV-STATCOM losses reach up to 7.7 % of the rated power in the worst case scenario. Two operation modes were tested for nighttime reactive power dispatch: constant v_{dc} and variable v_{dc} . The results show that the variable v_{dc} mode can reduce the losses by 8.9 % in comparison to the constant v_{dc} mode, demonstrating that variable DC voltage operation during nighttime is, therefore, preferable for PV-STATCOM operation at nighttime.

Therefore, main contributions of this work are: the proposed methodology capable of evaluating system overall power losses based on simulations rather than percentage estimates; the discussion of active power losses in reactive power support context and an overall system reactive power support capability map obtained for a wide range of operation points. This methodology provides useful information to PV farm owners and operators for assessing the economic viability of PV-STATCOM operation at night. The systematic analysis of power losses in PV-STATCOM applications presented in this work can also be applied to other systems connected to the grid through converters such as wind energy conversion systems (WECS), high voltage direct current transmission systems (HVDC), energy storage systems (ESS), etc.

In the context of solar power, future work consists in applying this methodology for different converter topologies such as a two-stage VSC or a Z-source converter. The limitations of reactive power support capability of different topologies might be compared to verify the relationship between power losses and reactive power support capability for other topologies as well.

The operation could be extended for day time and an adaptation of the proposed methodology can be developed for estimating power losses. A reactive power support capability map could be developed for day time operation considering the priority of active power generation. Furthermore, an analytical equation capable of estimating power losses

without simulations could be developed.

The overall control structure of the PV farm could be upgraded to include an automatic method for generating DC voltage levels for minimizing power losses in nighttime operation. Moreover, it could be evaluated if the operation outside of the MPP is more efficient if power losses are considered.

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