Abstract - This paper carries out the introduction to the operation of the photovoltaic panels, by the variation of radiation and temperature.

In this work the control of matrix converters was studied, that permit using the maximum power supplied for a photovoltaic panel and assure that the reactive current injected on the grid is zero.

The maximum power point was obtained with a MPPT, based in incremental impedance algorithm.

The input of the matrix converter has a characteristic of current supply, so it is necessary to dimensioning an appropriate RLC filter. In converters connected to the photovoltaic panel is necessary to dimension a first order filter to allow a smooth current and assure the MPPT correct operation.

The final part of this work allows visualization of the correct system's operation in a laboratory, through the figures obtained.

Keywords: photovoltaic panels, matrix converters, filter, MPPT, network injected current, active and reactive power.

I. INTRODUCTION

Nowadays the renewable energies have an important role in our lives, so a further study is necessary to obtain more efficiency at a lower cost.

The photovoltaic panel provides a possibility to use the renewable energies, in this case the energy of the sun. In Europe, Portugal is the country with most radiation, it has nearly 2300 hours/year in the North zone and 3000 hours/year in the Algarve.

To connect the photovoltaic panel to the electric grid it is necessary a converters, in this case an AC-AC matrix converters was used. It was modified to operate as an AC-DC converters. However the photovoltaic panel only supplies current, so the bidirectional interrupter does not has the current flux in both directions and the AC-DC matrix converters can be approximated to a current source inverter (CSI).

This converters has a smaller dimension and less weight than the conventional converters, because it has not elements of energy storage. Nevertheless the absence of these elements cause more oscillation sensitivity.[1]

To permit a better efficiency of the power delivered by the photovoltaic panel, a Maximum Power Point Tracker was used with the incremental impedance algorithm.[2]

It will be important to refer that reactive power injected in grid should be zero, and for that the q component current must be zero, thus the voltage and the current are in phase.

II. PHOTOVOLTAIC PANEL

The photovoltaic panel has been studied over time and can be represented by a schematic (Fig. 1). The photovoltaic panel is photovoltaic cells linked in parallel and/or series, they have shunt (Rsh) and series (Rs) resistor, which permits it to represent the leakage current to the ground and the internal losses due to the current flow, respectively.[parameters estimation for a model]

![Figure 1 – Photovoltaic panel schematic](image)

The panel equation (1) can be represented by:

$$I_M = I_{scM} - N_p V_{p}
\exp\left(\frac{q(V_M + R_{sm}I_M)}{nV_t}ight)
- \frac{V_M + R_{sm}I_M}{R_{sh}}$$

(1)

Where $I_M$, $V_M$, $V_{ocM}$, $I_{scM}$, $V_t = kT/q$, $R_{sm} = N_sR_p/N_p$ and $R_{sh} = N_sR_{sh}/N_p$.[3][4]

If we consider that $N_p$ and $N_s$ are equal to one, we could obtain one photovoltaic cell schematic.

A. External Factors Influence in the Efficiency

When the external factors change, radiation or temperature, it is important to know the new photovoltaic panel V-I characteristic and how it influences the power. The short circuit current (2) is proportional to the radiation and has a small temperature coefficient ($K_r$) and the open circuit voltage (3) depends logarithmically with radiation and has a negative temperature coefficient ($K_v$).[3]
\[ I_{SCM} = (I_{SCM}(T_{ref}) + K_v(T - T_{ref})) \frac{G}{G_{ref}} \]  
\[ V_{ocM} = V_{ocM}(T_{ref}) + \ln \left( \frac{G}{G_{ref}} \right) V_T + K_u T - T_{ref} \]

\( G_{REF} \) and \( T_{REF} \) are the radiation and temperature reference values, respectively, and they can be obtained in the photovoltaic panels datasheet [5]. Radiation \( G \) and temperature \( T \) values change with different place and instant.

