Sliding mode control schemes in DC-DC converter for photovoltaic maximum power point tracking

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Abstract (< or = 250 mots)

As a renewable energy source, photovoltaic (PV) systems can help reduce environmental impacts from fossil fuel usage. However, PV conversion efficiencies remain relatively low. Power electronics controllers play a vital role in optimizing PV system efficiency and performance. This study investigates using sliding mode control techniques to improve tracking of the maximum power point (MPP) in PV systems. Sliding mode offers robustness and stability benefits for power converters. Both single-loop and two-loop control architectures are examined. The single-loop scheme extracts MPP rapidly without needing a defined reference, while the two-loop includes both MPP tracking and search control loops. For the two-loop search, an optimized version of Cuckoo algorithm is proposed. The PV system models and controllers are simulated to compare performance. The single-loop controller reacts quicker under uniform conditions but can get trapped at local maxima. The two-loop controller converges on global MPP better under partial shading. Further opportunities exist to address practical implementation challenges of the sliding mode PV controllers.

Key words

sliding mode control; MPPT; photovoltaics; DC-DC converter; Cuckoo algorithm

1- Introduction

The conventional energy sources have limited reserves with climate concerns. Thus, the world is moving towards renewable energy sources (RESs). The RESs provide clean energy to address the concerns raised by conventional energy sources [1] . Increasing the share of renewable energy sources like photovoltaics (PV) can help reduce environmental impacts from conventional fossil fuels. In island nations like Madagascar, PV offers potential to electrify rural communities lacking grid connections. However, barriers remain due to the low conversion efficiency and high costs of PV systems. Advances in PV materials and manufacturing continue to reduce costs. Further innovations in power electronics and controls are needed to maximize efficiency and performance.

This study focuses on boosting PV output via optimized maximum power point tracking (MPPT). MPPT dynamically tunes the system operating point to extract maximal power as conditions like solar irradiation variation. The power converters regulating PV output require effective control strategies to achieve MPPT. In literature, several researchers are working to build successful models for MPPT techniques incorporated in solar PV systems for the supply of grid or isolated DC loads . Some of these works are presented in [2] [3] [4] [5] [6] [7]. Here, sliding mode control techniques are investigated for their stability and robustness advantages in power electronics applications. Both single-loop and two-loop control architectures are examined. The single-loop MPPT control scheme was introduced in the work of [8] [9] . It has the particularity of having a limited number of voltage sensors. The two-loop scheme includes MPPT control as well as the MPP search algorithm. The interaction between the two loops must be considered in the design. The control of the MPP must be fast compared to the search. This scheme was proposed in the work of [5]. A key question is whether the simpler single-loop system can provide adequate MPPT, or if a more complex two-loop controller with explicit searching is necessary. For the two-loop MPPT search, this work introduce a new version of a deterministic Cuckoo optimization algorithm. Comparative simulations assess the performance tradeoffs between the two control approaches.

2- Methodology

2.1. Description of the system and control methods

2.1.1. Sliding mode control (SMC) for single-loop MPPT

The current-voltage behavior of a PV cell can be represented by the single diode model, accounting for photon generated current, diode forward bias current, and parasitic resistances. Environmental factors like irradiance and temperature strongly influence the IV curve and power output.

Consider a boost converter connected to a PV panel with a resistive load as shown in Fig. 3.

The system can be described in two sets of equation depending on the state of transistor .

