Nonlinear Control Design for the Photovoltaic Isolated-Port Architecture with Submodule Integrated Converters

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Abstract—Differential power processing (DPP) isolated-port architecture with submodule integrated converters (subMICs) enables improved energy capture in photovoltaic (PV) power systems. This paper describes a control scheme for flyback subMICs operating in discontinuous conduction mode (DCM). The duty-cycle is driven in proportion to a voltage error, with no further processing, thus eliminating the need to measure or to control the current explicitly. The approach is well suited for very simple, analog PWM controller implementation, but the resulting control loops become nonlinear. The system stability is demonstrated using the Lyapunov stability theorem. Experimentally measured module-level efficiency is greater than 95% for a 72-cell PV module having 3 substrings with solar irradiation of 80%, 60% and 40%, respectively.

IV. INTRODUCTION

A photovoltaic (PV) string is commonly composed of PV modules connected in series. The modules are typically divided into submodules, which consist of substrings of PV cells bypassed by backplane diodes. To improve the power yield under mismatch or shading conditions, power may be processed at the module or submodule levels. It has been shown that energy yield improvements are higher if the granularity of distributed power processing is increased [1].

A common distributed power processing architecture is based on converters connected in series with each module [2-4] or sub-module [5]. The converters control the operating point locally, searching for module-level, or sub-module-level maximum power point (MPP). The converters may be connected in series, or in parallel, to a mutual DC bus. A disadvantage of this approach is that each converter must be rated at full power of the respective PV substring. Furthermore, the resulting insertion loss diminishes energy capture improvements.

To eliminate the insertion loss, several ‘differential power processing’ (DPP) architectures have been investigated [6-11]. With these architectures, the current flows directly through the PV string, without additional processing and insertion losses. The approach is to balance the string by matching the currents generated by the substrings. The DPP converters are connected in parallel to the substrings. They inject complementary currents that
equalize the operating points of the substrings, thus increasing the overall energy capture. The converters process only a fraction of the total power, so their losses are low. In the absence of mismatches or shading, the substring operating points are nearly equal. In this case, the DPP converters can be turned off, so that the overall conversion efficiency approaches 100%.

Two types of DPP architectures have been compared in [6]: the PV-to-bus architectures, and the PV-to-PV architectures. The PV-to-bus architectures transfer energy between the substrings and the overall string bus [7]. These architectures require converters with high voltage conversion ratio, in order to match the single substring voltage to the overall string voltage. Conversely, the PV-to-PV architectures transfer energy between neighboring substrings, using converters with conversion ratio close to 1:1. A number of such architectures have been presented. A PV-to-PV architecture that employs buck-boost converters is described in [8]. A system that uses Cuk converters is discussed in [9]. A switched capacitor converter is used in [10].

The isolated-port submodule integrated converter (subMIC) DPP architecture, introduced in [11], is shown in Fig. 1. The converter secondaries are connected to a mutual dc bus, called the ‘isolated-port’. The subMICs supply differential currents that balance the string. Substrings that generate more than the median power inject current to the isolated port. Substrings that generate less than the median power draw current from the isolated port. The port voltage \(v_{sec}\) represents the median substring voltage, which is used as a reference signal by the control loop in each subMIC.

An advantage of the isolated-port architecture is that it processes less power than other DPP architectures [6]. With the isolated-port, power processed by each converter is the minimum necessary to operate at MPP, as shown in [11]. Furthermore, the conversion ratio can be close to 1:1, allowing low-voltage components. As a result, the efficiency of the isolated port architecture is potentially higher, under shading, in comparison to other DPP architectures. It has been shown that the isolated-port subMIC architecture results in 7-11% improvements in annual energy yield in realistic system scenarios [12].

In the isolated port system considered in this paper, the subMICs are implemented using flyback converters operating in discontinuous conduction mode (DCM). In [11], the subMIC output current is controlled in proportion to a voltage difference between the substring and the isolated port voltage. A look-up table, implemented by a digital microcontroller, is embedded within the feedback loop to compensate for the non-linear gain of the DCM flyback, producing a current that is linear with respect to the voltage difference.

