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A PWM control for MPPT in Photo Voltaics with Continuous Power Monitoring

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Abstract: This paper describes a novel Maxim Power Point Tracking (MPPT) control for Photovoltaic Cells. The proposed control strategy uses a power monitor at the Solar Cell outport. The proposed scheme locates the maximum power by estimating the measured power and corresponding first derivative. The continuous power estimation allows a Pulse Width Modulation circuit to control the switching of a step-up DC-DC converter, setting the solar cell in an average maximum power operation. The manuscript describes the control laws and electronic circuit implementation, exhibiting an improvement in voltage ripple compared to state-of-the-art solutions.

Keywords: Event-based, MPPT, solar cell, DC-DC converter.

1. INTRODUCTION

Energy harvesting systems are an attractive alternative for low-power consumption devices, such as biomedical implants, wireless sensor nodes, and other electronic devices. However, these systems include new challenges on reliability, energy efficiency, cost, etc. One possible solution is to make a hybrid energy harvesting (HEH) system to ensure reliability [Rodriguez Cruz (2022)]. Another way is the implementation of low hardware MPPT algorithms, attending energy efficiency and costs. The MPPT circuits are essential blocks in energy harvesting systems. Their objective is to bring the generating system to the physical point where the energy source current and voltage supplied are at their maximum, see Fig. 1.

The recent advantages in MPPT systems present improvements with the appropriate design of power measurement systems [Romero Camacho (2017)]. With the correct power meter measure, it is possible to implement cumbersome control algorithms bringing the MPPT to the actual maximum point, in contrast with the works considering an approximation with the voltage-based measure.

An MPPT algorithm with high efficiency and reliability requires an specific design. For example, the work in [Aswan University and Abdel-Rahim (2020)] implements a Model-Predictive-Control reaching high efficiency without a power meter using an observer as a power meter.

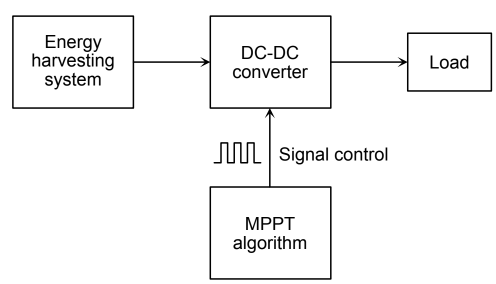

Fig. 1. Energy harvesting system with MPPT algorithm scheme

Therefore, power meters are not easy to implement, as discussed in the article [Abdelmoaty et al. (2017)], the author proposes a new MPPT circuit including a current and voltage sensing module, a power meter, a 3-point sample/compare, and a digital core. The analog power meter consists of a single-quadrant analog multiplier, which highlights the challenges in measuring power in autonomous energy harvesting systems because the main idea of these systems is to be self-polarized with the harvested energy.

The energy harvesting systems require the MPPT algorithm implementation, increasing the challenges. A bottleneck for the MPPT design is metering the power

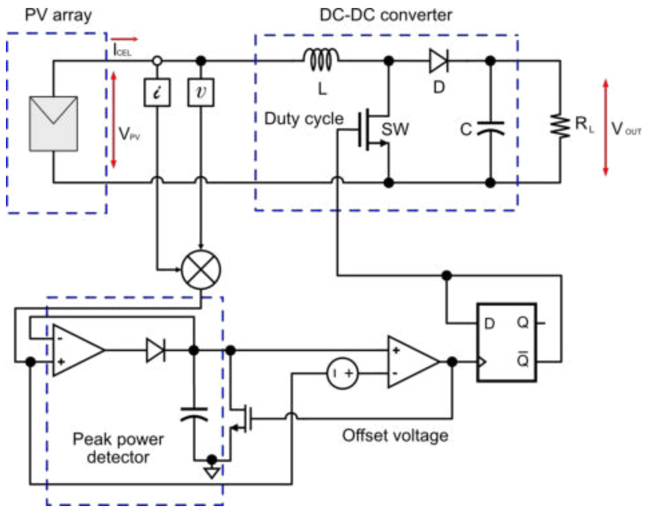

Fig. 2. Event-Based MPPT [Sang-Keun Ji et al. (2010)]