In discontinuous mode, the differential equation can be written as (1)

$$\begin{cases} \dot{i_{L_1}} = \frac{V_{PV}(i_L)}{L} - \frac{V_0}{L} \\ \dot{V_{o1}} = \frac{i_L}{C} - \frac{V_o}{CR_L} \end{cases} \quad (1)$$

In conduction mode, the differential equation can be written as (2)

$$\begin{cases} \dot{i_{L_2}} = \frac{V_{PV}(i_L)}{L} \\ \dot{V_{o2}} = -\frac{V_o}{CR_L} \end{cases} \quad (2)$$

Using the state- space averaging method, equations (1) and (2) can be combined into a set of equations of state to represent the dynamics of the system. Considering that the transistor is controlled by pulse width modulation (PWM), the duty cycle of the switching control is defined by δ, the equation of state to represent the dynamics of the system is defined by (3).

$$\begin{cases} \dot{i_L} = \frac{V_{PV}(i_L)}{L} - \frac{V_0}{L} + \frac{V_0}{L}\delta \\ \dot{V_o} = \frac{i_L}{C} - \frac{V_o}{CR_L} - \frac{i_L}{C}\delta \end{cases} \quad (3)$$

where C is the capacitance, L is the inductance, R_L is the resistive load, δ ε [1 0] is the duty cycle, which is also the command input. V_o is the output voltage and i_L is the inductor current. Considering Fig. 2, the sliding surface is defined by $\frac{dP_{PV}}{dI_{pV}} = 0$. This ensures that the state of the system reaches the surface and will produce maximum power output.

$$\frac{dP_{PV}}{dI_{PV}} = I_{PV}\left(2R_L + I_{PV}\frac{dR_L}{dI_{PV}}\right) = 0 \quad (4)$$

where $R_L = \frac{V_{PV}}{I_{PV}}$ is the load and et $I_{PV} = i_L$.

If $I_{PV} \neq 0$, then the sliding surface S is expressed by:

$$S \triangleq 2R_L + i_L\frac{dR_L}{dI_L} \quad (5)$$

The duty cycle can be written as:

$$\delta' = \begin{cases} \delta + \Delta\delta \ \ pour\ S > 0 \\ \delta - \Delta\delta \ \ pour\ S < 0 \end{cases} \quad (6)$$

The equivalent control function is determined from (7)

$$\dot{S} = \left[\frac{dS}{dX}\right]^T \dot{X} = \left[\frac{dS}{dX}\right]^T (\,f(X) + g(X)\,\delta_{eq}) = 0 \quad (7)$$

Taking into account the Eq. 4, the equivalent control can be written by (8)

$$\delta_{eq} = -\frac{\left[\frac{dS}{dX}\right]^T f(X)}{\left[\frac{dS}{dX}\right]^T g(X)} = 1 - \frac{V_{PV}(I_L)}{V_0} \quad (8)$$

where $0 \leq \delta_{eq} \leq 1$

The actual control function can be expressed as a function of Eq. 8: δ_{eq}

$$\delta_r = \begin{cases} 1 & \delta_{eq} + NS \geq 1 \\ \delta_{eq} + NS & 0 < \delta_{eq} + NS < 1 \\ 0 & \delta_{eq} + NS \leq 0 \end{cases} \quad (9)$$

N is a constant, the control is between δ_{eq} and NS, δ_{eq} is required to reach the surface $\dot{S} = 0$ and NS tracks the MPP.

Conditions of accessibility to the sliding surface S

The Eq. 7 can be rewritten

$$\dot{S} = (\,3\frac{dR_L}{dI_L} + I_L\frac{d^2R_L}{dI_L{}^2})(-\frac{V_0}{L}(1-\delta) + \frac{V_{PV}(I_L)}{L}) \quad (10)$$

Accessibility to the sliding surface is achieved for $S\dot{S} < 0$ under the following control conditions

$$\boldsymbol{O} < \delta_r < \mathbf{1},\ \dot{X} = \frac{V_0}{L}\ NS \quad (11)$$

As $\dot{S} < 0$, then $S\dot{S} < 0$. Access to the sliding surface is obtained for $O < \delta_r < 1$,

$$\delta_r = \mathbf{1},\ \dot{X} = \frac{V_{PV}(I_L)}{L} > 0 \quad (12)$$

As $\dot{S} < 0$, let consider two cases :