This paper presents a controller that drives the subMIC duty-cycle directly in proportion to the voltage difference, without measuring or controlling the current explicitly. This approach enables a simple analog control scheme, which is simple, robust and low-cost. However, the control-loop of the subMIC is described by non-linear dynamics. A main finding of this work is that despite this non-linearity the system is stable, and that the performance remains comparable to the results obtained in [11].

The paper is organized as follows. System operation is described in Section II, where it is shown that the operating points of the substrings are well equalized in steady-state, and that the differences in substring voltages are inversely proportional to the gain of the controller. In Section III, using the Lyapunov stability theorem, the system is shown to be globally stable with any number of substrings in series, and any set of parameters. Experimental results are presented in Section IV, while Section V concludes the paper.

II. SYSTEM OPERATION

Unlike traditional PV control methods, the substring MPPs in the system of Fig. 1 are not individually tracked. Instead, the substrings are controlled to have approximately equal voltages. Voltages balancing results in an operating point that is close to the ideal MPP.

Figure 2 compares the operating points of three substrings biased with different short-circuit currents: 4 A, 3 A, and 2 A, in a ‘Conergy’ S175MU PV module. The ideal MPPs and the operating points corresponding to equal substring voltages are shown. The operating points of equal voltages are close to the ideal MPPs, producing a total output power that is 99.7% of the ideal output power. Under light to moderate shading conditions, simple voltage balancing operates well, and produces an output power that is close to ideal.

The key to voltage balancing is the floating voltage of the isolated port, \(v_{sec}\). Each subMIC is controlled to equalize its primary and secondary voltages. As a result, the substring voltage, at the primary side, is equalized to the isolated port voltage, at the secondary side. Because all the substring voltages are equalized to the same isolated-port voltage, they are equalized to each other. This mechanism can be easily understood by assuming a linear current to voltage ratio:

\[
I_{pri,j} = K \cdot (V_{sub,j} - V_{sec})
\]

where \(I_{sec}\) is the average DC current at the primary side.

Figure 2. Voltage-Power curves and operating points: ideal MPPT (blue) vs. voltage balancing (black).
The converters inject currents that equalize the substring voltages. With a substring voltage \( V_{sub,i} \) higher than \( V_{sec} \), current is subtracted from the substring and is injected to the isolated port. With a substring voltage \( V_{sub,i} \) lower than \( V_{sec} \), current is injected to the substring and is subtracted from the isolated port. Assume, for simplicity, that \( K \) is very large. From (1) it follows that voltage differences approach zero, and all substring voltages are equal.

The subMICs are modeled by the large-signal, average circuit model of the flyback converter in DCM [13]:

\[
I_{pri,i} = \frac{T_s}{2L_{pri}} \cdot v_{sub,i} \cdot d_{pri,i}^2
\]

\[
I_{sec,i} = -\frac{T_s}{2L_{sec}} \cdot v_{sec} \cdot d_{sec,i}^2
\]

where \( T_s \) is the PWM switching period, and \( L_{pri} \) and \( L_{sec} \) are the transformer magnetizing inductances referred to the primary or secondary side, respectively.

Instead of controlling the current in response to the voltage difference, a simpler control rule is considered:

\[
d_i = K_p \cdot (v_{sub,i} - v_{sec})
\]

The duty-cycles are driven in proportion to the voltage differences. Term \( K_p \) is a constant gain. This control scheme is implemented by the analog circuit of Fig. 1(b). The operating point may be obtained by solving the system dynamics in (7), with all time derivatives set to zero. This produces the following set of equations:

\[
I_{pri,i} = \frac{T_s K_p^2}{2L_{pri}} \cdot (v_{sub,i} - v_{sec}) \cdot g_i (v_{sub,i} - v_{sec})
\]

By adding the load and the dynamics of capacitors, the full state-space dynamics are obtained. Both the subMIC dynamics and feedback dynamics are included:

\[
\frac{d}{dt} V_{sub,i} = \frac{1}{C_{pri}} (i_{g,i} - i_{pri,i} - i_{mod}) \quad \frac{d}{dt} V_{sec} = \frac{1}{N \cdot C_{sec}} \sum_i i_{sec,i}
\]

In this expression, the load is represented by an equivalent resistor \( R_{mod} = \frac{V_{mod}}{I_{mod}} \), as in Fig. 1(a). The expression \( I_{pri}(V_{sub,i}) \) is the I-V curve of the substring.