**B. The Photovoltaic Panel Prototype**

The objective of this work is study the supply electrical grid with a photovoltaic panel. To photovoltaic panel prototype was built based on schematic (Fig. 2). To simulate the KC50T panel, are needed 28 power diodes to obtain the same open circuit voltage. However for an easier realization the prototype has 27 diodes chain connected from collector to base of a bipolar power transistor. The shunt resistor with 200ohm permits a good approximation on a V-I characteristic.

![Figure 2 – Prototype panel schematic (a); prototype panel(b)](image)

After testing the photovoltaic panel prototype, in a laboratory, a V-I characteristic and a power curve were obtained (Fig. 3).

![Figure 3 – V-I characteristic curve (a); power curve (b)](image)

Comparing the maximum power of the photovoltaic panel prototype (54.72) with the KC50T panel (Fig. 3) it is observed that there is a minimal relative error (0.1%).

**III. MATRIX CONVERTERS**

The matrix converters permits the direct conversion to AC-AC without an electrolytic capacitor, that normally it is used for energy storage. Then it is possible to obtain converters with less weight and more durability. This converters allows obtaining current and voltage approximately sinusoidal, with reduced harmonics, frequency and power factor adjustability and also permits the bi-directional current flux.

In theory, this converters can have 512 different switching states, nevertheless there are some impossible states due to topologic restriction:

- The voltage of the electric grid side cannot be short-circuited.
- The current of the photovoltaic panel cannot be interrupted so it requires an alternated path to allow its continuity.

With this limitation the converters can only have 27 switching states [6].

![Figure 4 – Matrix converters AC-AC (a); bidirectional switch (b)](image)

**A. AC-DC Matrix Converter**

Because the photovoltaic panel only works in direct current, the 3rd arm of the matrix converters is not necessary, thus the 27 switching states became only 9 possible switching states. The bidirectional switches of the matrix converters, when connected to a photovoltaic panel, only have current flux in one direction. In fact, due to the simplifications that occurred on the matrix converters, it can be compared to a CSI (current source inverter), visualized in Fig 5.
Figure 5 – AC-DC Matrix Converters (comparing with CSI)

The relation between the electric grid voltage and photovoltaic voltage and between the input/output current can be obtained through equation (4) and (5) respectively.

\[
\begin{bmatrix} V_f \\ I_f \end{bmatrix} = S \begin{bmatrix} V_p \\ I_p \end{bmatrix} \tag{4}
\]

\[
\begin{bmatrix} I_d \\ I_c \end{bmatrix} = S \begin{bmatrix} I_a \\ I_b \end{bmatrix} \tag{5}
\]

Where \( S \) is the switching matrix possible, this is represented in equation (6):

\[
S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \end{bmatrix} \tag{6}
\]

Table 1 - Possible states for an AC-DC converters

<table>
<thead>
<tr>
<th>State</th>
<th>Switches ON</th>
<th>( V_D )</th>
<th>( V_C )</th>
<th>( V_{DC} )</th>
<th>( I_a )</th>
<th>( I_b )</th>
<th>( I_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( S_{11} ) ( S_{21} )</td>
<td>( V_a )</td>
<td>( V_b )</td>
<td>( V_{ab} )</td>
<td>( 0 )</td>
<td>( -I_{DC} )</td>
<td>( I_{DC} )</td>
</tr>
<tr>
<td>2</td>
<td>( S_{12} ) ( S_{21} )</td>
<td>( V_b )</td>
<td>( V_b )</td>
<td>( V_{bc} )</td>
<td>( 0 )</td>
<td>( -I_{BC} )</td>
<td>( I_{DC} )</td>
</tr>
<tr>
<td>3</td>
<td>( S_{12} ) ( S_{22} )</td>
<td>( V_a )</td>
<td>( V_b )</td>
<td>( V_{bc} )</td>
<td>( 0 )</td>
<td>( I_{BC} )</td>
<td>( -I_{DC} )</td>
</tr>
<tr>
<td>4</td>
<td>( S_{13} ) ( S_{22} )</td>
<td>( V_c )</td>
<td>( V_c )</td>
<td>( V_{bc} )</td>
<td>( 0 )</td>
<td>( I_{BC} )</td>
<td>( -I_{DC} )</td>
</tr>
<tr>
<td>5</td>
<td>( S_{12} ) ( S_{23} )</td>
<td>( V_a )</td>
<td>( V_c )</td>
<td>( V_{ca} )</td>
<td>( 0 )</td>
<td>( I_{DC} )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>6</td>
<td>( S_{13} ) ( S_{23} )</td>
<td>( V_c )</td>
<td>( V_c )</td>
<td>( V_{ca} )</td>
<td>( 0 )</td>
<td>( I_{DC} )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>7</td>
<td>( S_{11} ) ( S_{21} )</td>
<td>( V_a )</td>
<td>( V_a )</td>
<td>( V_{ab} )</td>
<td>( 0 )</td>
<td>( 0 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>8</td>
<td>( S_{12} ) ( S_{22} )</td>
<td>( V_b )</td>
<td>( V_b )</td>
<td>( V_{bc} )</td>
<td>( 0 )</td>
<td>( 0 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>9</td>
<td>( S_{13} ) ( S_{23} )</td>
<td>( V_c )</td>
<td>( V_c )</td>
<td>( V_{ca} )</td>
<td>( 0 )</td>
<td>( 0 )</td>
<td>( 0 )</td>
</tr>
</tbody>
</table>