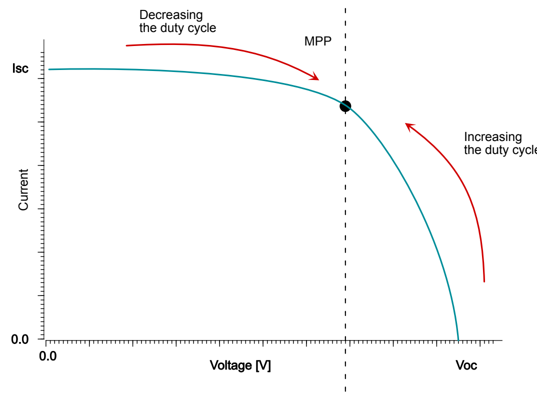

Fig. 3. Behavior of a solar cell depending on the DC-DC duty cycle of the converter

with some existing alternatives. This article proposes an MPPT control implemented with low resources and continuous power monitoring. The paper has the following organization: Section 2 presents a brief review of MPPT algorithms and the algorithm used as a base of this work. Section 3 describes the proposed circuit in detail and validates the solution. Section 4 presents the results obtained with simulations. Finally, Section 5 remarks on the conclusions.

2. MPPT SYSTEM OVERVIEW

This section summarizes the recent MPPT algorithms, highlighting the benefits and limitations from the control system and physical implementation. The purpose is to emphasize the importance of a correct power measurement block in the overall system performance.

2.1 MPPT algorithms

- The "perturb and observe" (P&O) algorithm is a well-known and functional solution. It belongs to the *direct* MPPT group because it has a relatively direct implementation. The algorithm injects small disturbances into the system, which drive the operating point of the systems close to the MPPT. The feature of the algorithm rises similar methods: The incremental conductance method (INC); The self-oscillation (SO) method; the "Stremum seeking" method, etc. These differ from the classical P&O in the variable of interest, the type, or the perturbation magnitude [Femia et al. (2017)].
- The Hill-Climbing algorithm presents a good performance in medium and high-power photovoltaic applications. In this algorithm, a duty cycle of the converter self-perturbates and observes the power changes. The perturbation defines the tracking direction and the efficiency of the algorithm. However, the magnitude of the perturbation increases the tracking speed with the disadvantage of control ripples around the maximum power region, harming the stability of the system Jately et al. (2021).
- Event-Based: The manuscript in [Sang-Keun Ji et al. (2010)] exhibits an algorithm monitoring the solar cell condition. The solution tracks the maximum power point (MPP) of a photovoltaic (PV) array in the analog domain, avoiding microprocessors or DSP controllers. The proposed method involves a simple analog control scheme consisting of a multiplier, peak power detector, comparator with offset voltage, a Flip-Flop D, and a one-switching cycle control sliding at the MPP-Offset point. The solution outstands because it eliminates the analog-to-digital data converter (ADC). The full-custom design relates the solution for application-specific systems with energy autonomy.

  A disadvantage of the Event-Based control is the large ripple for abrupt irradiation changes in the solar cell. The power ripple displaces the Maximum-Power-Point-Track, causing a probably unstable behavior. Moreover, the Event-Based scheme in [Sang-Keun Ji et al. (2010)] suggests a power meter in the analog multiplier domain, resulting in more system requirements and a nonlinear power mapping scheme [Wen et al. (2022)].

  The results for the Event-Based control exhibit fast MPPT dynamics and regulation performance. The benefit is the application-specific design with a possible on-chip implementation and operation with high efficiency (see Fig. 2).
- The improved event-based: the work in the reference [Romero Camacho (2017)] solves the limitation on dynamics for the event-based control, including an anti-divergence status system. The idea maintains the event-based benefits by calculating time derivatives and integral blocks, reducing the ripple, and maintaining the MPPT control.

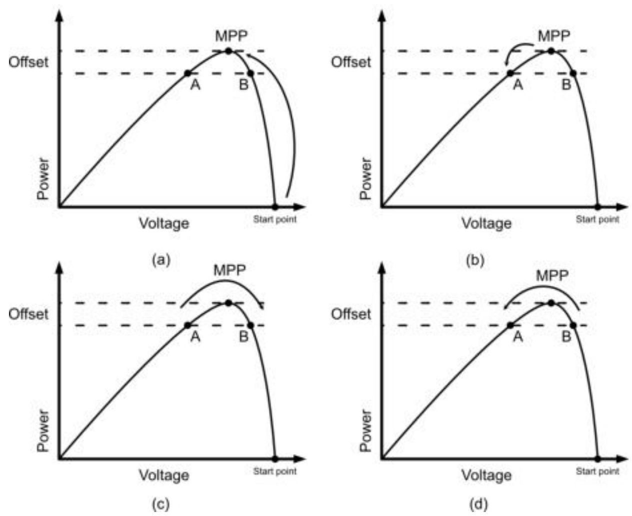

Fig. 4. Event description [Sang-Keun Ji et al. (2010)]

