Design and Assembly of a Power Electronics Conversion System for PV Applications

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Abstract—This paper is focused into PV applications of 700 W, which is representative of an average residential PV installation. In this paper it is performed the design of a power electronics converter for PV applications composed by a quadratic boost converter that upconverts the PV system output voltage, complemented by a MPPT system that optimizes the energy production. The DC/AC conversion is performed by a full-bridge single phase inverter using Sinusoidal Pulse Width Modulation (SPWM). A current controller and a voltage controller are used to guarantee the desired voltage level and current waveform.

It is obtained and analyzed the simulation results for different irradiance conditions to observe the proper response of the MPPT system and the output power injected to the grid.

Keywords— Photovoltaic system; quadratic boost converter; MPPT; voltage source inverter; SPWM

I. INTRODUCTION

Photovoltaic (PV) energy production had an exponential growth over the past decade, with the total cumulative installations reaching 303 GWp by the end of 2016 [1].

The increasing interest on photovoltaic energy due to its environmental friendly benefits and increased economical rentability is turning this into the most fast-growing energy source. The installation of a photovoltaic system in a domestic residence or a small community installation, requires the use of power electronics converters that convert the DC power from the photovoltaic system in AC power to be injected into the electrical grid.

One characteristic of a photovoltaic panel is that its voltage is too low to be used by an inverter. This way it is required a DC/DC converter to output the 400VDC to use in the inverter. To maximize the energy production, a Maximum Power Point Tracking (MPPT) system is frequently used. It can largely increase the energy yield, as it will change the PV operation point according to the environment conditions, such as irradiance or temperature [2], [3].

To connect the system to the power grid, it should be used isolation. The galvanic isolation can be achieved with a line-frequency or a high frequency transformer.

Galvanic isolation can be guaranteed with High Frequency Transformers (HFTs) or Line Frequency Transformers. The latter are bulky and usually present high efficiencies, whereas HFTs can achieve much higher power density at the cost of lower efficiency [5]. In these solutions with HFTs, usually an additional conversion stage is required. Also, Dual Active Bridge (DAB) [6] converters have been proposed, as they guarantee high-frequency galvanic isolation and soft-switching.

Solutions without galvanic isolation have been proposed as well. Current source inverters (CSI) have been presented as an alternative to voltage source inverters (VSI), as they perform the DC to AC conversion, guaranteeing voltage step-up capability. As a result, it is possible to connect the PV to the grid with one single converter, without the requirement of any additional transformer or step-up conversion stage [7].

In this paper, a solution for a PV conversion system without galvanic isolation is presented, controlled and tested. The DC/DC conversion stage guarantees the MPPT, and the connection to the grid is guaranteed with a VSI.

II. PROPOSED CONVERSION SYSTEM

The power electronic conversion system that is proposed does not include galvanic isolation and is composed by a DC/DC quadratic boost converter and a VSI in the connection to the grid (Fig. 1).

Fig. 1. Block diagram of the overall conversion system

A. Ideal Quadratic Boost Converter

The quadratic boost converter is used to step-up the voltage from the PV panels because it is usually too low to be connected directly to the grid side inverter, unless a step-up transformer is used in the connection to the grid [8], [9]. The quadratic boost converter was chosen due to its capability to achieve higher voltage gain, when compared to regular DC/DC boost converter, without requiring a transformer, which results in a more compact design. Also, the DC/DC converter will be used to guarantee the MPPT.
Fig. 2. Quadratic boost converter

For the ideal quadratic boost (with \( r_L = 0 \Omega \) and \( r_D = 0 \Omega \) in Fig. 2), the input/output voltage ratio is (1):

\[
\frac{V_{DC}}{V_{PV}} = \frac{1}{(1-\delta)^2}
\]

(1)

The duty cycle is therefore obtained as in (2):

\[
\delta = 1 - \sqrt{\frac{V_{PV}}{V_{DC}}}
\]

(2)

The value of the currents \( I_{L1} \) and \( I_{L2} \) on the filtering inductances and the average value of the output current \( I_{DC} \) are given by (3).

\[
\begin{align*}
I_{L1} &= \frac{P_{PV}}{V_{PV}} - \frac{I_{DC}}{(1-\delta)^2} \\
I_{L2} &= \frac{I_{DC}}{(1-\delta)} \\
I_{DC} &= \frac{P_{DC}}{V_{DC}}
\end{align*}
\]

(3)

**B. Sizing of the filtering components**

The components of the converter must be sized to fulfill the requirements of voltage and current ripple.