Applying the Concordia transformation (7) at current values of table 1, it was obtained table 2

\[
C = \begin{bmatrix} 2 & 1 \\ 2 & 2 \\ 1 & 1 \end{bmatrix} \tag{7}
\]

\[
\begin{bmatrix} I_a \\ I_b \end{bmatrix} = C^T \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{8}
\]

Table 2 – Current vector depending of the switches

<table>
<thead>
<tr>
<th>State (k)</th>
<th>Switches ON</th>
<th>Module ( L_k )</th>
<th>Angle ( \mu_k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( S_{11} ) ( S_{22} )</td>
<td>( \sqrt{2} L_{DC} )</td>
<td>-30</td>
</tr>
<tr>
<td>2</td>
<td>( S_{12} ) ( S_{21} )</td>
<td>( -\sqrt{2} L_{DC} )</td>
<td>-30</td>
</tr>
<tr>
<td>3</td>
<td>( S_{12} ) ( S_{23} )</td>
<td>( \sqrt{2} L_{DC} )</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>( S_{22} ) ( S_{13} )</td>
<td>( -\sqrt{2} L_{DC} )</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>( S_{11} ) ( S_{33} )</td>
<td>( \sqrt{2} L_{DC} )</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>( S_{21} ) ( S_{13} )</td>
<td>( -\sqrt{2} L_{DC} )</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>( S_{11} ) ( S_{21} )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>( S_{12} ) ( S_{22} )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>( S_{13} ) ( S_{23} )</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

B. LC Filter

To reduce the harmonic content, the matrix converters requires a damping LC filter.

\[ v_{cf} = v_i = V_m \cos \omega t \tag{9} \]

\[ i_{mat} = i_i - i_c \tag{10} \]

When \( i_{mat} = i_m \cos \omega t \) and \( i_c = C_f \Delta v_{cf} \leftrightarrow i_c = j \omega C_f v_{cf} \) is obtained the capacitor equation (11)

\[ C_f = \frac{I_m (m \text{min})}{\omega_1 \mu_{i_m} (\text{max})} g(\theta) \tag{11} \]

The relation between \( V_i/V_o \) can be expressed by the equation (12) [8].

\[ V_{mat}(s) \to \frac{V_i(s)}{V_i(s)} = \left( \frac{s L_f}{\mu_s} + 1 \right) \frac{1}{s C_f} \tag{12} \]

Table 3 – Damping LC filter values

<table>
<thead>
<tr>
<th>( \xi )</th>
<th>( C_f )</th>
<th>( L_f )</th>
<th>( r_i )</th>
<th>( Z_f )</th>
<th>( r_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>19.6 µF</td>
<td>4.3 mH</td>
<td>52.9 Ω</td>
<td>14.8 Ω</td>
<td>20.6 Ω</td>
</tr>
</tbody>
</table>
C. L Filter

The MPPT algorithm changes the operation point until it obtains the maximum power point. The oscillations on the input voltage and current should be minimal to minimize the oscillation power extracted from the photovoltaic panel. On the other hand, it is necessary that the oscillations be big enough to recognize the effects of switching in converters, to achieve that, the inductor needs to be correctly dimensioned.

