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A modified perturb and observe maximum power point tracking algorithm for a standalone single phase photovoltaic system using boost converter

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Abstract - *The photovoltaic solar energy becomes more and more one of the most abundant and an alternative source of electric energy. But its efficiency is very low. For this reason, several Maximum Power Point Tracking algorithms are used to track de maximum power. This paper proposes a modified Perturb and Observe (P&O) algorithm using a boost chopper. That algorithm was implemented under Matlab/Simulink/Simpowersystems/Simelectronics platform. Results obtained showed that the proposed algorithm gives better results compared to the conventional P&O algorithm. In fact, the extracted power's ripple factor using the conventional P&O method varies from 3.35 % to 5.30 %. Whereas the extracted power's ripple factor using the 'modified P&O' varies from 1.41 % to 2.86 %.*

Résumé - *L'énergie solaire photovoltaïque devient de plus en plus une des sources d'énergie électrique les plus abondantes et alternatives. Mais son efficacité est très faible. Pour cette raison, plusieurs algorithmes de suivi des points de puissance maximale sont utilisés pour suivre la puissance maximale. Cet article propose un algorithme de Perturb and Observe (P&O) modifié utilisant un hacheur d'appoint. Cet algorithme a été implémenté sous Matlab/Simulink/Simpowersystems/Simelectronics platform. Les résultats obtenus ont montré que l'algorithme proposé donne de meilleurs résultats que l'algorithme P&O classique. En effet, le facteur d'ondulation de la puissance extraite selon la méthode conventionnelle P&O varie de 3.35% à 5.30%. Alors que le facteur d'ondulation de la puissance extraite à l'aide du 'P&O modifié' varie de 1.41% à 2.86 %.*

Keywords: Boost converter - Maximum Power Point Tracking - Perturb and Observe Algorithm.

1. INTRODUCTION

Nowadays, the needs in energy of the human beings are growing tremendously. At the same time, there is a kind of a 'wild' industrialization following the frantic search for profit and abusive consumption of fossil energy [1-4]. This situation has many issues such as exhaustion of fossil fuel, green-house gases responsible for global warming, water, air and soil pollutions etc. [3, 5-7].

To solve this problem, researchers and specialists propose an alternative through renewable energy [8]. Among them, solar energy is one of the most abundant easily available and cost effective resource in the nature [6, 9-11]. But the exploitation of photovoltaic solar energy depends strongly on weather conditions changes and the nonlinearity of the Power - Voltage $(P-V)$ and Current - Voltage $(I-V)$ characteristics [12-15].

Several Maximum Power Point Tracking (MPPT) techniques have been developed for years to extract the maximum power that a PV module can generate. Each MPPT

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technique has its own advantages and disadvantages [16]. References [16, 17] present comparative studies of MPPT techniques. The fractional open circuit voltage and the fractional short circuit current are among the oldest methods. They are very inexpensive and do not require computation hardware.

But they use empirical mathematical equations to determine the Maximum Power Point (MPP). Moreover, they have power loss due to change in weather [16]. The Perturb and observe (P&O) algorithm is the most used method. P&O algorithm consists to perturb the PV output voltage and observe the output power to determine the peak power direction. This method is characterized by its good tracking capability and simplicity. But this method has a major drawback: P&O control fails to track the MPP during the rapid solar irradiation changes and continuous oscillation and low tracking speed of the extracted power [16, 17].

To overcome this situation, the increment conductance (IC) method have been implemented. The merit of this method is low oscillation near MPP. Nevertheless, its implementation is very complex [16, 18, 19]. In addition, a several number of intelligent methods have been adopted to estimate the voltage and the load current values such as fuzzy logic (FLC), artificial neural networks (ANN), particle swarm optimization (PSO) and genetic algorithms (GA).

Such methods known as soft-computing methods are extremely complex and require considerable knowledge in control system design. In addition, these methods exhibit good response and little oscillation near MPP, but they are not free of drawbacks. These techniques are frequently complex, thus they are needful of advanced high performance microcontrollers. They also require considerable knowledge in control system [6, 4, 10, 20]. Slide mode control (SMC) was recently used as MPPT command in photovoltaic systems. SMC is a non-linear control strategy which has several advantages such as robustness, good dynamical response and simplicity in its implementation [16, 21]. On the other hand, its major drawback is a chattering phenomenon.