### B. Operating Point Analysis

In this section it is shown that the accuracy of voltage balancing is governed by the gain \( K_p \). An upper bound on the voltage error \( |V_{sub,k} - V_{sub,j}| \) is shown to be inversely proportional to \( K_p \). Thus, with a higher gain, the voltage error is decreased, and the substrings voltages are better equalized.

The operating point may be obtained by solving the system dynamics in (7), with all time derivatives set to zero. This produces the following set of equations:

\[
I_{pri,i} (V_{sub,i}) - I_{pri,i} = \frac{1}{R_{mod}} \sum_i V_{sub,i}
\]

\[
I_{pri,i} = \frac{T_s K_p^2}{2L_{pri}} \cdot V_{sub,i} \cdot (V_{sub,i} - V_{sec}) \cdot g_i (V_{sub,i} - V_{sec})
\]

\[
\sum_i V_{sub,i} \cdot I_{pri,i} = 0
\]

The maximum and minimum voltages, \( V_{max} \) and \( V_{min} \) are defined as follows:

\[
V_{max} = V_{sub,k} = \max_i \{ V_{sub,i} \}
\]

\[
V_{min} = V_{sub,j} = \min_i \{ V_{sub,i} \}
\]

where index \( k \) represents the maximum-voltage substring, and index \( j \) represents the minimum-voltage substring. The secondary voltage \( V_{sec} \) is bounded by these voltages:

\[
V_{min} \leq V_{sec} \leq V_{max}
\]
Otherwise, the primary currents \( I_{pri,k} \) are either all positive, or all negative, and the power at the isolated-port cannot be balanced.

According to (8), the primary currents at substrings \( k \) and \( j \), are related to \( V_{max} \) and \( V_{min} \) by the expressions:

\[
I_{pri,k} = \frac{T_s K_p}{2L_{pri}} V_{max} (V_{max} - V_{sec})^2
\]
\[
I_{pri,j} = \frac{T_s K_p}{2L_{pri}} V_{min}^2 (V_{sec} - V_{min})^2
\]

Using the top equation in (8) yields:

\[
I_{pri,k} (V_{max}) - I_{pri,k} = \frac{1}{R_{mod}} \sum_i V_{sub,i}
\]
\[
I_{pri,j} (V_{min}) - I_{pri,j} = \frac{1}{R_{mod}} \sum_i V_{sub,i}
\]

which leads to:

\[
I_{pri,k} (V_{max}) - I_{pri,k} (V_{min}) = I_{pri,k} - I_{pri,j}
\]

Substitution of (11) yields:

\[
\frac{2L_{pri}}{T_s K_p} (I_{pri,k} (V_{max}) - I_{pri,j} (V_{min}))
\]

\( I_{sec} \) is defined the maximum short-circuit current over all substrings. At the right-hand side of (14), the currents are upper bounded by this constant:

\[
V_{max} (V_{max} - V_{sec})^2 + \frac{V_{sec}}{V_{min}} (V_{sec} - V_{min})^2 \leq \frac{2L_{pri} I_{sec}}{T_s} \frac{1}{K_p^2}
\]

Using the inequalities \( V_{max} < V_{sec} \) and \( V_{min} < V_{max} \), a weaker bound is obtained:

\[
V_{min} (V_{max} - V_{sec})^2 + \frac{V_{sec}}{V_{min}} (V_{sec} - V_{min})^2 \leq \frac{2L_{pri} I_{sec}}{T_s V_{min}} \frac{1}{K_p^2}
\]

\[
(V_{max} - V_{sec})^2 + (V_{sec} - V_{min})^2 \leq \frac{2L_{pri} I_{sec}}{T_s V_{min}} \frac{1}{K_p^2}
\]

By replacing the left-hand side expression with its minimum over \( V_{sec} \), one obtains:

\[
\frac{1}{2} (V_{max} - V_{min})^2 \leq \frac{2L_{pri} I_{sec}}{T_s V_{min}} \frac{1}{K_p^2}
\]

The voltage \( V_{min} \) is approximated by the average string voltage: \( V_{min} \approx V_{sec}/N \). This approximation is accurate when \( V_{max} \) approaches \( V_{min} \). This approximation produces:

\[
(V_{max} - V_{min})^2 \leq \frac{4NL_{pri} I_{sec}}{T_s V_{sec} K_p^2}
\]

which leads to:

\[
\text{for every } j, k : \quad |V_{sub,k} - V_{sub,j}| \leq \frac{4N L_{pri} I_{sec}}{T_s V_{sec} K_p^2}
\]

The result is that the voltage difference between any two substrings is inversely proportional to the gain \( K_p \). The square-root is a constant, a function of system parameters: \( N \) is the number of substrings, \( L_{pri} \) is the inductance, \( T_s \) is the PWM period, \( V_{sec} \) is the string voltage, and \( I_{sec} \) is the maximal short-circuit.

