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Maximum power point tracker using an intelligent sliding mode controller of a photovoltaic system

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ABSTRACT

The operating performance of a PV module/array is extremely reliant on the weather (temperature/irradiation) and non-linear. Thus, to ensure that the PV array produces the maximum possible power at any time and regardless of the external conditions, maximum power point tracking (MPPT) techniques are required. The solution suggested in this paper involves taking into account two cascaded controllers as follows; the incremental conductance (INC) controller, which is intended to provide a reference proportional to the PV array's optimal power P_{MPP}, and the sliding mode control (SMC), which is in charge of controlling the GPV voltage. The strategy of the SMC is to design a sliding surface that defines the operating point. The SMC combined with the INC aims to achieve fast MPPT action on PV systems using cascade control. The proposed controller is robust to changing weather conditions. In order to evaluate what is done, the results are compared with the INC+PI controller. When an abrupt change occurs, the SMC has a low transient and arrives to equilibrium sooner than the INC+PI controller. the results are presented by the PSIM software, and demonstrate the SMC controller's performance while confirming that the new approach has increased both production and energy efficiency.

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1. INTRODUCTION

Solar photovoltaic energy is an important source, it is renewable, inexhaustible and non-polluting, which makes it increasingly used as a source of energy in various applications. For a good exploitation of all photovoltaic modules, the modules will be connected to a mechanism that enables the search and tracking of the maximum power point (MPPT). Getting the MPP with the lowest oscillation near the operational point is difficult, considerable work has therefore been devoted to improving the performance of the system, we cite, perturbation and observation (P&O) [1], incremental conductance (INC) [2], fuzzy logic (FL) [3] fractional open circuit voltage (FOCV) [4], and fractional short circuit current (FSCC) [5].

The major problem with all these MPPTs is the degree of dependence of the tracking response on the disturbance size. Additionally, even under stable conditions, the tracking signal oscillates approximately about its reference point [6]. To keep MPP monitoring accurate, a second loop, typically a PI controller, must be used [7]. Especially when the criteria for dynamic features and precision are quite strict, these control laws may not be sufficient or dependable. The MPP at a particular situation is typically the specific operating point for the system model, which needs to be linearized by using a sliding controller (SMC) to adjust the input current of the inductor or capacitor of the boost converter combined with the GPV module, the working approach described in the literature [8] addresses this issue and ensures the overall stability of the system at all operating points.

The measurement of the PV module's output current and voltage, as well as a comparison of the values of ($\frac{dI_{PV}}{dV_{PV}}$) and ($-\frac{I_{PV}}{V_{PV}}$) are necessary for the incremental conductance operating theory. It then decides whether to reduce or increase the control value appropriately. There are two fundamental tenets for the SMC controller. First, a specific sliding surface is designed as the operating point. Realizing a control law that will bring the operating point to a specific surface in a finite amount of time [9] is the second step. Using the reference current acquired through incremental conductance as the basis for the input capacitor current regulation, as demonstrated in [10], the aforementioned conditions are met. Existence, attainability, and similar control conditions are three crucial variables for SMC stability [11].

Utilizing cascade control, SMC in conjunction with INC seeks to achieve quick MPPT action on PV systems. To maintain general stability over the whole working range, this method stays away from the usage of linearized models. This results in a more compact design and lowers the system's cost and complexity. Theoretical investigations have provided considerable evidence for sliding mode control. The fundamental goal is to exact the appropriate reaction by forcing the dynamics of the system under control. Such a control has the benefit of being robust to system disturbances and uncertainties, which is what makes it so intriguing [12].

A pulse width modulation (PWM) is applied to the switch in order to get the PV system to operate in the required MPP manner. Maximizing the energy produced by the GPV and enhancing system stability has been the main focus of this work based on the integral SMC with INC in the PV system [13] shows in Figure 1. We start the presentation of this work with a brief description of the studied system, we will go on to describe each element, starting with the PV panel and its features, the boost converter for the interface between the PV panels and loads and it increases some applications' input voltage, which must be higher than the voltage obtained from the PV, then we move to the studied method which is the first order sliding mode passing through the conductance increment algorithm. We discuss the results, show how the proposed integral sliding mode controllers when used in conjunction with the INC are more effective than the PI method, and draw a conclusion.