Hence this phenomenon induces many undesirable oscillations in control signal. Synergetic Control (SC) as a solution is proposed in reference [17] to ensure stability of PV system with fast dynamic response. Synergetic Control like Slide Mode Control is a non-linear control strategy. It allowed changing the system structure by switching from one set of continuous functions of state to another functions to another at any instant [18]. SC has the advantage of finite time convergence and tiny state error. In addition, it should achieve similar performance without chattering phenomenon.

As said before concerning the MPP reaching, one of the most popular and used is the P&O method. It is characterized by an easy implementation. However, the extraction of the power from the PV generator by this MPPT method presents strong oscillations around the MPP [6, 12, 13] that cause power losses.

Consequently, there is therefore a performance problem. The aim of this work is to modify the P&O algorithm in order to reduce the oscillations and consequently enhance the extracted power from the Photovoltaic module.

2. METHOD AND MODELING

2.1 System configuration

There are two PV system's configurations: the direct configuration and the indirect configuration. In the first configuration, the PV Generator (PVG) is directly connected to the load. So, it cannot transfer efficiently the produced power by the PVG . The last one known as MPPT configuration (figure1) is the one which has better efficiency [22].

The DC-DC converter (boost converter) is inserted between the PVG and the load to provide load impedance matching with PV source in order to transfer the maximum power to the load.

The MPPT command get the measures sensed by the current and voltage sensors from the PVG. The data are processed in other to drive the DC-DC converter by generating the suitable duty cycle with the help of MPPT algorithms.

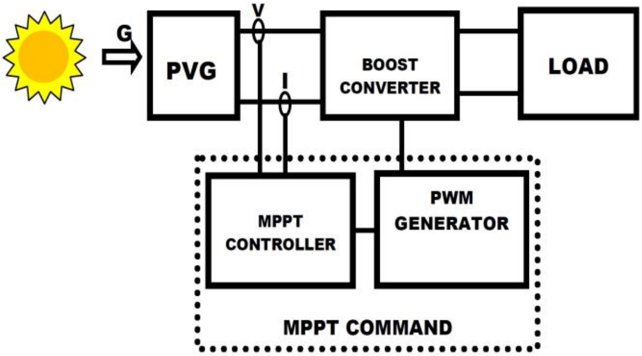


Fig. 1: System's configuration

2.2 The photovoltaic generator

2.2.1 The characteristics of the PVG

The photovoltaic generator (PVG) used in this work is Solkar 36W. The characteristics of this solar panel are recorded in the **Table** below [23].

Table 1: Solkar 36W solar panel characteristics

Characteristics	Reference	Value
Type	Polycristalline	
Maximum power	P_m	37.08 W
Maximum voltage	V_{mp}	16.56 V
Maximum current	I_{mp}	2.25 A
Open circuit voltage	V_{oc}	21.6 V
Short-circuit current	I_{sc}	2.55 A
Temperature range	- 40 °C à + 85 °C	
Number of cells in series	N_s	36
Number of cells in parallel	N_p	1

2.2.2 The PV cell

Several models of photovoltaic cells exist [22]:

- the model with two diodes;
- the ideal model with a single diode;
- the real model with a single diode.

For reasons of simplicity and performance, we opted for the real diode model [23, 25]. Figure 2 shows the electrical diagram of the chosen PV cell's model.