C. Stability Analysis

In this section, the stability of the system is analyzed using the Lyapunov stability theorem. The strategy is to define a Lyapunov energy function, and to show that it is decreasing in time, at all points in state-space. According to the Lyapunov’s theorem, this is a sufficient condition for the equilibrium point to be globally stable.

Typical state-space trajectories are shown in Fig. 3: These are obtained by numerical solution of the dynamics in (7). The simulated system is composed of \( N = 2 \) substrings, with non-symmetrical short-circuit currents 4 A and 3 A, as in Fig. 2. The system parameters are given in Table I. The gain is \( K_p = 2 \). For all trajectories, \( v_{sec} \) is initiated at the average of voltages: \( v_{sec} = (v_{sub,1} + v_{sub,2})/2 \). Since the system has 3 state variables, \( v_{sec} \) is not shown. The system converges to its equilibrium point from any initialisation point, implying that the system is globally stable.

The following proof of stability relies on two assumptions: first, the I-V curves of all substrings are assumed monotonically decreasing: a higher voltage produces a lower current. The second assumption is that the substrings are matched, i.e. that the I-V curves of all substrings are equal. With this assumption, all the substring voltages are equal to the voltage at the isolated port. This equilibrium voltage is defined as \( V_{m} \):

\[
V_{m} = V_{sec} = V_{m}
\]

A Lyapunov energy function is defined with respect to this equilibrium point:

\[
E = \frac{1}{2} C_{pri} \sum_i (v_{sub,i} - V_{m})^2 + \frac{1}{2} N C_{sec} (v_{sec} - V_{m})^2
\]

For stability, the energy should be monotonically decreasing:

\[
\frac{dE}{dt} = C_{pri} \sum_i (v_{sub,i} - V_{m}) \frac{dv_{sub,i}}{dt} + N C_{sec} (v_{sec} - V_{m}) \frac{dv_{sec}}{dt} < 0
\]
Figure 3. Simulation of state-space trajectories. The system converges to the equilibrium from any initial point.

This condition should be true for all state-space points, except at the equilibrium point, where \( \frac{dE}{dt} = 0 \).

Substitution of the system dynamics (7) in (22) and replacing the load with \( R_{\text{mod}} = \frac{V_{\text{mod}}}{I_{\text{mod}}} = \frac{N V_m}{I_p(V_m)} \), after some algebraic manipulations result in:

\[
\frac{dE}{dt} = \sum_i \left( I_{p_v} (V_{\text{sub},i}) - I_{p_v} (V_m) \right) (\frac{1}{N} \sum_i V_{\text{sub},i} - V_m) + \frac{T_p K_p^2}{2 L_{\text{pri}}} \sum_i \left( V_{\text{sub},i} - V_{\text{sec}} \right) g_i (V_{\text{sub},i} - V_{\text{sec}}) + \frac{T_p K_p^2}{2 L_{\text{pri}}} \sum_i \left( V_{\text{sub},i} - V_{\text{sec}} \right) g_i (V_{\text{sub},i} - V_{\text{sec}})
\]

Collection of common terms yields:

\[
\frac{dE}{dt} = X_1 + X_2 + X_3
\]

\( X_1 = -\frac{1}{N V_m} I_p (V_m) \left( \sum_i V_{\text{sub},i} - V_m \right)^2 \) (24)

\( X_2 = -\frac{T_p K_p^2}{2 L_{\text{sec}}} \frac{V_m}{V_{\text{sec}}} \sum_i \left( V_{\text{sub},i} - V_{\text{sec}} \right) g_i (V_{\text{sub},i} - V_{\text{sec}}) \)

\( X_3 = \sum_i \left( V_{\text{sub},i} - V_m \right) \left( I_{p_v} (V_{\text{sub},i}) - I_{p_v} (V_m) \right) \)

