Distributed Electronic Converter for Discrete Solar Panels

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Abstract – The goal of this work is to develop a new topology of distributed electronic converters for photovoltaic systems, capable of managing each module individually, optimizing the production of energy when they are subjected to different lighting conditions, such as partial shadowing.

A photovoltaic module model is developed, allowing for its computational representation, and its parameters are defined so that it can accurately represent a real commercial module. Moreover, the shadowing problem is described and so are its consequences in current photovoltaic systems.

On the one hand, intending to represent the conventional solution used nowadays, a boost DC-DC converter is studied, its components are determined, and its model is simulated. On the other hand, the same method is applied to the new topology that is proposed in this work, knowing that both configurations must implement the MPPT algorithm. To complete both photovoltaic systems, a full-bridge inverter was used in each, after implementing current and voltage control.

Finally, a side-by-side analysis in terms of energy produced is carried out for the two systems. With this analysis it was possible to conclude that the distributed electronic converter for discrete solar panels, as presented in this study, has a better performance in places which frequently have one or more shadowed modules, while the others are fully illuminated.

Index Terms: Solar panel, Shadowing, Distributed converter, Energetic gain.

I. INTRODUCTION

Since the 90’s, wind and solar energies have been the ones with the largest growth rate [1]. By the end of 2013, the world power capacity based on renewable energies already totaled to approximately 560 GW [2].

However, there is still a lot to be done in terms of technological development, so the renewable energies can be a sustainable substitute of conventional means of electricity production. Solar panels are responsible for converting the energy from the sun, which reaches earth’s surface as radiation, into electric energy. Even though its main problem is the low efficiency of this conversion, there are other aspects that can be improved. In particular, the electronic converters, which are used to extract the maximum amount of energy that the panel can provide and deliver it to the electric grid can still be optimized.

The typical solar panel used in microgeneration applications can be divided in smaller independent parts called modules. When illuminated, each of these modules produces electric energy in a continuous form. Usually, they are all connected to each other, mostly in series, and an electronic converter is responsible for tracking the maximum power point.

However, if the modules are not equally illuminated, the solar panel performance is greatly affected and that could easily happen as consequence of a shadow casted by a neighboring construction or any kind of dirt that might accumulate on its surface. If multiple cells are connected in series, which happens in photovoltaic modules, then they must carry the same current, regardless of how illuminated they are. This current is usually imposed by the least illuminated cells, but it some cases these cells might be forced into a reverse mode of operation where they are subjected to a negative voltage [3]. This may lead to phenomenon called hot-spot which is an excessive overheating that can cause permanent damage [4].

To avoid this effect, a bypass diode is connected in reverse across a certain group of cells, offering an alternative path to the current flow and preventing the shaded cell from acting as a load [4]. Despite protecting the solar panel from hot-spots, this strategy causes some power dissipation in the bypass diode and wastes the energy generated by all the bypassed cells.

This is the problem that is addressed in this study, with a small change: instead of considering individual cells, only modules are considered. The idea is to apply an independent DC-DC converter to each module so that all modules can deliver the maximum amount of power available, even with different levels of illumination. This solution is compared with the conventional one to determine the energetic gain that it accomplishes.

II. SOLAR PANEL

Since this study is based on computational simulation, in particular using the Simulink toolbox from Matlab, there was a need to develop a model that could represent the
chosen photovoltaic modules, which have the specifications shown in Table 1 [5].

<table>
<thead>
<tr>
<th></th>
<th>( P_{DC}^T )</th>
<th>( V_{MP}^T )</th>
<th>( I_{MP}^T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power</td>
<td>310 Wp</td>
<td>8.53 A</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>( \eta^T )</td>
<td>15.9%</td>
<td></td>
</tr>
<tr>
<td>Rated Current</td>
<td>8.53 A</td>
<td>36.3 V</td>
<td></td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>( V_{MP}^T )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short-circuit Current</td>
<td>( I_{cc}^T )</td>
<td>8.99 A</td>
<td></td>
</tr>
<tr>
<td>Open Circuit Current</td>
<td>( V_{ca}^T )</td>
<td>45.6 V</td>
<td></td>
</tr>
<tr>
<td>Temperature Coefficient of ( V_{ca} )</td>
<td>( \mu_{ca} )</td>
<td>-0.146 V/K</td>
<td></td>
</tr>
<tr>
<td>Temperature Coefficient of ( I_{cc} )</td>
<td>( \mu_{cc} )</td>
<td>4.50 mA/K</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 – Specifications provided by the module’s manufacturer

The mathematic model used to describe each module is based on the “one diode and five parameters” model presented in [6], which is based on the equivalent circuit depicted in Figure 1.