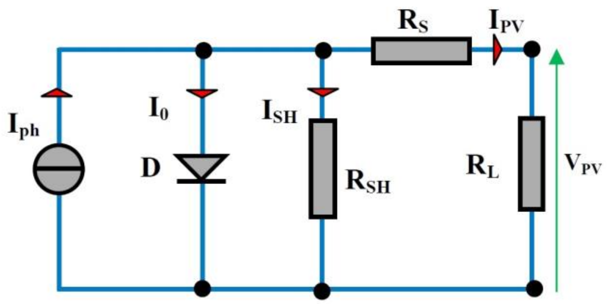


Fig. 2: Electrical diagram of a PV cell

Where, I_{ph}, Photocurrent generated by the PV cell; I_0, Saturation current of the diode; I_{SH}, Saturation current of the resistance; I_{PV}, Output current of the PV cell; V_{PV}, Output voltage of the PV cell; R_{SH}, Intrinsic shunt resistance; R_S, Intrinsic resistance series; R_L, Resistance of the load; D, Diode.

2.2.3 Mathematical model

The photocurrent is given by the following formula [23].

$$I_{ph} = \left[I_{SCr} + K_i\,(T - T_r)\right]\left[G / G_o\right] \tag{1}$$

The reverse saturation current is [23].

$$I_{rs} = \frac{I_{SCr}}{\left(\exp\left\{\dfrac{q\,V_{oc}}{N_S\,kat}\right\} - 1\right)} \tag{2}$$

The saturation current of the PV cell depends on the temperature and is expressed as follows [23].

$$I_0 = I_{rs}\,(T / T_r)^3 \exp\left\{\left((q\,E_{g_0}) / (BK)\right)\left[\frac{1}{T_r} - \frac{1}{T}\right]\right\} \tag{3}$$

The output current of the PV cell is obtained by [23].

$$I_{PV} = I_{ph} - I_0 \tag{4}$$

The nomenclature of quantities involved in equations (1), (2), (3) and (4).

V_{pv}, Output voltage of the PV cell; I_{pv}, Output current of the PV cell; T, Ambient temperature in K; $T_r = 298\,K$ (25 °C, reference temperature); I_{ph}, Photocurrent generated by the PV cell; I_0, Saturation current of the diode; $A{=}B{=}1.6$, Ideality factor; $K = 1.3805 \times 10^{23} J/K$, Boltzman constant; $q = 1.6 \times 10^{-19}\,C$, Electric charge of the electron; R_S, Series resistance of the PV cell; K_i, Short-circuit current temperature coefficient at $I_{SCr} = 0.0017\,A/°C$; $E_{go} = 1.1eV$, Energy required to tear an electron to the silicon atom; G, Instantaneous irradiation received by the PV cell; $G_0 = 1000 W/m^2$, Maximum irradiation received by the PV cell.

2.2.4 Matlab model of the PV cell

Using the mathematical model of the PV cell of references [26-29] and its related equations, one can, step by step, build the model on Matlab platform.

2.3 Boost converter

The Boost converter is basically an electronic circuit represented in figure 3. It's a DC-DC converter which is suitable for PV applications. The output voltage V_S is always greater than the input voltage V_E. Hence the name boost. This circuit is used in the MPPT command for impedance matching. The input voltage V_E and output voltage V_S have the same sign{equation (5)} [25, 30, 31].

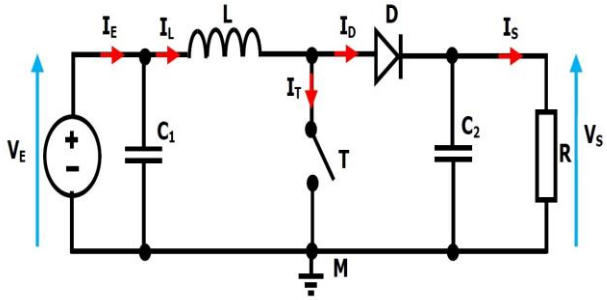


Fig. 3: Electrical diagram of boost converter

The output and input voltages are related by the equation [10, 22].

$$V_S = V_E / (1 - \alpha) \tag{5}$$

α, is the duty cycle of the control signal of the electronic switch T of the boost converter.

The designing parameters of the boost converter are recorded in **Table 2** [23].