The derivative of energy is written as a sum of three terms: \( X_1, X_2, X_3 \). All of these terms are negative. The term \( X_1 \) is negative simply because it is a minus of positive terms. The term \( X_2 \) is negative because \( (v_{\text{sub},i} - v_{\text{sec}})^3 g_i (v_{\text{sub},i} - v_{\text{sec}}) \) is always positive. The term \( X_3 \) is negative because \( I_{p_v} (v_{\text{sub},i}) \) is monotonically decreasing:

\[
\begin{align*}
 & v_{\text{sub},i} > V_m \Rightarrow I_{p_v} (v_{\text{sub},i}) < I_{p_v} (V_m) \\
 & v_{\text{sub},i} < V_m \Rightarrow I_{p_v} (v_{\text{sub},i}) > I_{p_v} (V_m)
\end{align*}
\]

(25)

For both cases, \( v_{\text{sub},i} > V_m \) or \( v_{\text{sub},i} < V_m \), \( X_3 \) is negative. The derivative is also negative, because \( X_1, X_2, X_3 \) are all negative, so the energy at (21) is monotonically decreasing:

\[
X_1 < 0 \quad X_2 < 0 \quad X_3 < 0 \Rightarrow \frac{dE}{dt} < 0
\]

(26)

which completes the stability proof.

IV. EXPERIMENTAL RESULTS

The system is tested using a ‘Conergy’ S175MU PV module. This is a 72-cell module with three 24-cell substrings. The setup is shown in Fig. 4. The system parameters are given in Table I. The three substrings are biased at varying currents, in the range 0 – 4 A, to emulate varying solar irradiations. Measured V-P curves are shown in Fig. 2. A programmable load emulates the external MPPT, and controls the module terminal voltage, \( V_{\text{mod}} \). Three subMICs are connected in parallel to the substrings, as shown in Fig. 1(a). The subMIC flyback power-stage is the same as the power-stage described in [11].

Results are summarized in Figures 5-8. Figure 5 shows efficiency as a function of gain \( K_p \) for two shading conditions: no shading, and moderate shading, in which the substrings are biased at 2 A, 3 A, 4 A. With any gain \( K_p \) greater than a threshold value \( (K_p = 2 \text{ in this setup}) \), efficiency remains essentially the same. The reason is that with a high enough gain, the voltage error is low, as proven theoretically by (19). The gain \( K_p \) can be selected over a wide range. This leads to a robust design, relatively immune to changes in system parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of substrings</td>
<td>( N )</td>
<td>3</td>
</tr>
<tr>
<td>PV module nominal MPP voltage (no shading, bias currents = 4 A)</td>
<td>( V_{\text{mod}} )</td>
<td>38.2 V</td>
</tr>
<tr>
<td>PV module nominal MPP current (no shading, bias currents = 4 A)</td>
<td>( I_{\text{mod}} )</td>
<td>3.76 A</td>
</tr>
<tr>
<td>PV module nominal load (no shading, bias currents = 4 A)</td>
<td>( R_{\text{mod}} )</td>
<td>10.16 Ω</td>
</tr>
<tr>
<td>Substring max short circuit current (max. bias current)</td>
<td>( I_{\text{sc}} )</td>
<td>4 A</td>
</tr>
<tr>
<td>Magnetizing inductance on the primary</td>
<td>( L_{\text{pri}} )</td>
<td>2.3 μH</td>
</tr>
<tr>
<td>Magnetizing inductance on the secondary</td>
<td>( L_{\text{sec}} )</td>
<td>2.3 μH</td>
</tr>
<tr>
<td>Capacitance on the primary</td>
<td>( C_{\text{pri}} )</td>
<td>188 μF</td>
</tr>
<tr>
<td>Capacitance on the secondary</td>
<td>( C_{\text{sec}} )</td>
<td>40 μF</td>
</tr>
<tr>
<td>PWM switching period</td>
<td>( T_s )</td>
<td>10 μS</td>
</tr>
<tr>
<td>Nominal gain</td>
<td>( K_p )</td>
<td>2 ([1/V])</td>
</tr>
</tbody>
</table>
The efficiency, shown in Fig. 5, appears to remain the same, regardless of $K_p$, as long as the gain is high. However, at closer inspection, an optimal value of gain $K_p$ can be found that maximizes the output power. The existence of this optimal value may be explained by inspection of the V-P curves in Fig. 2. The MPPs corresponding to different bias currents reside very close to a straight line. When the gain $K_p$ is equal to the slope of this line, the substring are operated very close to their ideal MPPs, and the system efficiency is maximized. However, the improvement of efficiency, compared to simple voltage balancing, is typically very small. The optimal gain in the example of Fig. 5 is $K_p = 2 \,[1/V]$. The efficiency with this gain is less than 0.1% higher in comparison to the efficiency at high gains. A conclusion is that improvements that could be obtained using the optimal gain or performing true substring-level MPP are negligible. The system can simply be designed with a gain higher than optimal, to ensure high efficiency at various shading scenarios.