The inductors are sized according to (4), where the ripple of currents \( I_{L1} \) and \( I_{L2} \) is represented by \( \Delta I_{L1} \) and \( \Delta I_{L2} \), respectively, and should be negligible when compared to the currents rated values.

\[
\begin{align*}
L_1 &= \frac{V_{DC} (1-\delta)^2 \delta}{\Delta I_{L1} f} \\
L_2 &= \frac{V_{DC}}{4 \Delta I_{L2} f}
\end{align*}
\]

(4)

The capacitors are sized according to (5), where \( \Delta V_{C1} \) is the voltage ripple in capacitor \( C_1 \).

\[
\begin{align*}
C_1 &= \frac{P_{DC} \delta}{(1-\delta) V_{DC} \Delta V_{C1} f} \\
C_{DC} &= \frac{P_{DC}}{\omega V_{DC} \Delta V_{DC}}
\end{align*}
\]

(5)

**C. Non-ideal Quadratic Boost Converter: Voltage gain**

Considering the non-ideal converter (Fig. 2), when semiconductor \( S \) is ON \([nT+\delta T; (n+1)T]\), then the voltages at the inductors \( L_1 \) and \( L_2 \) can be obtained from (6), where \( v_{L1} \) and \( v_{L2} \) represent, respectively, the voltage drop on the parasitic resistances \( r_{L1} \) and \( r_{L2} \) of inductors \( L_1 \) and \( L_2 \) (\( v_{L1} = v_{L1} = r_{L1} i_{L1} \) and \( v_{L2} = r_{L2} i_{L2} \)). The voltage drop on diode \( D_3 \) when it is ON is \( v_{D3} \). Where \( v_D = V_{D1} + r_{D1} i_{L1} \) and \( v_D = V_{D2} + r_{D2} i_{L2} \) (linearized approach). The voltage drop on semiconductor \( S \) when it is ON is \( v_S = V_S + r_S i_S \).

\[
\begin{align*}
v_{L1} &= U - v_{L1} - v_{D3} - v_S \\
v_{L2} &= V_{DC} - v_{L2} - v_S
\end{align*}
\]

(6)

When semiconductor \( S \) is OFF \([nT+\delta T; (n+1)T]\), then the voltages at the inductors \( L_1 \) and \( L_2 \) can be obtained from (7), where \( v_{D1} \) and \( v_{D2} \) represent, respectively, the voltage drop on diodes \( D_1 \) and \( D_2 \). Where \( v_D = V_{D1} + r_{D1} i_{L1} \) and \( v_D = V_{D2} + r_{D2} i_{L2} \) (linearized approach).

\[
\begin{align*}
v_{L1} &= U - v_{L1} - v_{C1} - v_{D1} \\
v_{L2} &= V_{DC} - v_{L2} - v_{D2} - V_{DC}
\end{align*}
\]

(7)

The average value of voltages \( v_{L1} \) and \( v_{L2} \) can be calculated from (6) and (7) and will be equal to zero in steady state. Then, solving the resultant equations, the output voltage can be calculated as a function of the PV system voltage \( V_{PV} \).

\[
\begin{align*}
V_{DC} &= \frac{V_{PV}}{(1-\delta)^2} - \frac{v_{L1}}{(1-\delta)^2} - \frac{v_{L2}}{1-\delta} \\
&= \frac{v_{D3} \delta}{(1-\delta)^2} + \frac{v_S \delta^2}{1-\delta} - \frac{v_{D1}}{1-\delta} - \frac{v_{D2}}{1-\delta}
\end{align*}
\]

(8)

It is considered that all the semiconductors have similar characteristics (9).

\[
\begin{align*}
r_S &= r_{D3} = r_{D1} = r_{D2} \\
V_S &= V_{D3} = V_{D1} = V_{D2}
\end{align*}
\]

(9)

Considering (8) and (9), the output/input voltage relation can be calculated from (10), where \( R_{DC} = V_{DC} f_{DC} \). Compared to (1), it can be seen that the output voltage can be highly reduced by the values of parasitic resistances.

\[
\frac{V_{DC}}{U} = \frac{1 - \frac{2V_S}{U} (1-\delta)}{(1-\delta)^2 + \frac{r_{L1} + r_S (1-\delta)}{R_{DC}(1-\delta)^2} + \frac{r_{L2} + r_S}{R_{DC}}}
\]

(10)

**D. Efficiency of the Quadratic Boost Converter**

To estimate the converter efficiency, it is necessary to calculate the losses in the filtering inductances, in the filtering capacitors, the ON state losses and the switching losses.