Table 2: operating parameters of the boost converter

Parameters	Symbol	Value
Switching frequency	f	10 kHz
Inductance	L	290 μH
Input capacitor	C_1	250 μH
Out put apacitor	C_2	330 μH
Load	R	35 Ω
Transistor	IF	IRSO45
Diode	D	1N4007

2.3.1 Study hypothesis

For the analysis of the boost converter the following assumptions are made [26]:

- The circuit is operating in the steady state.
- The inductor current is continuous(always positive).
- The capacitor is very large, and the output voltage is held constant at voltage V_S. This Restriction will be relaxed later to show the effects of finite capacitance.

- The switching period is T, the switch is closed for time αT and open for time $(1-\alpha)T$.
- The components are ideal.

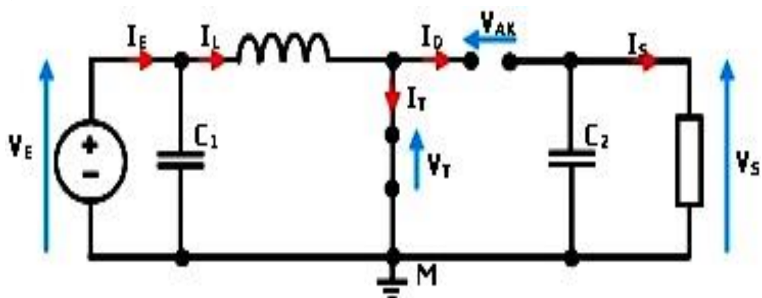
2.3.2 Operating principle

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current. When being charged, it acts as a load and absorbs energy (somewhat like a resistor); when being discharged it acts as an energy source (somewhat like a battery).

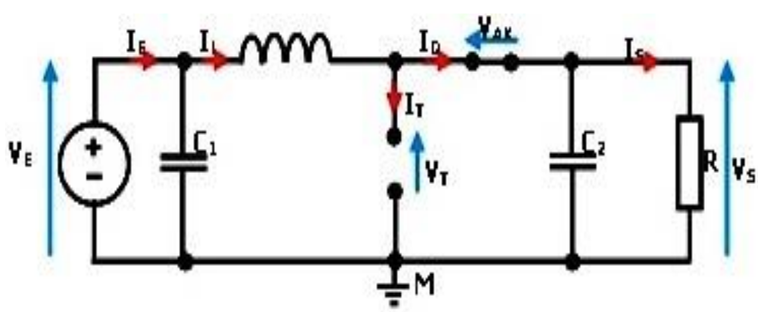
The voltage produced during the discharge phase is related to the rate of change of current, and not to the original charging voltage, thus allowing different input and output voltages. The basic principle of a Boost converter consists of 2 distinct states (figure 4) [33, 34].

- In the On-state, the switch T (figure 4**a**) is closed, resulting in an increase in the inductor current;

- In the Off-state, the switch T (figure 4**b**) is open and the only path offered to inductor current is through the freewheeling diode D, the capacitor C_2 and the load R. These results in transferring the energy accumulated during the On-state into the capacitor.



(a): switch on mode



(b): switch off mode

Fig. 4: Operating modes of the boost converter

2.4 MPPT algorithms

2.4.1 Perturb and observe (P&O) algorithm

The classical P&O algorithm is widely used in literature because of its ease of implementation. The purpose of this algorithm is to operate the system at its maximum power by incrementing and decrementing the operating point voltage and observing the effect of this perturbation on the power output of the GPV [3, 35]. According to this observation, the algorithm decides on the act to be done during the next iteration. Four cases are considered and summarized in **Table 3**.

Table 3: functioning table of the P&O algorithm

Case	ΔV	ΔP	ΔP/ΔV	Tracking Direction	Control Action
1	+	+	+	Good	Increment
2	-	+	-	Bad	Increment
3	+	-	-	Bad	Decrement
4	-	-	+	Good	Decrement