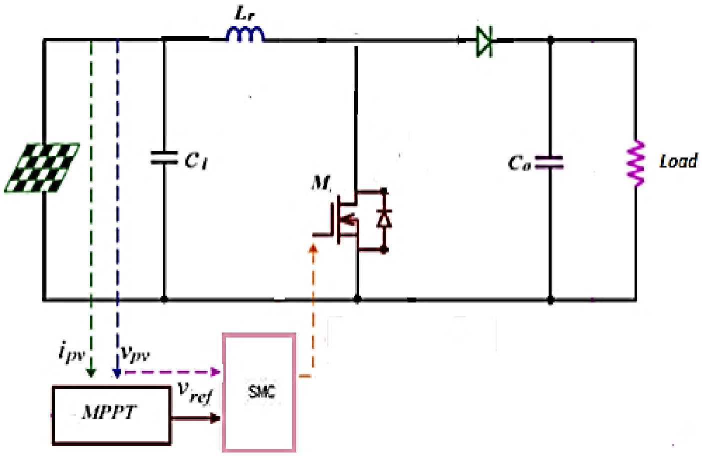

Figure 1. Circuital scheme of the sliding mode controller (SMC) loop

2. PHOTOVOLTAIC SYSTEM

2.1. Photovoltaic generator

In essence, a PV power conversion system is made up of four components Figure 2. A photovoltaic system, a DC/DC converter, for impedance adaptation, an integrated control algorithm and the load (battery/inverter) [14], [15]. A PV cell is a P-N junction that converts light energy directly into electric current due to the photovoltaic effect. To build a PV panel and deliver the required maximum electrical output, solar cells can be connected in series or parallel depending on the photo-energy conversion efficiency of the semiconductor making up the cell [16]. A mathematical model has been developed to simulate a photovoltaic panel, which depends on external parameters such as operating temperature or panel orientation. The Figure 3 shows the equivalent circuit of a single solar cell, where I_{PV} and V_{PV}, respectively, stand for the PV panel's current and voltage [17].

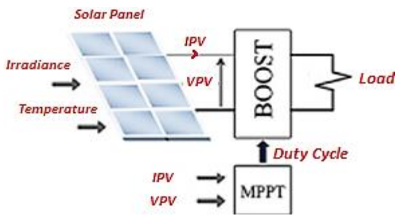

Figure 2. Description of the system studied

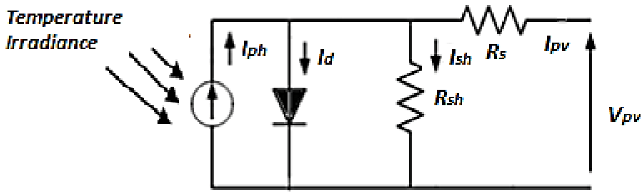

Figure 3. Electrical system of a solar cell that is equivalent

Equation represents the voltage-current characteristic of the solar cell (1).

$$I_{PV} = I_{Ph} - I_0\left[\exp\left(\frac{V+R_S.I_{PV}}{V_{th}.a}\right)-1\right]-\frac{V+R_S.I_{PV}}{R_{Sh}} \quad (1)$$

Where ais the ideality factor of the diode, I_{Ph} is the photocurrent, I_0 is the saturation current, R_S is the cell's series resistance, R_{Sh} is its parallel resistance, and V_{th} is the thermal voltage in (2) and (3) provide the formulas for the photocurrent and the saturation current:

$$I_{Ph} = (I_{sc} + K_i dT)\frac{G}{G_n} \quad (2)$$

$$I_0 = \frac{I_{sc}+K_i dT}{exp\left[\frac{V_{oc}+K_v dT}{V_{th}.a}\right]-1} \quad (3)$$

Where T is the temperature, Voc is the open-circuit voltage, G is the solar irradiance, Kv is the open-circuit temperature coefficient, and Gn is the nominal solar irradiance. Isc is the short-circuit current. Ki is the short-circuit temperature coefficient. Equation represents the voltage-current characteristic of the PV array (4).

$$I_{PV} = N_{PP}I_{Ph} - N_{PP}I_0\left[exp\left(\frac{V+(R_S\frac{N_{SS}}{N_{PP}})I_{PV}}{V_{th}.a}\right)-1\right]-\frac{V+(R_S\frac{N_{SS}}{N_{PP}})I_{PV}}{R_{Sh}\frac{N_{SS}}{N_{PP}}} \quad (4)$$

N_{PP} and N_{ss}, respectively, stand for the parallel and series numbers of modules.