The schematic that represents the filter connected between the photovoltaic panel and the matrix converters can be visualized in Fig. 7

![Figure 7 - First order filter](image)

The drop voltage in inductor is defined for the following equation (11)

\[
v_{\text{LDC}} = (v_{\text{mat,DC}} - v_{\text{panel}}) = L_{\text{DC}} \frac{di_{\text{L}}}{dt}
\]

When \( \Delta t = 1/(2f_s) \) it is obtain (12)

\[
L_{\text{DC}} = (v_{\text{mat,DC}} - v_{\text{panel}}) \frac{\Delta t}{2f_s} = \frac{(v_{\text{mat,DC}} - v_{\text{panel}})}{2f_s \Delta t}
\]

<table>
<thead>
<tr>
<th>Table 4 - First order filter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_s = 5 \text{ kHz} )</td>
</tr>
<tr>
<td>( \Delta i_l = 0.165A )</td>
</tr>
</tbody>
</table>

IV. SYSTEM CONTROL

A. Power Control

The MPPT used is based on the derivation of the power in function to the voltage and on the maximum power point (MPP) the derivative is null. The power is given by

\[
P = VI
\]

Deriving the power in function to the voltage and equalling it to zero. In equation (18) the I/V represents the opposite of instantaneous conductance of the photovoltaic cells and dI/dV represent the incremental conductance, that are equal in MPP.

\[
\frac{dP}{dV} = 0 \leftrightarrow l + V \frac{dl}{dV} = 0 \leftrightarrow -l \frac{V}{dV} = \frac{dl}{dV}
\]

From Fig. 8 it is possible to observe that on the right of the MPP dI/dV<1/V it is necessary to reduce the voltage to find the MPP and on the left of the MPP dI/dV>1/V it is necessary to increase the voltage to find the MPP. For example, to move point 1 to the right it is necessary to increase the voltage and on the other hand to move point 4 to the left it is necessary to reduce the voltage [9].

![Figure 8 - Power curve in function of V](image)

To decide which voltage to apply in converters output, it is needed to know the voltage localization on the electrical grid. It is considered that the electrical grid voltage (19)

\[
\begin{align*}
V_a &= \sqrt{2} V_e \cos (\alpha t) \\
V_b &= \sqrt{2} V_e \cos \left(\alpha t - \frac{2\pi}{3}\right) \\
V_c &= \sqrt{2} V_e \cos \left(\alpha t - \frac{4\pi}{3}\right)
\end{align*}
\]

Through the algebraic manipulation it is possible to obtain the compound voltage. The compound voltage is represented and divided in 6 different zones in Fig 9.

![Figure 9 - Division of the voltage by zones](image)

The equation (13) in a certain instant, it is applying a vector that increases or decreases the voltage. If the vector applied on the converters is greater than the photovoltaic panel voltage a negative voltage is obtained however if the vector applied is smaller than the photovoltaic panel voltage a positive voltage is obtained.

Nevertheless it is necessary to point out that there are two vectors on the same zone that are inconclusive.
For example in zone 1, considering a photovoltaic panel with 25V and applying a V_ab vector a negative voltage is originated just below zero. When V_bc vector is in zone 1 its voltage can be smaller, greater or equal to the panel voltage, thus the V_bc vector will be despised and these considerations are also applied to other vectors in different zones.