(1) if $\delta_{eq} = 1$, then $V_{PV}(I_{L)} = 0$. Considering Fig. 6, the system is therefore to the left of the MPP where S<0 . Then $\delta_{eq} + NS$ will be less than 1 , which is contradictory for $\boldsymbol{\delta_r = 1}$

(2) if $\delta_{eq} < 1$ and $\delta_{eq} + NS \geq 1$, then S>0 , $S\dot{S} < 0$

$$\boldsymbol{\delta_r = 0},\ \dot{X} = -\frac{V_0}{L} + \frac{V_{PV}(I_{L)}}{L} < 0 \tag{13}$$

In this case, the output voltageV_0 is greater than à V_{PV}, this implies $\dot{S} < 0$.

Let consider two cases :

(1) if $\delta_{eq} = 0$, this implies $V_{PV}(I_{L)} = V_0$. In this case the panel is considered to be connected directly to the load and S>0 . This case is contradictory to have $\boldsymbol{\delta_r = 0}$

(2) if $\delta_{eq} > 0$ and $\delta_{eq} + NS \leq 0$, this implies S<0 then $S\dot{S} < 0$

In summary, the existence of the MPP is guaranteed by using the control δ_r of Eq. 9. To avoid controller saturation for $\delta_r = 0$ and $\delta_r = 1$, the value of the constant N must not be large, such that $N \leq \frac{1}{|S|_{max}}$. $|S|_{max}$ is the absolute value of the maximum value of S. It is reached when

$$\delta_{eq} = 0\ .\ |S|_{max} \approx R_L \tag{14}$$

Thus to avoid saturations N must be chosen such that $\boldsymbol{N \leq \frac{1}{R_L}}$

2.1.2. Sliding mode control with two-loop for MPPT

The sliding-mode control for a two-loop scheme can be expressed as:

$$\delta = \delta_{eq} + \delta_r \tag{15}$$

$$\delta_{eq} = 1 - \frac{V_{PV}}{V_0} \tag{16}$$

$$\delta_r = -N\ sgn\ (S) \tag{17}$$

where N>0

$$S = I_L - I_{MPP} \tag{18}$$

where I_{MPP} is the MPP current

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The conditions of accessibility to the sliding surface is obtained for $S\dot{S} < 0$.

Considering the function $V = \frac{1}{2}S^2$.

With Eq. 7, we have :

$$\dot{V} = S\dot{S} = (-(1-\delta)V_0 + V_P + K)\frac{1}{L}S \tag{19}$$

where K is constant

Consider the Eq. (15), (16) et (17), we have

$$\dot{V} = \frac{1}{L}(-N|S|V_0 + KS) \tag{20}$$

$$\dot{V} < \frac{1}{L}(-N|S|V_0 + |K||S|) \tag{21}$$

$$\dot{V} < \frac{1}{L}|S|(-NV_0 + |K|) \tag{22}$$

Accessibility to the sliding surface is ensured for:

$$\boldsymbol{N} > \frac{|\boldsymbol{K}|}{\boldsymbol{V_0}} \tag{23}$$

This condition is not met for t=0 because V_0 can be equal to 0. But it will be assured once the boost converter works because $V_0 > V_{PV}$.

2.1.3. Determination of I_{MPP} based on the Cuckoo search algorithm

Cuckoo Search (CS) was first proposed by [10] . The algorithm emulates the strategy of aggressive breeding of cuckoo birds. Compared to other techniques, CS has proven to be more robust, has better convergence and is more effective. [11]. In the context of the sliding mode control MPPT and giving the parameter of accessing the sliding surface, the structure of the CS algorithm is shown in Fig. 5 . The structure take example of the Hill Climbing method, but does not include Levy's flight step [12].