2.2 Maximum Power Point Estimation

Fig. 3 exhibits the solar cell current to voltage feature. The cell acts as a current source (in the short circuit configuration I_{sc}) or as a voltage source (for the open circuit configuration V_{oc}). The maximum power point locates at the zero slope condition in the Power to Voltage curve, located at the *MPP* in Fig. 3.

The voltage-to-current variation depends on the duty cycle for the switching conversion. The initial operation point of the MPPT is at the open circuit condition, where the voltage is maximum $V_{pv} = V_{oc}$, and the current is $I_{cel} = 0$. Figure 2 shows the event-based DC-DC converter switching the short circuit and open circuit condition through the "SW" state. The operation point oscillates between the open-circuit and short-circuits conditions, and Fig. 4 (a) exhibits the states for the event-based approximation.

The operation point moves by the MPPT point, where the event-based solution stores this in the peak power detector. The voltage drops to the A point in the Figure, which is lower than the maximum power point. The switch opens in the state referred to in Fig. 4 (b). The following event in Fig. 4 (c) locates the operation point to the maximum power point. The event-based scheme stores the value that opens the switch until the voltage drops to the offset value. The system oscillates between Fig. 4 (c) and Fig. 4 (d).

In the article [Romero Camacho (2017)], the author proposes, based on the discussed MPPT algorithm, an improved algorithm suitable for abrupt variations in irradiation levels, including a "Zero Power Detector" block Fig. 5.

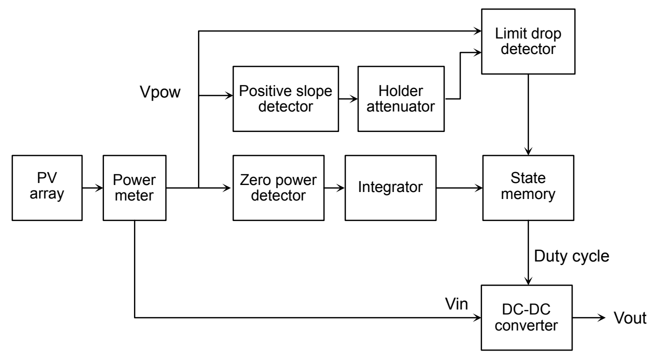

Fig. 5. Event based improved MPPT

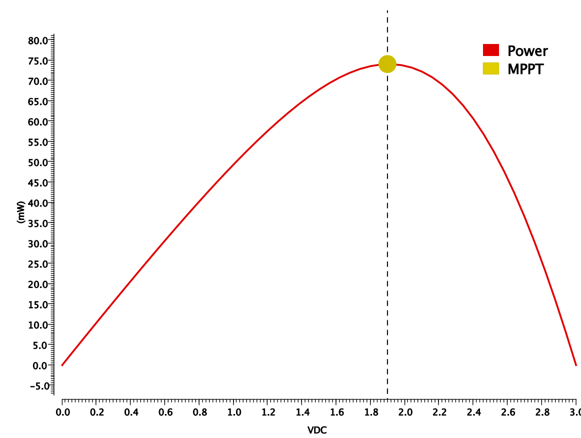

Fig. 6. P-V curve for proposed solar cell

2.3 Design and construction of MPPT circuits

The Maximum-Power-Point-Tracking circuits require the design parameters according to the specifications of the system. This work considers the low-power application with a 3 V range and hundreds of milliwatts because the contemporaneous applications use a bias voltage close to threshold values.

This subsection shows the recreation of the design and simulation of recent MPPT circuits using Cadence Virtuoso, comparing the existing algorithms and highlighting the contributions of this work.

A necessary parameter for these circuits is the solar cell Power-to-Voltage feature. Fig. 6 shows the curve for the energy source with the maximum power point to 1.9 V under a $1\,\mathrm{kW/m^2}$ of irradiation, the limit power for the solar cell is in the order of 75 mW. This work considers the same solar cell model to have a fair comparison.