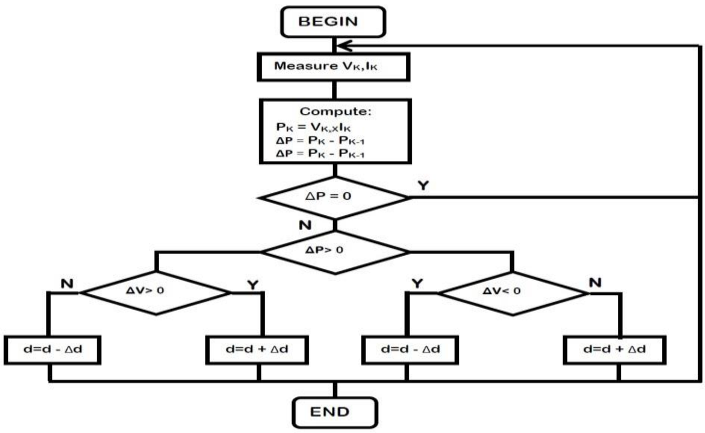


Fig. 5: The conventional P&O flowchart algorithm

2.4.2 Modified perturb and observe algorithm

The principle of this new method is based on the minimization of the variation of the power extracted. The proposed method acts on two distinct aspects:

- In dynamic mode: reach faster the MPP.

- In static mode: significantly reduce the oscillations, once the MPP reached by keeping constant the duty cycle for an absolute variation of ΔP lower than a positive K threshold.

2.5 Simulation model

Figure 7 shows the developed PV system model on the Matlab/Simulink/sympowersystems platform. The whole model illustrated by figure 7**a**, is made of PV generator module, DC-DC boost converterwith MPPT command (MPPT controller and PWM generator) connected to the load is implemented in the Matlab/Simulink environment.

The used PVG (figure 7**b**) in the simulation is the Solkar 36W whom the characteristics are given in **Table 1**. Figure 7**c** represents the detailed diagram of the boost converter of Figure 7**a**.

The boost converter parameters are recorded in **Table 2**. Simulink functions are used to achieve the MPPT controllers.

The conventional P&O and the modified P&O based MPPT controllers are compared owing to two switch positions (figure 7**a**). The PWM generator of the whole model is modeled in Simulink as shown is figure 7**d**.

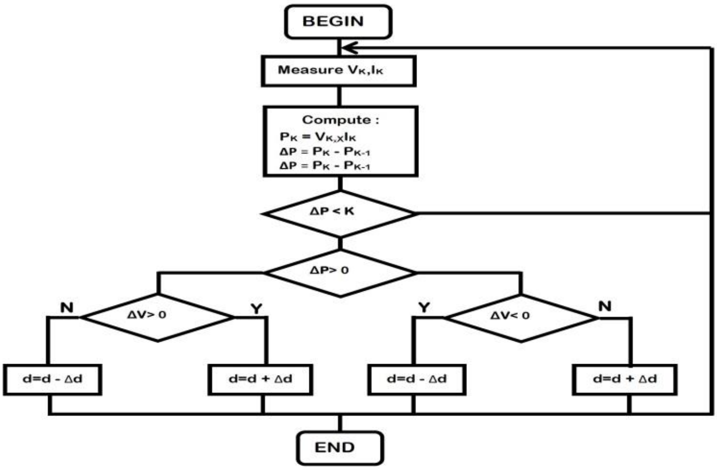
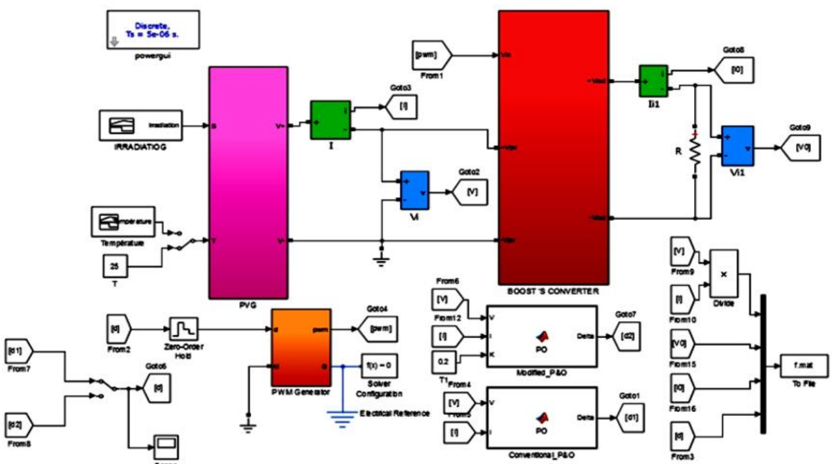
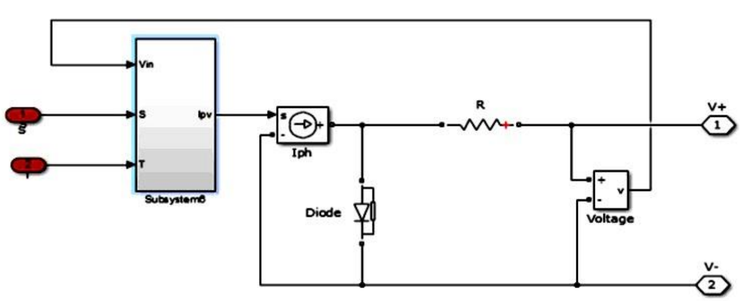