The Polycrystalline photovoltaic module VICTRON 270 W, issued to analyze and validate the MPPT algorithm, Table 1 displays the electrical parameters of the module. The I-V characteristic has a single, non-linear optimal point where the power is at its highest in MPP. I_{MPP} and V_{MPP} are the matching ideal voltage and current, Figure 4.

Table 1. Electrical characteristics of PV module

Parameters	Value
Nominal power [Wp] P_{MPP}	270
V_{MPP} (voltage at nominal power) [V]	31.7
I_{MPP} (current at nominal power) [A]	8.52
Voc (open-circuit voltage) [V]	38.04
Isc (short-circuit current [A]	9.21

STC (1000 W/m^2, AM 1.5 cell temperature 25°C)

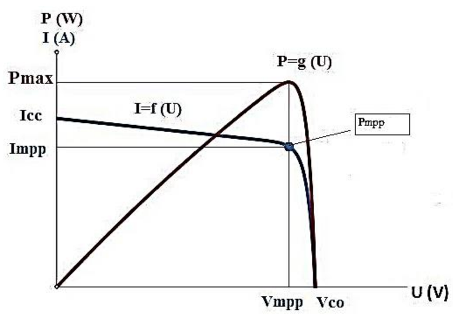

Figure 4. I-V and P-V characteristics of a photovoltaic module

2.2. DC/DC converter

The interface that enables adaptation between the PV panel and the load to extract the most power from the PV is the DC/DC converter, which is used to regulate and stabilize the signals supplied into it Figure 5 [18]. A switch, primarily a transistor, is affected by the tracking system, which delivers its control current in accordance with a duty cycle chosen by an algorithm to ensure maximum power output. The transistor switch is conducting for time t∈[0,T] when switching period T and duty cycle are both set to. These equations can be used to simulate the converter.

$$\frac{di(t)_L}{dt} = \frac{V_1}{L} \tag{5}$$

$$\frac{di(t)_2}{dt} = \frac{V_2}{R_L * C_S} \tag{6}$$

When t ∈] αT, T], or the second portion of the cycle, the transistor is blocked. The converter can be modeled by the following:

$$\frac{di(t)_L}{dt} = \frac{V_1 - V_2}{L} \tag{7}$$

$$\frac{dV(t)_2}{dt} = \frac{i_L}{C_S} - \frac{V_2}{R_L * C_S} \tag{8}$$

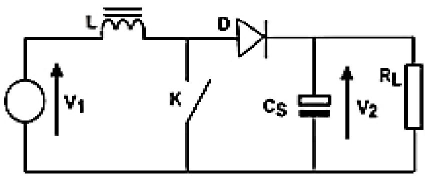

Figure 5. Diagram of the boost converter

3. ALGORITHM AND METHOD

3.1. Incremental of conductance (INC) algorithm

The INC has been suggested as a way to get around some of the P&O method's restrictions, namely steady state error and convergence speed [19]. It combines a number of significant advantages, including the ability to respond quickly to sudden changes in solar irradiation, and is frequently recognized as the best technique based on the perturbation and observation principle. The photovoltaic module's conductance and its elemental variation can be described as follows:

$$G = \frac{I_{PV}}{V_{PV}} \tag{9}$$

$$dG = \frac{dI_{PV}}{dV_{PV}} \tag{10}$$

The incremental conductance is contrasted with the instantaneous conductance to follow the MPP. Once the MPP is attained, the PV array operation is sustained at that point and the disturbance is stopped unless a change in dI_{PV} is noted. In this case, the algorithm decrement or increment the V_{PV} voltage of the PV array to track a new MPP [20], [21]. The size of the increment determines the rate at which the MPP is tracked. The following are the key equation used in this technique [22]. The conventional INC algorithm requires the measurement of the PV array V_{PV} voltage and I_{PV} current to determine the correct direction of the disturbance, as shown in the algorithm in Figure 6.