The principle is as follows:

1- The current from the PV panel is measured at three times $I_i = k_i I_{sc}$
2- Sort in ascending order the powers at the currents taken,

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- $P(I_a) \geq P(I_b) \geq P(I_c)$

3- if I_a is on the mostright or leftmost, modify the currents as follows:

- $$\begin{cases} I_{a,new} = I_a \\ I_{b,new} = I_b + \varepsilon(I_a - I_b) \\ I_{c,new} = I_a + \varepsilon(I_a - I_{b,new}) \end{cases} \quad (24)$$

- $\varepsilon > 0$ is a constant

Else

- $$\begin{cases} I_{a,new} = I_a \\ I_{b,new} = I_b + \varepsilon(I_a - I_b) \\ I_{c,new} = I_c + \varepsilon(I_a - I_c) \end{cases} \quad (25)$$

4- The values of I_a, I_b, I_c must be between

- $[0.01 I_{sc}, 0.99 I_{sc}]$
- if $max\{|I_a - I_b|, |I_a - I_c|\} < 0.01$, stop the search

3- Results

The PV panel model, the boost converter model with the SMC control with one and two loops for the MPPT is simulated under Orcad PSPICE. Figure 3 shows the circuit corresponding to the simulation. Simulation parameters are presented in Tables I and II.

By performing a transient simulation, Fig. 4 illustrates the result of MPP monitoring with irradiance 500 to 1000 W/m^2 at the same temperature of 300 K and a resisitive load of 150 Ω. The system reaches the steady state of both irradiance levels in the millisecond range for the one-loop scheme.

For the two-loop scheme, in order to track and avoid transient fluctuations, the tracking loop must be faster than the search loop. Therefore, the search loop period is selected as 30ms, which is greater than the tracking loop stabilization time. Figure 5 shows that the two-loop scheme converges to the MPP in 270 ms.

4- Discussion

In this study, a switched system model was introduced to design a maximum power tracking controller for photovoltaic systems based using sliding mode control approach by choosing the area defined by $\frac{dP_{PV}}{dI_{PV}} = 0$. The stability of the control system was also studied. Unlike other approaches in the literature, such as presented in [13], no desired reference was required with the one-loop scheme and it was verified through simulation that this scheme is robust to the operating conditions and parameter changes of photovoltaic cells. On the other hand, the deterministic Cuckoo (SC) search algorithm was used for the determination of the maximum power point in the two-loop scheme. It is shown that the one-loop scheme has faster responses than the two-loop scheme. However, since the single-loop is primarily designed for uniform irradiance conditions, it will work with the local power point. The two-loop scheme converges to the MPP and shows better responses in partially shaded conditions.

There are some practical problems with the implementation of SMC for DC-DC converters. Issues such as the requirement for constant operation of the switching frequency in the SMC and the need to redefine the slip coefficients to meet the practical constraints of the components have been addressed in some previous studies. [14] . Aspects related to the implementation of SMC controllers should be further studied in order to obtain sufficient information to design practical SMC controllers for DC-DC converters. First the choice of system state variables, i.e. voltage, current, their derivatives and/or integrals, is important because it affects the performance of the control as well as the complexity of the implementation. In addition, for PWM-based SM controllers, indirect implementation of the original SM control law can lead to an unexpected complication in signal calculation and is therefore not always implementable. Therefore, the choice of state variables is essential for the successful implementation of the controller.

5- Conclusion

Simple single-loop sliding mode MPPT offers very rapid tracking but risks local maxima under partial shading. The addition of a Cuckoo search algorithm enables the two-loop controller to converge on the global maximum power point at the cost of greater complexity. This tradeoff between tracking speed and search optimality warrants further investigation. Advancing sliding mode controllers could help unlock the full potential of PV systems to provide clean and affordable electricity globally but further studies must be done for practical implementation.