![Figure 1 – Equivalent circuit of the “one diode and five parameters” model](image)

The five parameters of the model, \( m \), \( R_{sh} \), \( R_s \), \( I_{cc}^T \) and \( I_{ca}^T \), are calculated for Standard Test Conditions (\( G^T=1000\) W/m\(^2\) and \( \theta^T=25^\circ \)) using the following equations:

\[
I_{MP}^T = I_{cc}^T - \frac{V_{MP}^T}{R_{sh}} = \left( I_{cc}^T - \frac{V_{ca}^T}{R_{sh}} \right) e^{-\frac{V_{ca}^T}{mV_T}} + \frac{V_{ca}^T}{R_{sh}} \tag{1}
\]

\[
I_{MP}^T + \frac{\left( R_{sh} I_{cc}^T - V_{ca}^T + R_s I_{ca}^T \right) e^{-\frac{V_{ca}^T}{mV_T}}}{mV_T R_{sh}} = \frac{1}{R_{sh}} \tag{2}
\]

\[
\frac{\left( R_{sh} I_{cc}^T - V_{ca}^T + R_s I_{ca}^T \right) e^{-\frac{V_{ca}^T}{mV_T}}}{mV_T R_{sh}} + \frac{R_s}{R_{sh}} = 0 \tag{3}
\]

\[
I_{ca}^T = \left( I_{cc}^T - \frac{V_{ca}^T}{R_{sh}} - \frac{V_{ca}^T}{mV_T} \right) e^{-\frac{V_{ca}^T}{mV_T}} \tag{4}
\]

\[
I_{cc}^T = I_0 e^{\frac{V_{ca}^T}{mV_T}} + \frac{V_{ca}^T}{R_{sh}} \tag{5}
\]

The three first parameters are constant, but \( I_0 \) and \( I_{cc} \) depend on temperature and irradiance. These variations are taken into account using (4) and (5), and knowing that \( I_{cc} \) and \( V_{ca} \) depend on these factors according to:

\[
I_{cc} = \frac{G}{G^T} \left[ I_{cc}^T + \mu_{cc} (T_c - T_c^T) \right] \tag{6}
\]

\[
V_{ca} = V_{ca}^T + \mu_{ca} (T_c - T_c^T) + mV_T \ln \left( \frac{G}{G^T} \right) \tag{7}
\]

This model was implemented in a Simulink schematic based on the circuit from Figure 1, replacing the current source and the diode by a controlled voltage source given by:

\[
V_D = mV_T \ln \left( \frac{I_0 - I_{cc}}{I_0} + 1 \right) \tag{8}
\]

This representation produces an approximated result since it means that the current \( I_{sh} \) is not taken into account, however, this simplification as a small impact because the value of \( R_{sh} \) is usually very high. The characteristic curves for different irradiances given by this model are shown in Figure 2.

![Figure 2 – Characteristic curves of the model](image)

### III. BOOST CONVERTER

The DC-DC boost converter [7] [8] used as representation of the conventional solution for photovoltaic systems will be briefly described in this Section, and its circuit is illustrated in Figure 3. The continuous voltage source will be replaced by a series of 10 photovoltaic modules, each with a bypass diode in parallel.
Being a common type of converter, its detailed theoretical analysis has been extensively reported\cite{8}.

This converter is responsible for implementing the MPPT algorithm. To accomplish that it controls the input average current in order to ensure that the maximum power is being extracted from the photovoltaic panel, when all the modules are equally illuminated. This control depends on the command signal generated for the MOSFET Q based on measurements the panel’s voltage and current.

Since the goal is to find the point of panel’s characteristic curve where the power is higher, the command signal can be obtained calculating the derivative of the power, with respect to the current. This calculation is given approximately by \cite{13}:\[
\frac{dP}{dt} = V + I \frac{dV}{dt} \approx v(t) + i(t) \frac{v(t) - v(t - \Delta t)}{i(t) - i(t - \Delta t)}
\] (9)

where $\Delta t$ is the time interval between samples.