The losses in the filtering inductances, related to the power \( P_{DC} \) in the DC link are calculated (11), where \( R_{DC} = V_{DC} f_{DC} \).

\[
\begin{align*}
\frac{P_{r_{L1}}}{P_{DC}} &= \frac{r_{L1} I_{L1}^2}{V_{DC} f_{DC}} = \frac{r_{L1}}{R_{DC} (1-\delta)^2} \\
\frac{P_{r_{L2}}}{P_{DC}} &= \frac{r_{L2} I_{L2}^2}{V_{DC} f_{DC}} = \frac{r_{L2}}{R_{DC} (1-\delta)^2}
\end{align*}
\]

(11)

The power losses at the inductors can be calculated from (11). Establishing the maximum power losses, it is then possible to determine the maximum admissible values for the inductors parasitic resistances, \( r_{L1} \) and \( r_{L2} \).
The conduction losses in semiconductor $S$ are obtained from (12):

$$P_S = V_S I_{S av} + r_S I_{S RMS}^2 = V_S \delta (2-\delta) \left( \frac{1}{1-\delta} \right)^2 I_{DC} + r_S \left( \frac{\sqrt{\delta} (2-\delta)}{1-\delta} \right)^2 I_{DC}$$

(12)

The conduction losses in diode $D_1$ are estimated from (13):

$$P_{D1} = V_{D1} I_{D1 av} + r_{D1} I_{D1 RMS}^2 = V_{D1} \left( \frac{1 - \delta}{1-\delta} \right)^2 I_{DC} + r_{D1} \left( \frac{\sqrt{\delta} (1-\delta)}{1-\delta} \right)^2 I_{DC}$$

(13)

The conduction losses in diode $D_2$ are calculated from (14):

$$P_{D2} = V_{D2} I_{D2 av} + r_{D2} I_{D2 RMS}^2 = V_{D2} I_{DC} + r_{D2} \left( \frac{1}{\sqrt{1-\delta}} \right)^2 I_{DC}$$

(14)

The conduction losses in diode $D_3$ are calculated from (15):

$$P_{D3} = V_{D3} I_{D3 av} + r_{D3} I_{D3 RMS}^2 = V_{D3} \frac{\delta}{(1-\delta)^2} I_{DC} + r_{D3} \left( \frac{\sqrt{\delta}}{1-\delta} \right)^2 I_{DC}$$

(15)

The conduction losses, related to the power $P_{DC}$ in the DC link are calculated in (16), considering (9), (12), (13), (14) and (15).

$$\frac{\sum P_{\text{losses,} \text{ON}}}{P_{DC}} = \frac{P_S + P_{D1} + P_{D2} + P_{D3}}{V_{DC} I_{DC}} = \frac{2 V_S}{(1-\delta)^2} \frac{V_{DC}}{V_{DC}} + \frac{2 + \delta - \delta^2}{(1-\delta)^4} \frac{r_S}{R_{DC}}$$

(16)

Considering all the power losses (11) and (16), and including the switching losses, the efficiency of the converter can be obtained from (17):

$$\eta = \frac{1}{1+\frac{\sum P_{\text{losses}}}{P_{DC}}}$$

(17)

E. Voltage Source Inverter (VSI)

The VSI (Fig. 3) performs the DC/AC conversion, enabling the connection of the PV system to the power grid.

A three-level Sinusoidal Pulse Width Modulation (SPWM), was chosen to guarantee minimum distortion in the grid current. The grid side filtering inductance is calculated from (18), where $f_s$ is the switching frequency, $i_{RMS}$ is the fundamental harmonic of the grid side current, and $THD_i$ is the Total Harmonic Distortion of the grid side current.

$$L_{grid} = \frac{V_{DC}}{8\sqrt{3} f_s i_{RMS} THD_i}$$

(18)

III. PV SYSTEM CONTROL

To ensure that the system performs as expected it is necessary to guarantee the MPPT, the DC link voltage control and the grid side currents control.

A. MPPT – Maximum Power Point Tracking

The output power of the photovoltaic panels changes depending on the environmental conditions, as temperature and irradiance. Without an MPPT system, some of the energy available will not be used. Therefore, an MPPT system is very useful to guarantee that the available power is used.