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7- Tables

Table I: Photovoltaic module parameters

Parameter	Value	Parameter	Value
I_L	$5.981*10^{-8}$ (A)	A	1.2
I_{sc}	3.81 (A)	E_g	1.21 (eV)
T_{cell}	298 (K)	R_s	3 Ω
k	$1.38*10^{-23}$ (J/K)	R_p	10MΩ
q	$1.6*10^{-19}$ (C)		

Table II: The calculated values of the MPP

G (W/m^2)	V_{MPP} (V)	I_{MPP} (A)	$P_{MPP}=V_{MPP}*I_{MPP}$ (W)
200	30.7	0.63	19.34
400	30.8	1.26	38.80
600	30.38	1.87	56.81
800	29.7	2.46	73.06
1000	28.84	3.04	86.67

8- Figures

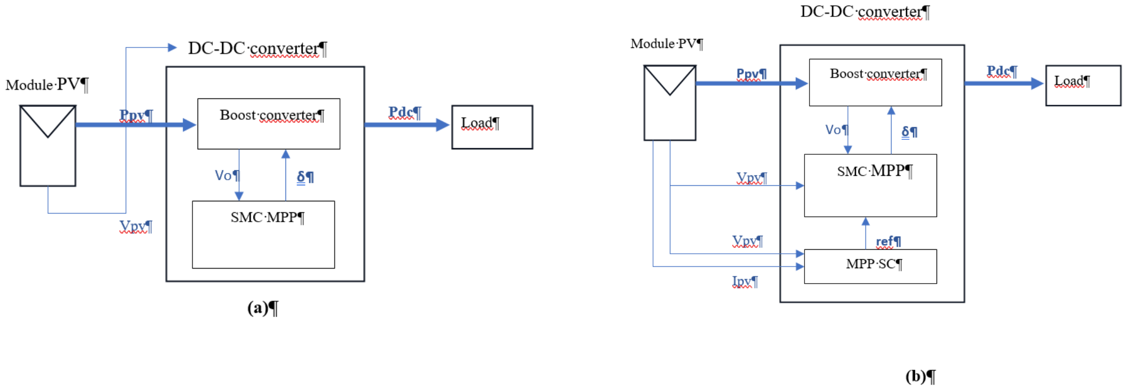


Figure 1: Sliding control (a) one-loop and (b) two-loop

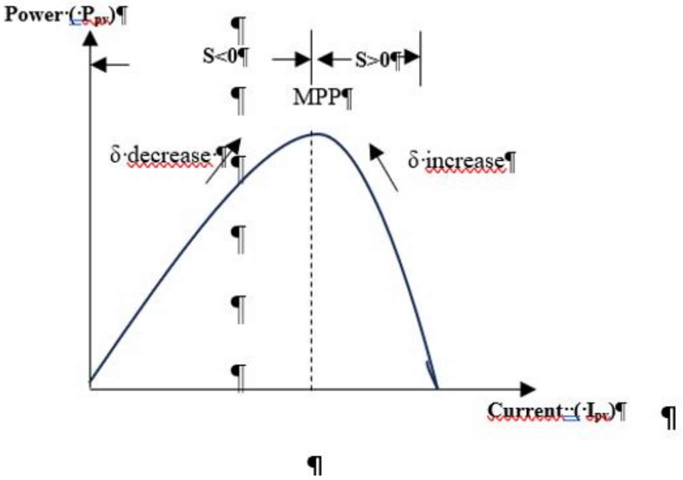
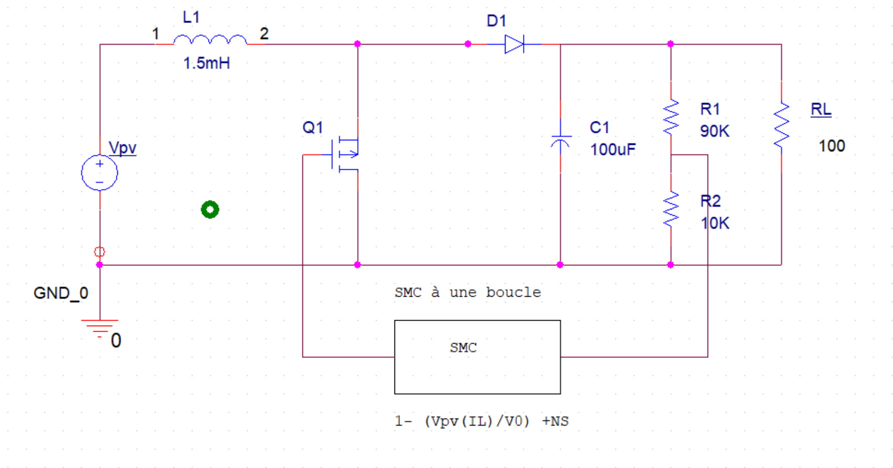
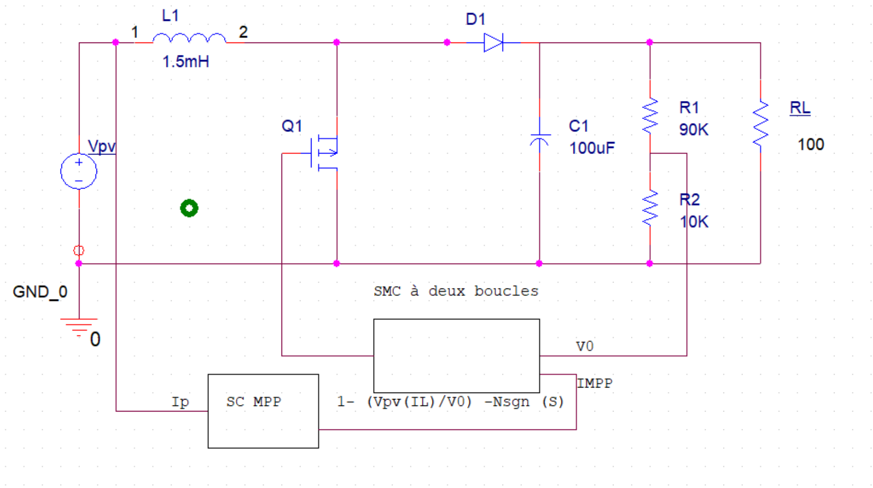