Ideally, this derivative would be equal to zero, meaning that the power would always be as high as it could be. This situation however, cannot occur since it would mean that the converter would have an infinite frequency. For that reason, an interval of variation for the power derivative, and consequently for the current, was determined and implemented using a hysteresis comparator. The limits of this interval were determined, based on the relation between voltage and current given by the model, so that they would correspond to a maximum current ripple of 5% in standard test conditions.

After determining the parameters that characterize all circuit components, and considering an ideal solar panel modeled by a continuous voltage source for Standard Test Conditions, the converter was simulated. The main results are shown in Figures 4 to 7.

These results and all the others that were obtained confirmed that the photovoltaic panel and the Boost converter are working properly and accordingly with the theoretical predictions \cite{6}\cite{8}. Moreover, they allowed the estimation of the converter’s efficiency, resulting in about 97.6%.

IV. DISTRIBUTED CONVERTER

As mentioned above, the solution that is proposed in this study requires that each module has its own individual converter, with maximum power point tracking capabilities. To accomplish that, the converters were connected in two groups in series, each with 5 converters in parallel. This means that each converter must convert the output voltage of a single module into half of the inverter’s input voltage.

The topology chosen for these converters is the one depicted in Figure 8. This configuration can be named as Isolated SEPIC (Single-Ended Primary Inductor Converter). Since this circuit is not very common, it is convenient to perform a theoretical analysis first.
In terms of regulation, this converter is similar to the one detailed on Section III, since it also has a single transistor to control the current that flows through the input coil. Moreover, it also has an output diode. However, between these two semiconductors, this converter has a capacitor and a high frequency transformer, allowing higher conversion rates.

Based on the ideal characteristics of each component, it was possible to obtain the waveforms shown in Figure 9 and Figure 10.

**Figure 8 – Distributed converter**

In addition to the waveforms, some important relations were obtained:

A. Inductor Voltage

\[
\frac{1}{T} \int_0^T v_{L_i} \, dt = 0 \iff V_{L_i}^{\text{min}} = -\frac{\delta U}{1-\delta} \quad (10)
\]

B. Transistor Current

\[
i_{Q_i}^{\text{av}} = \frac{1}{T} \int_0^T i_Q \, dt = I_{L_i} \iff I_Q^{\text{max}} = \frac{I_{L_i}}{\delta} \quad (11)
\]

C. Transistor Voltage

\[
v_{Q_i}^{\text{av}} = \frac{1}{T} \int_0^T v_Q \, dt = U \iff V_Q^{\text{max}} = \frac{U}{1-\delta} \quad (12)
\]

**Figure 9 – Ideal current waveforms**

**Figure 10 – Ideal voltage waveforms**

D. Input Capacitor Current

\[
\frac{1}{T} \int_0^T i_{C_i} \, dt = 0 \iff I_{C_i}^{\text{min}} = \frac{\delta U}{1-\delta} \quad (13)
\]

E. Input Capacitor Voltage

\[v_{C_i}^{\text{av}} = U \quad (14)\]

F. Transformer Voltages

\[
v_{T1}^{\text{av}} = \frac{1}{T} \int_0^T v_{T1} \, dt = 0 \iff V_{T1}^{\text{av}} = \frac{\delta U}{1-\delta} \quad (15)
\]

\[
v_{T2}^{\text{av}} = \frac{1}{T} \int_0^T v_{T2} \, dt = 0 \iff V_{T2}^{\text{min}} = \frac{\delta U}{1-\delta} \quad (16)
\]

G. Diode Current

\[
i_{D_i}^{\text{av}} = \frac{1}{T} \int_0^T i_D \, dt = \frac{V_o}{R_o} \iff I_D^{\text{max}} = \frac{V_o}{(1-\delta)R_o} \quad (17)
\]
H. Diode Voltage

\[ v_{d_{av}} = \frac{1}{T} \int_0^T v_d \, dt = -V_o \leftrightarrow V_{d_{min}} = -\frac{V_o}{\delta} \]  

(18)

I. Duty Cycle

\[ \delta = \frac{V_o}{U m_F + V_o} \]  

(19)

where \( m_F \) is the transformer’s ratio.

To determine the circuit component’s characteristic values of the it was considered that the module can be modeled as a continuous voltage source with a value equal to the module’s maximum power point voltage, for standard test conditions \((U=36.3 \, \text{V})\). Since it was considered the same input voltage for the inverter as before \((450 \, \text{V})\), the output voltage of each converter should be about 225 V. The transformation ratio chosen was 5.