There are different MPPT methods: some are simple to implement but not so effective, which is the case of indirect methods; and others, called direct methods [2], [10], can track precisely the MPP. The direct methods consist on measuring the voltage and current of the photovoltaic panels and using those measurements to analyze the maximum value of the voltage-power curve. Two of the most known direct methods are the Perturb and Observe (P&O) and the Incremental Conductance (IC) [2], [3], [10].

Fig. 3. Full bridge single phase voltage inverter

In this project a direct method approach, different from the P&O and the IC methods, is used. The detection of the MPP is achieved by searching the derivative of the power curve $(dP/d\phi)$. The MPP is achieved when the derivative of the power reaches zero (19).
\[
\frac{dp}{dt} = 0 \quad (19)
\]

To search the MPP the operation point of the solar panels is progressively changed by regulating the control signal of the switch of the DC/DC converter:
- When \((dp/dt)=0\), then the current should be increased and switch \(S\) should be turned ON;
- When \((dp/dt)>0\), then the current should be decreased and switch \(S\) should be turned OFF;

Considering that the change on the irradiance conditions are slow, causing slow changes of the current and voltage, it is possible to do the following approach:
\[
\frac{dp}{dt} = 0 \iff V + I \frac{dv}{dt} \approx V + I \frac{\Delta V}{\Delta t} \quad (20)
\]

The derivative of the power \((20)\) can be computed, as in \(21)\) [11]:
\[
\frac{dp}{dt} = v(t) + i(t) \frac{v(t) - v(t - \Delta t)}{i(t) - i(t - \Delta t)} \quad (21)
\]

Because the MPPT is constantly measuring and converging to the MPP, it means that independently of the change of the irradiance conditions, the system will always track the MPP.

**B. AC Current Controller**

A Proportional and Integral (PI) \((22)\) current controller was chosen to control the AC current injected in the grid (Fig. 5).

\[
G_{PI}(s) = \frac{1 + sz_T}{sT_p} = K_p + \frac{K_i}{s} \quad (22)
\]

The PI controller enables the AC current control and guarantees a nearly zero steady state error [13]. Moreover, the controller ensures that the AC output current has the same waveform and is in phase with the grid voltage, resulting in a nearly unitary power factor (PF).

**C. DC Link Voltage Controller**

A PI voltage controller is used to control the voltage in the DC link \((V_{DC})\) at 400V. This controller will set the reference for the current to be injected in the grid, which means that when the voltage at the capacitor \(V_{DC}\) decreases the system will inject less current in the grid, keeping the capacitor voltage at the desired level [12], [14].

It is assumed that the current controlled VSI can be represented as a first order transfer function, with gain \(G_i\) \((28)\) [12] and a pole \(T_a=2T_{grid}\):
\[
G_i = \frac{V_{grid\_peak}}{2V_{DC}} \quad (28)
\]

From \([12]\) the transfer function for the voltage controller is obtained, and the proportional and the integral gain can be computed [12]:
\[
\begin{align*}
K_{pD} &= \frac{V_{DC}}{u_c} \quad (24) \\
K_{pi} &= \frac{2.15 C_{DC} \alpha_i}{\alpha_G G_i (1.75)^2 (T_{dev})^2} \\
K_{iv} &= \frac{C_{DC} \alpha_i}{\alpha_G G_i (1.75)^2 (T_{dev})^2}
\end{align*}
\]
IV. SIMULATION RESULTS

The simulation of the PV conversion system was performed using MATLAB Simulink software. Two PV panels connected in series were used to obtain a nominal power around 700W. Table 1 shows the parameters of each one of the PV panels:

<table>
<thead>
<tr>
<th>$P_N$</th>
<th>$V_{PV}$</th>
<th>$I_{PV}$</th>
<th>$V_{oc}$</th>
<th>$I_{sc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>335 W</td>
<td>57.3 V</td>
<td>5.58 A</td>
<td>67.9 V</td>
<td>6.23 A</td>
</tr>
</tbody>
</table>

The DC/DC conversion stage was sized to step-up the voltage of the PV panels to 400V, at the output of the quadratic boost converter. Considering the specifications of the panels, the filter values are presented in Table 2, where a switching frequency $f_s = 10150$ Hz was considered, and the losses in the filtering inductances (11) have been considered as 0.4% of the output power.