$$\frac{dI_{PV}}{dV_{PV}} = -\frac{I_{PV}}{V_{PV}} at\ MPP \tag{11}$$

$$\frac{dI_{PV}}{dV_{PV}} > -\frac{I_{PV}}{V_{PV}} at\ left\ of\ MPP \tag{12}$$

$$\frac{dI_{PV}}{dV_{PV}} < -\frac{I_{PV}}{V_{PV}} a\ tright\ of\ MPP \tag{13}$$

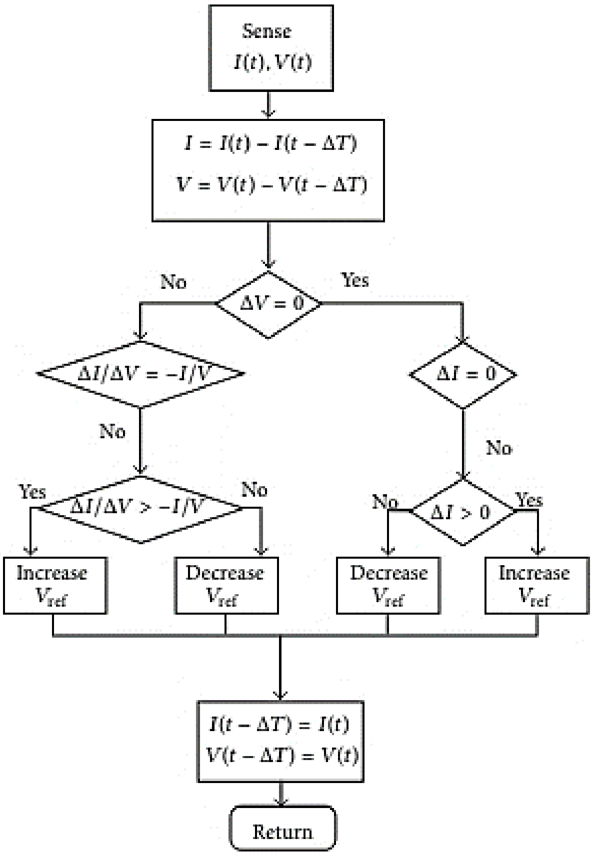

Figure 6. Flowchart of the INC algorithm

3.2. Design of a sliding mode controller (SMC)

Sliding mode control has undergone significant development in recent years. This is primarily caused by the attribute of quick and finite-time error convergence as well as the high robustness against modeling errors and particular types of external disturbances [23], [24]. With the aim of having the dynamics of the system reach a specific sliding surface and remain there until equilibrium is attained, a sliding surface or hypersurface is created using the switching functions of the state variables, on which this nonlinear command is based on Figure 7. As long as the criteria of the sliding control are met, this dynamic then becomes insensitive to disturbances, whether external or parametric [25].

The solution put forth in this work entails taking into account two controllers working in cascade as the INC controller, which is intended to provide a reference proportional to the photovoltaic generator's P_{MPP}, and the SMC controller, which is in charge of the GPV's regulation. Second order voltage mode (PID) SMC controller is the controller under investigation [26]. In order to lower the steady-state error of the real system managed by the SM, it incorporates an additional integral voltage error component into the control algorithm. The usage of this technology in power converters and other applications known as SM integral control have generated a lot of recent interest [27], [28]. The x for the control variable of the PID SMC can be stated in the following form.

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} V_{ref} - \beta V_{PV} \\ \frac{d}{dx}(V_{ref} - \beta V_{PV}) \\ \int V_{ref} - \beta V_{PV} \end{bmatrix} \quad (14)$$

Where x1, x2, and x3 stand for the voltage error, the voltage error's dynamics (or rate of change), and the voltage error's integral, respectively. The continuous conduction mode (CCM) converter's behavioral models are then swapped out in (14), and the temporal differentiation of that equation results in the state-space descriptions needed for the construction of the GPV and boost converter controller.