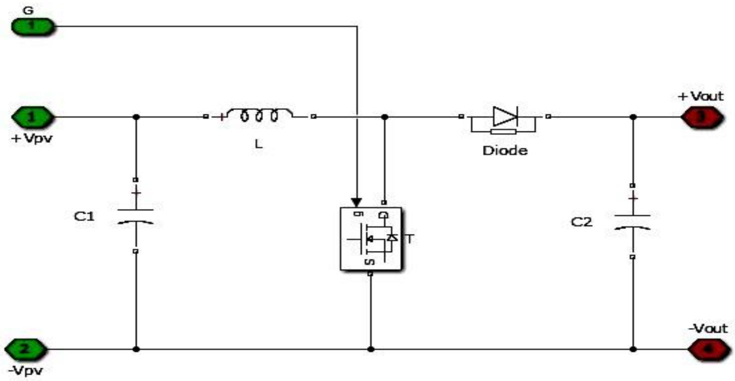
Fig. 6: The modified P&O flowchart algorithm



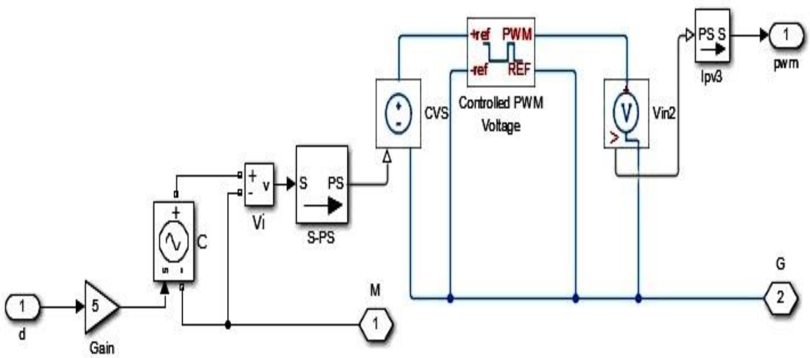
(**a**): The whole PV system model



(**b**): Photovoltaic Generator's model



(**c**): boost converter's model



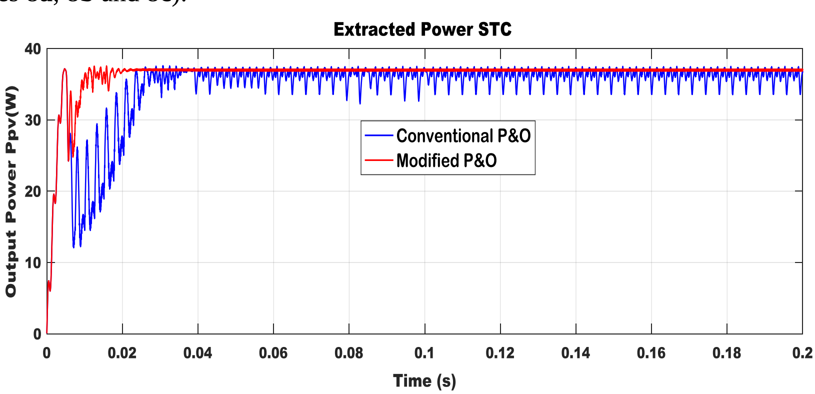
(**d**): PWM generator model

Fig. 7: Matlab PV system model

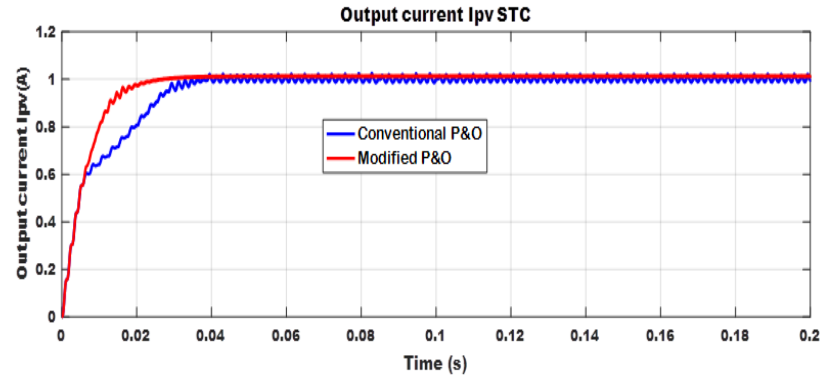
3. RESULTS AND DISCUSSIONS

3.1 Standard test conditions

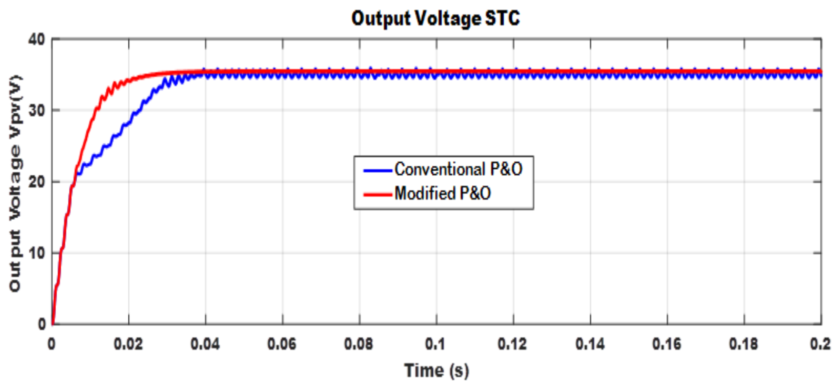
The irradiation over a period of 0.2 s gives, after simulation, the curves of the figures below (figure 8). One can see a strong oscillation