Figure 7 presents the transient simulation using the algorithm proposed [Romero Camacho (2017)] and the parameters in Table 1.

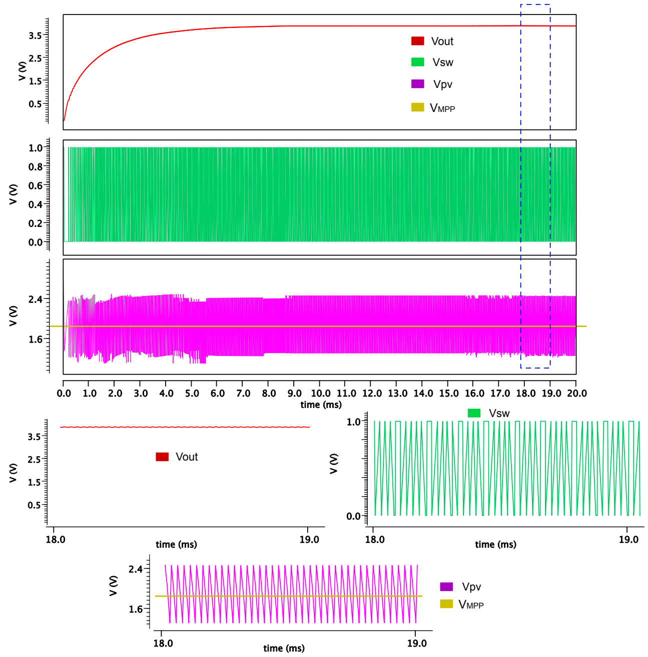

Fig. 7. MPPT recreation results [Romero Camacho (2017)]

Parameter	Symbol	Value
open circuit voltage @25C	V_{oc}	3 V
short circuit current @1kW/m^2	I_{sc}	50 mA
load capacitor	C	4 µF
load inductor	L	1.87 mH
load resistance	R	300 Ω

Table 1. Solar Cell and CD-CD converter parameters

The system has the steady state at the maximum power point (output DC-DC converter):

$$V_{out} \approx 3.6\text{V}$$
$$f_{SW} \approx 27.77\text{kHz}$$
$$V_{pv} \in [2.5\ ,\ 1.0]V$$

where for the proposed cell the $V_{MPP} \approx 1.9$ V (Fig. 6). The duty cycle for this control is close to $D_{sw} \approx 62\%$.

The control system in this work uses the frequency of operation from this improved event-based control system because the switching frequency and maximum power point ranges depend on the previous characterization of solar cells.

3. THE PROPOSED METHOD DESCRIPTION

The design and circuit implementation of the event-based and improved MPPT algorithms highlights the control strategies. A deep insight into the circuits reveals the tracking mechanism is a function of the power-to-voltage slope. The existing MPPT systems approximate power in different forms, but the nonlinear relationships calculating the voltage to the current product in a physical implementation limit the solutions. A power meter with the solar cells' current and voltage characteristics product is mandatory, even with the mentioned limitations. This work uses the concept and proposes a simple but efficient control, calculating the slope definition through a derivative element. Fig. 8 shows the block level description of the system in this work.

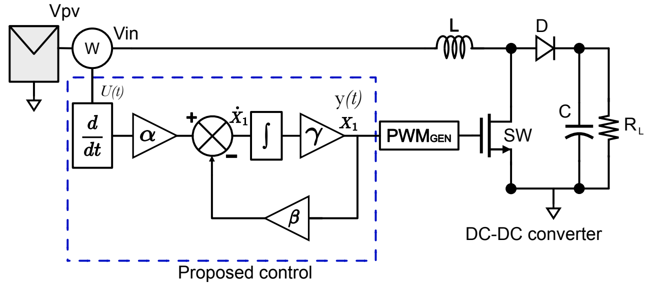

Fig. 8. MPPT proposed

The power estimation uses the variables:

$$\text{SolPower} = V_{pv}I_{pv} = W(t) \qquad (1)$$

Where the signal $U(t)$ is proportional to W(t):

$$U(t) = K * W(t) \qquad (2)$$

The analog derivative uses an α factor, setting the dynamics of the system for a proportional and integral control loop. The α coefficient attenuates the proportional voltage variation for stability. The control system takes $U(y)$ as input, and $y(t)$ is the output from the controller used by the PWMGen to determinate the duty cycle of the switch used by the DC-DC converter. The space state representation of this proposed control is the following:

$$x_1 = y(t) \qquad (3)$$
$$\dot{x}_1 = \dot{y}(t) \qquad (4)$$
$$\dot{x}_1 = -\beta\gamma x_1 + u(t) \qquad (5)$$
$$y = -\alpha\beta\gamma^2 x_1 + \alpha\gamma u(t) \qquad (6)$$