<table>
<thead>
<tr>
<th>$L_1$</th>
<th>$L_2$</th>
<th>$C_1$</th>
<th>$C_{sc}$</th>
<th>$r_{s1}$</th>
<th>$r_{s2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.86 mH</td>
<td>16.35 mH</td>
<td>6.3 μF</td>
<td>1 mF</td>
<td>0.03 Ω</td>
<td>0.1 Ω</td>
</tr>
</tbody>
</table>

For the semiconductors, it was considered $V_r = 1.5$ V and $r_{s2} = 0.01$ Ω.

The grid side filtering inductor was calculated ($L_{grid} = 20$ mH), considering a THD, lower than 5% in (18).

Based on (27) and (29) the controllers proportional and integral gains have been determined, as shown on Table 3.

<table>
<thead>
<tr>
<th>Current controller</th>
<th>Voltage controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_p$</td>
<td>$K_i$</td>
</tr>
<tr>
<td>0.51</td>
<td>2000</td>
</tr>
</tbody>
</table>

A. Steady-state operation

Some results have been obtained and presented in Fig. 8, considering that the PV system is operated at its rated power.

![Fig. 8](image)

By analyzing the simulation results Fig. 8a it is visible that the voltage at the DC link keeps the expected value of around 400V and presents a ripple below 1.5% of $V_{DC}$.

The DC/AC conversion by the inverter enable the injection of the energy produced by the photovoltaic system in the grid.

The control of the grid current is performed as expected. As the Fig. 8b) presents, the current has a nearly sinusoidal waveform, and the displacement factor between the current and the voltage is nearly zero, resulting in a nearly unitary Power Factor ($P_f = 1$).

The current injected in the grid has a THD of 5%, which fulfills the standards in force.

The measured efficiency is 93.4%, which is according to the value calculated from (19).

B. MPPT operation

The MPPT system is expected to adjust the quadratic boost semiconductors switching to guarantee the operation of the photovoltaic system at its maximum power.

To assess the MPPT performance at dynamic conditions, a change in irradiance conditions, from 1000 W/m$^2$ to 820 W/m$^2$ was simulated.

Fig. 9 shows that the MPP search is successful for different irradiance conditions, reaching and holding its operation at the MPP (Fig. 9b). The convergence to the maximum point occurs very fast. When the irradiance reduction occurs, the new power point is reached, decreasing its value, as expected. The variation of the power is approximately proportional to the variation of the irradiance (Fig. 9a and Fig. 9b), because the voltage does not change significantly. Fig. 9c) shows that the voltage in the DC link is controlled, reaching the 400V after the transient that results from the irradiance reduction. The output AC current also decreases its amplitude due to the reduction of the PV power, as presented in Fig. 9d).
Fig. 9. Transient performance of the system with variable irradiance from 1000W/m² to 820W/m²: a) Irradiance; b) Operation power point of the PV; c) Voltage $V_{DC}$ at the DC link; d) Current (red) and voltage (blue, scaled to 1/50x factor) waveforms in the connection to the grid.

V. EXPERIMENTAL RESULTS

The construction of a prototype demonstrates experimentally the theoretical concepts and allows the comparison between the simulation results and the real-world setup. As result the prototype of the quadratic boost converter was assembled according to the previous sizing, as shown in Figure 10, that is then connected to a prototype of the inverter, previously developed in another thesis.

Fig. 10. Prototype of the quadratic boost converter

The performance of the converter with the control of the $I_{PV}$ is presented in Figure 31, which displays the upconversion of the voltage with a gain of around 3.7. The current is being controlled to follow a specified magnitude. This way the switching of the semiconductors occurs depending whether the current needs to be increased or decreased.

The efficiency of this converter was measured as $\eta=91\%$, which is slightly below the theoretical calculations. This evidences the non-ideal factors of the components.

VI. CONCLUSION

A power electronics conversion system targeted for residential 700W PV system was designed.

A DC/DC converter was sized to step-up the PV voltage value, and to guarantee the PV operation at its maximum power point (MPPT), even with varying irradiance conditions.

A VSI was used to guarantee the connection to the grid, and the controllers were designed to guarantee the control of the whole PV system, including the grid currents and the intermediate DC link.

The simulation results have shown that the system performs correctly: the DC link voltage is kept at 400V and the current injected in the grid presents low THD and nearly unitary power factor.
The assembled prototype shows that the proposed conversion system is in fact a real option that converts the PV power and injects it in the grid, with a fairly good performance and efficiency.

REFERENCES