Table 5 – Vdc values for a different vector in determined zone

<table>
<thead>
<tr>
<th>Voltage Zone</th>
<th>V_ab</th>
<th>V_bc</th>
<th>V_ca</th>
<th>V_ca</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>x</td>
<td>x</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>2</td>
<td>x</td>
<td>&gt; 0</td>
<td>x</td>
<td>x</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>3</td>
<td>&gt; 0</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>x</td>
<td>x</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>4</td>
<td>&gt; 0</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>x</td>
<td>x</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>5</td>
<td>x</td>
<td>x</td>
<td>&gt; 0</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>6</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>x</td>
<td>x</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
</tbody>
</table>

In Table 5 it is possible to observe that more than one vector can increase or decrease the voltage, so it is necessary to make a current vector selection to enable the power factor control.

B. The Injected Current Control in the Electrical Grid

To control the power injected in the electrical grid it is necessary that the reactive current is zero, for that it must be necessary to resort to the use of the Blondel-Park transformation.

\[
T = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \rho & -\sin \rho & 1 \\ \cos \left(\frac{\rho - 2\pi}{3}\right) & -\sin \left(\frac{\rho - 2\pi}{3}\right) & \frac{1}{\sqrt{2}} \\ \cos \left(\frac{\rho - 4\pi}{3}\right) & -\sin \left(\frac{\rho - 4\pi}{3}\right) & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{18}
\]

Considering that in the input of the converters there is a balanced system of current it can be represented

\[
i_d = \sqrt{3} I \cos(\omega t + \alpha) \\
i_q = \sqrt{3} I \cos(\alpha - \frac{2\pi}{3}) \\
i_c = \sqrt{3} I \cos(\omega t + \alpha - \frac{4\pi}{3})
\tag{19}
\]

\[
\begin{bmatrix} i_d \\ i_q \end{bmatrix} = T \begin{bmatrix} i_d \\ i_q \\ i_c \end{bmatrix}
\tag{20}
\]

Being \(\rho = \omega t + \alpha_m\) and \(\alpha_u = \alpha_m\)

\[
\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{3} I \begin{bmatrix} \cos(\alpha_u - \alpha_m) \\ \sin(\alpha_u - \alpha_m) \end{bmatrix} \Rightarrow i_d = \sqrt{3} I \cos(\alpha_u - \alpha_m) \quad i_q = 0
\tag{21}
\]

For example, if the d component of the current is in zone 2, the q component of the current is in quadrature, i.e., in zone 2, thus to increase \(i_q\) the vector 1, 4 or 5 can be applied, and to decrease \(i_q\) the vector 2, 3 or 6 can be applied and for maintain the same \(I_q\), the vector 7, 8 or 9 can be applied Fig 10.

Figure 10 – Representation of the Iq current component fixed in

Table 6 – Iqdlt values when it is apply vectors in determined zone

<table>
<thead>
<tr>
<th>Voltage Zone</th>
<th>V_ab</th>
<th>V_bc</th>
<th>V_ca</th>
<th>V_ca</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>&gt; 0</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>&gt; 0</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>&gt; 0</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

C. Active and Reactive Power

For a better conclusion of results, it is interesting to verify the active and reactive power. The ideal reactive power is null and ideally the current is in phase with the voltage. The greater the current and voltage, the higher the active power.

Active and reactive power can be represented by equation (22) and (23) respectively [10]

\[
p(t) = v_a i_d + v_b i_q + v_c i_c = v_a i_d + v_b i_q \tag{22}
\]

\[
q(t) = v_b i_d - v_a i_q \tag{23}
\]
V. EXPERIMENTAL RESULTS

The laboratory assembly can be observed in:

![Laboratory schematic](image)

Figure 11 – Laboratory schematic

In this assembly there are a photovoltaic simulator panel (prototype panel or power diodes in series), an L filter, an acquisition board that acquires voltage and current signals from the simulator panel and also acquires the electrical grid voltage to make the synchronism.

The variables observed in this assembly are voltage on the electrical grid, the current and voltage (on abc and dq co-ordinate), the current and the voltage for the maximum power point and the active and reactive power.

A. Simulation of the photovoltaic panel with diodes in series

The power diodes connected in series enable to obtain a similar V-I characteristic to the photovoltaic panel and allow observing the voltage and current for which the power is maximums.