The system contains a PWMgen Block running to frequency and duty cycle of $F = 27.77$kHz and $D = 62\%$ in a steady state. The free-running oscillating frequency is the average value for the open loop function in a continuous mode operation approaching the maximum power point (described in the previous Section). The control loop uses negative feedback, positioning the system dynamics to the Maximum Power Point of the solar cell.

Table 2 displays the parameters in the control loop. Note the solar cell uses the previously estimated models in [Romero Camacho (2017)].

The integral element in the control loop reduces the steady state error, reducing the magnitude between the

Parameter	Symbol	Value
derivative gain	α	100n
integral gain	γ	10n
proportional gain	β	1μ

Table 2. Parameters used in PID proposed control

measured power and the switching nature of the DC-DC converter. From the signal processing point of view, the Differential and Integral relationship establishes a low-pass characteristic for the control variables and a high-pass structure for the disturbances in the continuous time processing.

4. TRANSIENT SIMULATION RESULTS

The scheme presented in this work uses the solar cell and topology similar to the state-of-the-art solutions to exhibit the contributions. The simulation setup uses the Cadence® Virtuoso Electronic Design Automation tool with Spectre as the analog mixed-signal system simulator. The scheme in Fig. 8 uses Verilog for the Power-Meter description, and the Proportional to Integral control loop uses macro models for the derivative and integral control. The PWM block and DC-DC switching circuit use the existing devices in the UMC65nm Process Design kit for the application-specific integrated circuit design.

An initial test compares the proposed control with the solar connected to the DC-DC converter with a PWM signal switching (open loop test), and the second test compares the proposed scheme with the event-based solution. The parameters to evaluate are the V_{pv} to V_{MPP} and the ripple voltage V_{pv}.

First comparative – Direct PWM connection

Fig. 9 shows the results of the first test. Compared with a direct PWM connection (open loop), the proposed control maintains the solar cell output voltage V_{PV} closer to the MPP. An open loop connection doesn't allow the solar cell operates in MPP.

Using the same parameters in a step-up DC-DC converter, the proposed control output voltage V_{out} is 8.7% bigger than the open loop connection ($V_{out} = 3.9$ and $V_{out_{openloop}} = 3.4$). Using this control, the voltage V_{out} exhibits a reduction (4%) in voltage drop, compared with an open loop connection. These results confirm that, with the proposed control, the solar cell operates closer to the MPP, and the output voltage V_{out} is stable.

Second comparative – Event-based algorithm

Fig. 10 shows the results of the second test, compared with the improved event-based algorithm. The proposed control has 8% less ripple voltage ($V_{PV} \in [2.6, 1.45]$ and $V_{PV_{event-based}} \in [2.4, 1.15]$). Also, the proposed control