In terms of the MPPT algorithm, the strategy used for this converter is similar to the one described in the previous Section. Nonetheless, since in this case each module is being controlled independently, and knowing that the energy produced must be extracted even for reduced irradiances, the converter’s input current may be very small. In those cases, it is important to adapt the current ripple amplitude to its average value, i.e. smaller currents should have smaller ripple. For that reason, the controller was modified so that the hysteresis comparator’s limits change based on the value of the converter’s input current.

In this case, two different simulations were performed: one with just a single module-converter pair and the other with the complete set of ten pairs. As it was considered for the Boost converter, in both cases the circuit load is a resistor. The main results obtained for the first case are shown in Figures 11 to 15.

For the complete set of modules and converters, the waveforms registered for each one were similar and the total output voltage can be observed in Figure 15. It is also possible to conclude that the conversion efficiency is approximately equal to the one obtained for a single converter.

V. INVERTER

Despite the topology chosen for the DC-DC converter, and as long as the solar panel intends to inject the produced power in the electric grid, there is always the need to convert the output DC voltage into an AC voltage. For that purpose, the single-phase full-bridge inverter of Figure 16 was connected to both DC-DC converters and to a model of the grid.
As mentioned before, the ideal input continuous voltage of this inverter is 450V. Its output must be alternating voltage and current, almost in phase with each other and with the grid’s frequency. The RMS value of this voltage will be close to the grid’s voltage RMS value (230 V). As for the current, its RMS value will depend on the amount of power being generated at each instant.

This inverter has two interlocked control objectives that it has to attain, both reflected on the pre-filtered current $i_{PWM}$. It has to guarantee that this current is approximately sinusoidal, following a given reference, and it also has to ensure that this reference has the correct amplitude so that the amount of energy produced is equal to the one injected in the grid.

As for the first objective, it was developed a non-linear current control assuming the existence of a sinusoidal reference current. This control is based on two hysteresis comparators that receive the error $e$, given by the difference between the reference current and $i_{PWM}$. The characteristic curves of these comparators are shown in Figure 17.

As it can be observed, these comparators produce two binary variables that depend on the maximum variation allowed for $i_{PWM}$, which is set to be 10% of the RMS value of the reference current. According to these curves, three different operating modes can be defined [9] [10] [11]:

- $\rho = 1, \lambda = 1 \rightarrow e > \frac{\Delta i_{PWM}}{2} \rightarrow i_{PWM}$ must rise $\rightarrow v_{PWM} = V_{DC} \rightarrow y_1 = y_4 = 1$
- $\rho = 0, \lambda = 0 \rightarrow e < -\frac{\Delta i_{PWM}}{2} \rightarrow i_{PWM}$ must fall $\rightarrow v_{PWM} = -V_{DC} \rightarrow y_2 = y_3 = 1$

As for the second control objective, which is the determination of the current reference amplitude, it can also be seen as the control of the converter’s input voltage. That is a consequence of maintaining the equilibrium of powers across the input capacitor. If the power received from the DC-DC converter is equal to the power injected by the inverter then this voltage should have a stable average value. However, it is important to note that this capacitor must support the instantaneous difference between the two powers, since one is approximately continuous and the other alternating, resulting in an oscillating voltage.

To keep the converter’s input voltage at around 450 V, as previously discussed, it was used the linear controller presented in Figure 18 [8]. The controller’s parameters were calculated based on the closed-loop transfer function, assuming that its characteristic polynomial’s coefficients are related with each other according to $b_k^2 = 2b_{k-1}b_{k+1}$.

The resulting expressions for controller’s parameters are:

$$\begin{align*}
K_i &= -\frac{C_{DC}}{8T_d^2G_{inv}} \\
K_p &= -\frac{C_{DC}}{2G_{inv}T_d}
\end{align*}$$

where $T_d$ is the delay introduced by the inverter, which was considered to be 20 ms, and $G_{inv}$ is its voltage gain, given by:

$$G_{inv} = \frac{V_{AC RMS}}{V_{DC}}$$

As for the LC filter, its components were determined based on the equivalent circuit of Figure 19, where the
power injected in the electric grid is represented by a resistor given by:

\[ R_{eq} = \frac{V_r^2}{P_o} \]  

(22)

where \( V_r \) is the nominal RMS value of the grid’s voltage and \( P_o \) is the injected power, which was considered to be equal to the photovoltaic system’s nominal power.