![Composite voltage in grid 35V (Isc=7.65A)](image)

Figure 12 – Composite voltage in grid 35V (Isc=7.65A)

- a) Current and voltage
- Yellow – Injected current in grid (Ia) (5A/Div)
- Green – Simple voltage (Va) (200V/Div)
- Blue – Direct voltage (40V/Div)
- Purple – Direct current (5A/Div)

- b) Current, voltage and power
- Yellow – Reactive current (2A/div)
- Green – Reactive power injected (4VAr/Div)
- Purple – Active power injected in grid (62.5W/Div)

When the photovoltaic panel is in open circuit, with a current of 7.65A it has a voltage of 27V. Connecting the panel with the system, it can be observed that the current and the voltage for the maximum power are 2.65A and 25.12V, respectively.

The current and the voltage for the maximum power point are not the expected. To the panel characteristic obtained in laboratory, the current and voltage for the maximum power are 6.87A and 17.6V, it can be conclude that the diodes when connected to the system dissipate energy.

![Simulation of Figure 12](image)

Figure 13 – Simulation of Figure 12

- a) Current and voltage
- Yellow – Injected current in grid (Ia) (5A/Div)
- Green – Simple voltage (Va) (20V/Div)
- Purple – Direct voltage (20V/Div)
- Blue – Direct current (5A/Div)

- b) Current, voltage and power
- Yellow – Reactive current (2A/Div)
- Green – Reactive power injected (4VAr/Div)
- Purple – Active power injected in grid (62.5W/Div)

When the number of diodes changes from 22 to 36 were obtained the following results:

![Simulation of Figure 14](image)

Figure 14 – Composite voltage in grid 60V (Isc=7.65A)

- a) Current and voltage
- Yellow – Injected current in grid (Ia) (5A/Div)
- Green – Simple voltage (Va) (200V/Div)
- Purple – Direct voltage (40V/Div)
- Blue – Direct current (5A/Div)

- b) Current, voltage and power
- Yellow – Reactive current (2A/Div)
- Green – Reactive power injected (4VAr/Div)
- Purple – Active power injected in grid (105W/Div)

Comparing Fig.12 and Fig.14 it is possible to verify that when the numbers of diodes in series
increase, the MPP voltage increases. By the increase of the number of diodes the drop voltage increase but the output current of the photovoltaic panel should be constant, nevertheless it increases. This can be justifying with the different V-I characteristic when photovoltaic panel is connected to the system.

i. Maximum Power Point Tracker Behaviour

To verify the controller response to an abrupt variation of current, it is installed a resistor in parallel with the source, rapidly varying the resistor until short-circuit, i.e., decreasing the input current in diodes until it be null.

![Figure 16 – MPPT voltage with 36 diodes in chains](image1)

<table>
<thead>
<tr>
<th>a) Current and voltage</th>
<th>b) Current, voltage and power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow – Injected current in grid (Ia) (5A/Div)</td>
<td>Yellow – Reactive current (2A/div)</td>
</tr>
<tr>
<td>Green – Simple voltage (Va) (200V/Div)</td>
<td>Green – Reactive power injected (4VAr/Div)</td>
</tr>
<tr>
<td>Blue – Direct voltage (20V/Div)</td>
<td>Blue – Direct voltage (21V/Div)</td>
</tr>
<tr>
<td>Purple – Direct current (5A/Div)</td>
<td>Purple – Active power injected in grid (105W/Div)</td>
</tr>
</tbody>
</table>

Decreasing the current of the diodes, the maximum power point tends to zero, forcing the voltage to decrease. After increasing the current in the diodes, the MPPT starts it operation and recovers the values before the perturbation, so it can be concluded that the MPPT controller is sensitive to the perturbation and it recovers quickly. It was possible to verify that the MPPT works correctly.