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ -\frac{1}{C_{in}.L} & -\frac{1}{R_{eq}.C_{in}} & 0\\ 1 & 0 & 0\end{bmatrix}.\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}0\\ -\frac{\beta.V_b}{C_{in}.L}\\ 0\end{bmatrix}.U + \begin{bmatrix}0\\ V_{ref}\\ C_{in}.L\end{bmatrix} \quad (15)$$

The standard form of the space-of-state equation gives:

$$\dot{x} = Ax + BV + D \quad (16)$$

The next stage after acquiring the state space descriptions is the controller design. It is advised to use a generic SM control law with a switching function for systems like this, such as:

$$u = \begin{cases}1 \; when \; S > 0\\ 0 \; when \; S < 0\end{cases} \quad (17)$$

where S, the trajectory of the instantaneous state, is represented by (18).

$$S = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 = J^T x \quad (18)$$

With; $J^T = [\alpha_1 \alpha_2 \alpha_3]$; $\alpha_1, \alpha_2, \alpha_3$, representing the sliding coefficients.

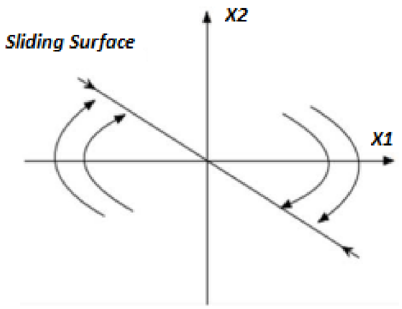

Figure 7. Illustration of the convergence of the sliding surface

4. RESULTS AND DISCUSSION

This section's goal is to present the findings from the sliding mode control (SMC) technique and contrast them with the INC connected to the traditional PI controller. The PSIM program displays the outcomes as indicated in Figure 8. It involves changing the irradiation and observing its effects while keeping the load and the temperature T.

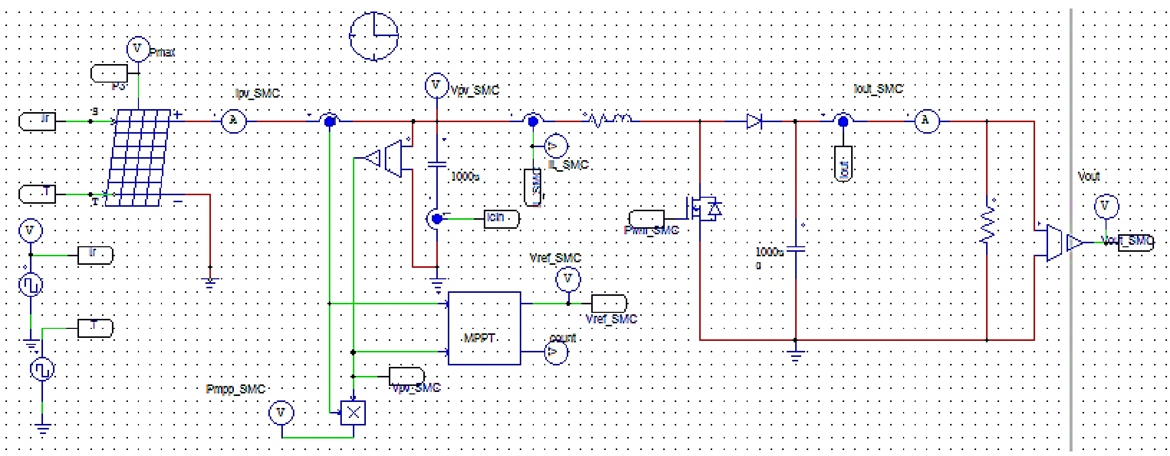

Figure 8. Circuital scheme for simulation of SMC loop in PSIM

Figure 9 displays the outcomes for duration of one second. In each figure, the PV power for the INC +SMC and INC +PI techniques is evaluated. To show the response time, a zoom is applied at the start of the profile. Changing the irradiance (from 1000 W/m^2 to 650 W/m^2) while holding the load constant at 100 and the temperature at 25°C is used to evaluate the SMC control. Figure 9 displays the corresponding simulations in comparison to the outcomes of the PI controller.