![Figure 19 – Equivalent circuit for the LC filter](image)

This filter’s cut-off frequency, \( \omega_c \), was set to be 10 times the grid frequency and its chosen damping coefficient, \( \xi \), was \( \sqrt{2}/2 \). Based on these values, the circuit parameters were calculated by:

\[ L_f = \frac{2R_{eq}\xi}{\omega_c} \]  

(23)

\[ C_f = \frac{1}{2\omega_cR_{eq}\xi} \]  

(24)

The electric grid was modeled by the equivalent circuit shown in Figure 20, and its parameters were calculated according to [12], considering a cable length of 500m.

![Figure 20 – Equivalent circuit of the electric grid](image)

Once again, after determining all the circuit components’ values, the inverter was simulated. The results are shown in the following figures.

![Figure 21 – Inverter’s input voltage](image)

![Figure 22 – Inverter’s pre-filtered output current in detail](image)

![Figure 23 – Inverter’s pre-filtered output voltage](image)

![Figure 24 – Inverter’s filtered output current](image)

Once again it is possible to conclude that the results are in line with the expectations. In particular, the filtered output current that is injected in the electric grid has a Total Harmonic Distortion of only 2.42%. As for the inverter’s efficiency, these results indicate that it should be around 97.1%.

VI. COMPARISON

In this Section is done a performance analysis of the two topologies under different shadowing conditions. First, it is important to note that it was not considered the existence of a transformer in the conventional system, which is often present to provide galvanic isolation between the solar panel and the grid. This additional element will be responsible for an extra amount of losses, decreasing the gap between the two results. For that reason, an efficiency of 98% was considered for the results obtained by simulation.

The first step was to compare the two complete systems under Standard Test Conditions. In this case, the output power obtained for each system by simulation was:

- Conventional system – \( P_{out}=2897 \) W
- Distributed system – \( P_{out}=2834 \) W

As it was expected, given the lower efficiency of the
distributed DC-DC converter, its injected power is 2.17% lower than the conventional one. Considering only the efficiency, it is possible to conclude that the distributed topology is more appropriate for places where partial shadowing is frequent.

Simulation’s results are presented in Table 2. These tests were made considering that all modules have the same temperature (θr=25°C) but different irradiances: shadowed modules were set to have irradiances of 200 W/m² or 400 W/m², and the rest were set to Standard Test Conditions.

<table>
<thead>
<tr>
<th># shaded modules</th>
<th>Irradiance of shaded modules</th>
<th>Output power</th>
<th>Energetic gain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Conventional system</td>
<td>Distributed system</td>
</tr>
<tr>
<td>1</td>
<td>200 W/m²</td>
<td>2606 W</td>
<td>2605 W</td>
</tr>
<tr>
<td>1</td>
<td>400 W/m²</td>
<td>2606 W</td>
<td>2667 W</td>
</tr>
<tr>
<td>3</td>
<td>200 W/m²</td>
<td>2007 W</td>
<td>2151 W</td>
</tr>
<tr>
<td>3</td>
<td>400 W/m²</td>
<td>2007 W</td>
<td>2337 W</td>
</tr>
</tbody>
</table>

Table 2 – Results obtained by simulation

Analyzing these results, it is easy to conclude that even using a converter with a lower efficiency, the energy extracted from shadowed modules with partial shadowing conditions, that otherwise would be lost, is very significant.

VII. CONCLUSIONS

In this work was proposed a complete solution to solve the partial shadowing problems that affects many installations of solar panels. After implementing a model for photovoltaic modules, developing circuits and their controllers for the conventional and the distributed topologies, and also for the inverter connected to both, the energetic performance of these systems was evaluated.

The extra energy that is extracted from the shadowed modules by the distributed converter, in conditions of partial shadowing, is sufficient to compensate for the lower efficiency compared with the conventional topology. Thus, the main conclusion is that for safety (by avoiding hotspots) and performance reasons the use of a distributed converter topology is highly recommended for installations where the partial shadowing phenomenon is likely to occur.

Future studies may focus on improving the efficiency of the DC-DC converter for the distributed topology, so that it becomes equivalent to the conventional solutions used nowadays, even when partial shadowing is not present. This could strongly contribute to establish distributed topologies as standard practice, making solar panels safer and more efficient. Another interesting line of study would be scaling the DC-DC converters to the photovoltaic cell level, managing each one’s power point independently. This would allow to further increase the efficiency of the energy extraction.

REFERENCES