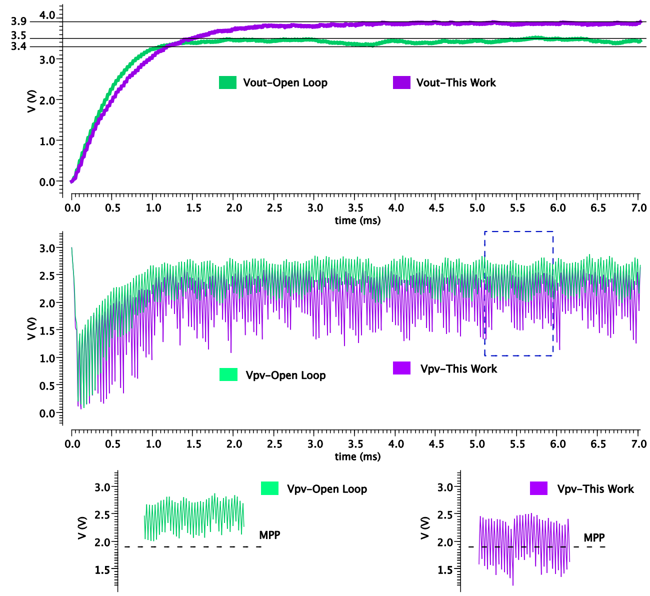

Fig. 9. 1st Comparative – Direct PWM connection vs. this work

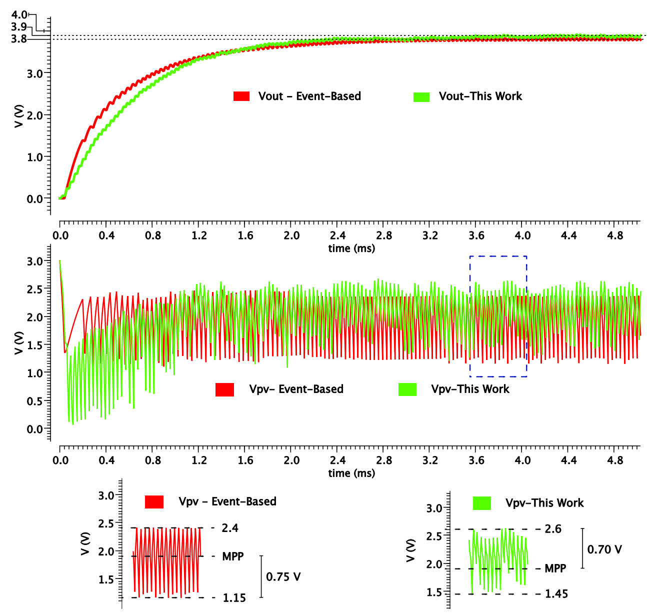

Fig. 10. MPPT Results comparative vs. event-based MPPT algorithm

operates closer to the MPP than the improved event-based; the maximum difference from V_{MPP} is 0.7 V while the event-based is 0.75 V.

In steady state, the improved event-based operating frequency $F_{SW} \approx 28.5$kHz and the duty cycle $D_{SW} \approx 62\%$ while the proposed control produces a $F_{SW_{PWMgen}} \approx 27.77$kHz and a duty cycle $D_{PWMgen} \approx 58\%$, these parameters allow the proposed control to maintain the solar cell operating close to the MPP.

Algorithm	Efficiency	Complexity	Discrete Elements	Power Meter Implementation
P & O Sharma et al. (2019)	85%	Low	N/A	N/A
Hill Climbing Enne et al. (2013)	99.5%	High	No	No
Event-based Sang-Keun Ji et al. (2010)	99.11%	Low	Yes	Yes
Improved event-based Romero Camacho (2017)	91-94.5%	Medium	Yes	Yes
Present Work	95%	Low	No	Yes

Table 3. MPPT algorithms comparative

Table 3 shows the summarized characteristics of the proposed control compared with the algorithms presented in section II. The P&O algorithm is the most common algorithm because it is easy to implement with afordable resources. The algorithm proposed in [Sharma et al. (2019)] improves the P&O algorithm. This improvement, designed in Simulink without a power meter, requires a previous characterization of the changes caused by acperturbation. The complexity of the algorithm is as low as the one proposed in this work, but the proposed control exhibits an increment in efficiency. On the other hand, in [Enne et al. (2013)], the Hill Climbing algorithm reaches a higher efficiency (99.5%), but it requires more hardware compared with the proposed control.

The solution in [Sang-Keun Ji et al. (2010)](Event-Based) reaches a high efficiency (99.11%), but the ripple voltage produced in the solar cell V_{vp} is high, and the behavior under abrupt irradiance changes is not the best. In [Romero Camacho (2017)], the author improves the Event-Based algorithm, getting a better response to irradiance changes with high efficiency. Compared with these two algorithms, the proposed control in this work presents good efficiency with a reduced complexity, employing less hardware without a state memory.

5. CONCLUSION

This work shows the possible implementation of a Maximum Power Point Tracking circuit with a simple proportional integral control loop. The paper discusses the mechanism of maximum power tracking through the estimation of power and the continuous time monitoring of the voltage to power slope. The proposed control law uses the continuous time derivative of the solar cells' power, reducing the error and approaching the DC-DC converter switching feature to the maximum power of the solar cell. The circuit implementation of the proposed control uses the application-specific electronic circuit design, avoiding analog to digital converters. The continuous monitoring of the power feature reduces the voltage ripple in the control.

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