With no shading, the system efficiency is higher than 99.5% because essentially no power is processed, and the subMICs are idle, consuming very low power.

A moderate shading scenario is summarized as follows for the experimental system with a gain of $K_p = 2 \,[1/V]$:

- Biasing currents = 2 A, 3 A, 4 A
- Output power of the string = 101.5 W
- Ideal output power (sum of MPPs) = 106.2 W
- Total power processed by subMICs = 33.5 W
- Average flyback efficiency = 86 %
- Total loss in subMICs = 4.7 W
- Overall efficiency = 95.6 %

The bias conditions in this example correspond to the solar irradiation of 80%, 60% and 40% for the 3 substrings in the module, respectively. One may note that the subMIC efficiency is relatively low (86 %), as the power stage has not been optimized. Nevertheless, the overall efficiency is 95.6 % because only partial power, 32 %, is being processed.

Figure 6 shows the substring voltage difference, as a function of gain $K_p$. This difference is calculated by subtracting the minimal substring voltage from the maximal substring voltage: $V_{\text{max}} - V_{\text{min}}$. The measurements are compared to the theoretical upper bound of (19). For a higher gain, the voltage difference decreases, as predicted theoretically.

Figure 7 is a stability test, showing a step response of the system. The current of substring 1 is stepped from 3 A to 2 A, and then from 2 A to 3 A. The load is $R_{\text{mod}} = 11 \,\Omega$, and the gain is $K_p = 2$. Substrings 2 and 3 are biased at constant currents: 3 A and 4 A. The substring voltages and the isolated port voltage exhibit a smooth first order response, with no ringing, and converge to steady state in about 10 ms.

Figure 8 shows the V-P curves of the module, for various gain values. The substrings are biased at 2 A, 3 A, 4 A. With $K_p = 0$, the subMICs are off, and the curve exhibits the typical partial shading shape for the module with 3 bypass diodes, with two local minima. With a gain of $K_p > 2$, the subMICs are balancing the substrings well and the module power curve is smooth, with a single global MPP. This result points to another advantage of the subMIC DPP architecture: the downstream power electronics can employ a simple MPP tracking algorithm, operating over a narrow range of MPP voltages. No special MPPT algorithms are needed to handle shaded scenarios.
This work proposes a simple control scheme for the isolated-port differential power processing (DPP) architecture using submodule integrated converters (subMICs). When the subMICs are implemented using flyback converters operating in discontinuous conduction mode (DCM), it is shown that a very simple control approach can be applied: the converter duty-cycle is driven in proportion to the voltage-difference across the subMIC. There is no need to measure or to control the current explicitly. Each subMIC is controlled autonomously, with no need for central control or subMIC-to-subMIC signal communication. A primary advantage of the proposed controller is its simple, low cost implementation, based on a small number of standard analog components.

The proposed system is shown to be stable, robust and efficient. Stability is proven by the Lyapunov stability theorem, assuming matched conditions. The system is stable regardless of system parameters, with any proportional gain and with any number of substrings. The system quickly converges to steady state, from any initial point.

The overall efficiency is high due to differential power processing. With no shading, no power is processed, and the system demonstrates efficiency greater than 99.5%. For a 72-cell PV module example having three 24-cell substrings, experimentally measured efficiency is greater than 95% for the case when the substrines have solar irradiation of 80%, 60% and 40%, respectively. In addition, at the string level, the system results in a smooth power curve, with no local minima. This enables simple MPPT tracking, with any shading scenario.

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