B. Photovoltaic Panel Prototype

Using the photovoltaic panel prototype as panel simulator and using the schematic on Fig. 11, it was possible to visualize that the influence of the variation of the solar radiation and keeping the radiation constant and ranging the voltage it was possible to verify the modifications. Finally it was verified the phase shift in current.

i. Variation of solar radiation

Through the variation of the current in power supply was simulated the variation of solar radiation.

![Figure 17 – Prototype with 30V in grid (G=1000 W/m²)](image2)

![Figure 18 – Prototype with 30V in grid (G=846 W/m²)](image3)

![Figure 19 – Prototype with 30V in grid (G=700 W/m²)](image4)

The variation of the radiation was possible to estimate, considering that the reference radiation value is 1000W/m² for a short-circuit current of 3.31A, through the equation (2).

Considering that the current and voltage for the maximum power point can vary equally with the short-circuit current and open circuit voltage. For a constant temperature, the theoretical values were obtained.
Comparing the theory with the experimental values, there are some differences that can be explained with prototype power losses (diodes and bipolar power transistor) and the inherent errors on reading and precision of the equipment. These losses cause a change on the V-I characteristic panel.

The experimental results allow illustrating that with the variation of the radiation the voltage has a small variation and the current has a higher variation.

The theoretical and experimental powers have a relative error around 4%.

From Fig.19 it is possible to verify that when the current decreases the noise in circuit increases and the MPPT causes an increase the oscillations in the direct voltage.

![Figure 20 – Simulation of Figure 17](image1)
![Figure 21 - Simulation of Figure 18](image2)

### Table 7 – Theory and experimental values

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1000</td>
<td>17.40</td>
<td>3.11</td>
<td>54.11</td>
<td>19.91</td>
<td>2.62</td>
<td>52.16</td>
</tr>
<tr>
<td>846</td>
<td>17.20</td>
<td>2.63</td>
<td>45.25</td>
<td>19.49</td>
<td>2.23</td>
<td>43.46</td>
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<tr>
<td>700</td>
<td>16.97</td>
<td>2.18</td>
<td>36.95</td>
<td>18.41</td>
<td>1.98</td>
<td>36.45</td>
</tr>
</tbody>
</table>

![Figure 22 – Simulation of Figure 19](image3)

Observing Fig. 20, Fig.21 and Fig. 22 comparing with experimental results figures, the noises is lower. However on direct current there are small variations due to semiconductor switching that produce variations on the direct voltage.

#### ii. Operation Conditions Variation

![Figure 23 – Prototype with 40V in grid](image4)
![Figure 24 – Prototype with 35V in grid](image5)

Keeping the same current in supply (radiation) and changing the grid voltage, through the Figure 17 and Figure 23 it can be observed that the injected powers on electrical grid are equally. When the voltage on grid is increased, the current tends to decrease lightly to maintain the energy balance unchanged.

![Figure 25 – Prototype with 35V in grid](image6)
In Fig. 24 the currents are phase shifts of 120 between themselves. The Ia current and Va voltage are in opposite phases.

VI. CONCLUSIONS

This work studies a system that permits link a photovoltaic panel to an electric grid through a matrix converter.

Through theoretical studies of the photovoltaic panel was possible to observe the behaviour due to different radiations and temperatures. However in laboratory can only be tested the radiation variation.

After photovoltaic panel construction the V-I characteristic was verified, however when the system is linked to the matrix converters there are losses on the diode and on the transistor.

In laboratory was made a simulation that permits illustrating the variation of solar radiation, verify the correct operation of the MPPT, for a quick variation of radiation, and search the current and voltage that permit obtain the maximum power point.

Observing the powers, especially the reactive power, and observing the voltage and current can be concluded that the controller of the current works correctly in laboratory, so it was allowed to see that the current is in phase with the voltage (opposition of phase due to the direction of reading) and the reactive power is approximately zero.

Despite the good results obtained in this work, there are some things that can be improved in future works, for example, use a real photovoltaic panel instead of a panel prototype. It is still possible to improved the control of matrix converters, depending of the error can be applied a more accurate vector, i.e., to smaller error apply a smaller vector and to a higher error apply a higher vector.

VII. REFERENCES