Figure 2: Duty cycle vs region of operation



(a)



(b)

Figure 3: (a) Boost converter with (a) one loop SMC, (b) two loop SMC

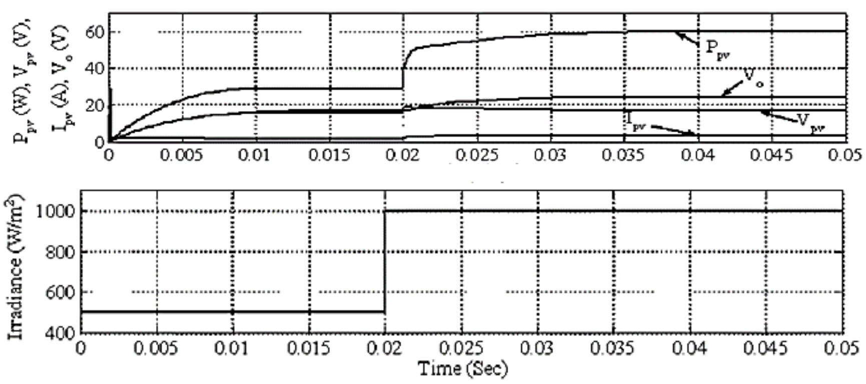


Figure 4: One loop scheme SMC response to G 500 to 1000W/m^2 , T= 300K

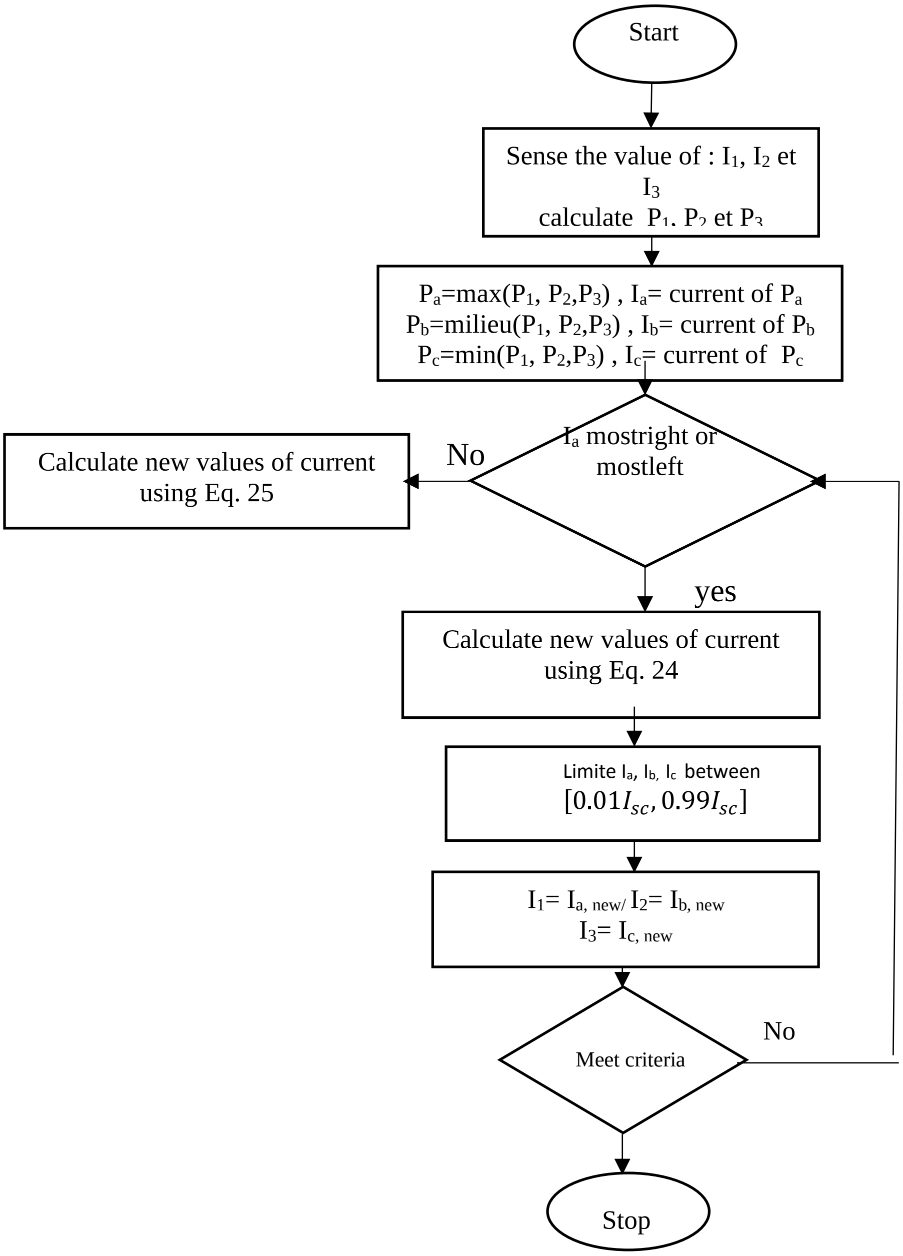


Figure 5: Optimized Cuckoo search (SC) algorithm

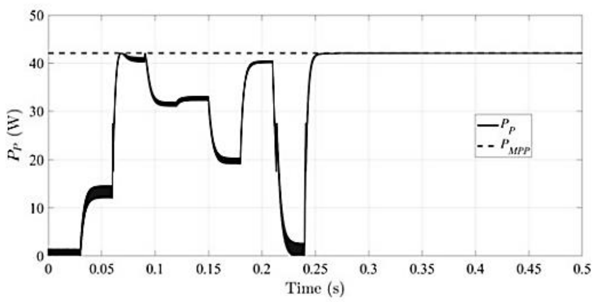


Figure 6: Two loop scheme response to G from 500 to 1000 W/m^2 , T=300K