We note that the produced characteristic curves are proportional to changes in irradiation, each change in irradiation leads to a decrease or increase in the energy value as shown in Figure 9. Figure 9(a) represents the variation of irradiation between 1000 W/m^2 to 650 W/m^2. The low tracking speed of the INC+PI method is confirmed by the results in case of change of irradiation in Figure 9(b). Figure 9(c) demonstrates that the results obtained after varying irradiance approximately confirm the INC+PI method's slow tracking speed (0.34 ms). On the other hand, using the proposed INC +SMC control, we notice that high tracking performance is demonstrated about (0.15 ms). Moreover, when there is no overshoot of the irradiance change, showing an instantaneous effect on the PV voltage, the fluctuation around the V_{MPP} is smaller (green curve). In steady state, the powers always remain maximized, unless there is some other nuance. The optimal current is impacted by the abrupt shift in irradiance, as seen in Figure 9(d).

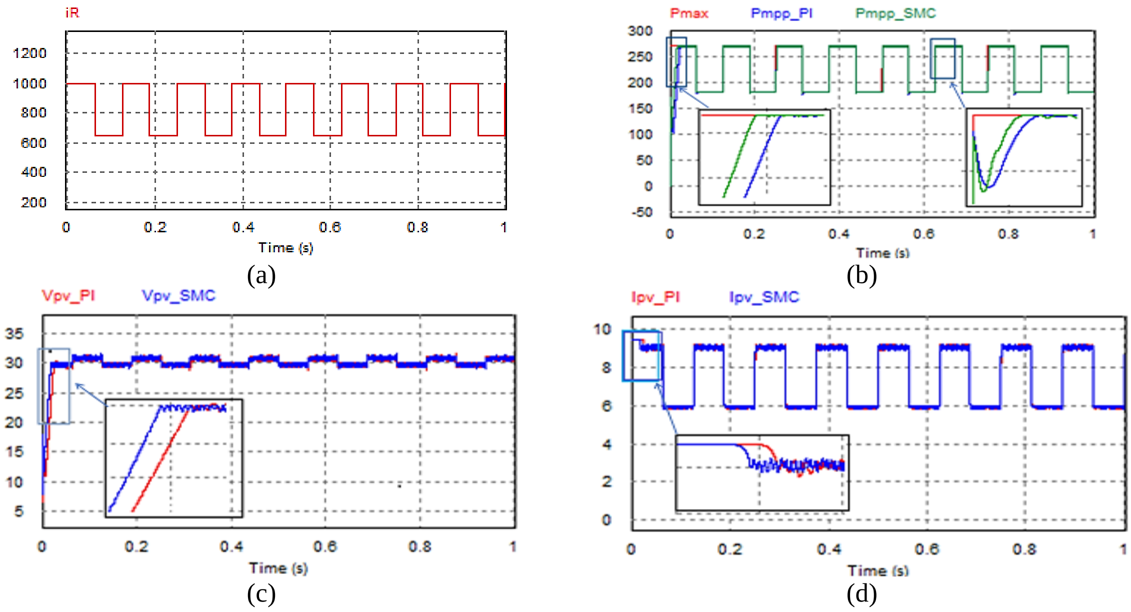

Figure 9. Comparison between SMC and PI controller for irradiance variation (650 W/m^2 to 1000 W/m^2), (a) irradiance variation from 1000 W/m^2 to 650 W/m^2, (b) GPV power characteristics, (c) GPV voltage, and (d) GPV current

This outcome shows how the PV system's MPP was calculated using the SMC under various irradiation situations. Its durability and stability in comparison to the conventional controller have been demonstrated through design and simulation. The results demonstrate that the SMC+INC can rapidly and effectively follow the reference values using the boost converter. Around the steady-state MPP, there is no oscillation. The control law in use is simple to apply. On the basis of different types of DC/DC converters, other PV system applications can use the same analysis and design of the SMC.

5. CONCLUSION

The transmission of electrical energy from a GPV to a PV system is maximized by the control strategy presented in this research. The suggested control technique, which attempts to improve system performance in all-weather circumstances, is based on the SMC theory and MPPT control. The simulation's findings support the claim that this approach is successful and outperforms the conventional PI controller in terms of performance. The PWM-based SMC and the MPPT-based PI controller simulation results are compared, and the comparison reveals that the SMC is able to attain the ideal operating point with high performance during a fast shift in solar radiation. The system's response to variations in the irradiance's demonstrates how the method might reduce trajectory errors when tracking targets.

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