generated by the classical P & O method; while the oscillations are very small with the modified P & O method (figures 8**a**, 8**b** and 8**c**).



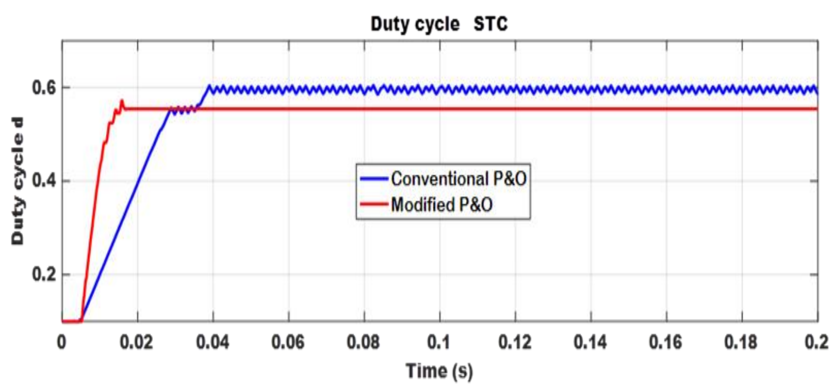
(**a**): Ouput power P_{PV} (W)



(**b**): Ouput current I_{PV} (A)



(**c**): Output voltage V_{PV} (V)



(**d**): duty cycle

Fig. 8: Simulation results in STC

In addition, the oscillation is almost non-existent for the duty cycle (Figure 8d). Moreover, one can observe a greater speed in reaching the MPP from the modified P & O algorithm.

3.2 Comparison of the methods for various values of irradiation

For the following values of irradiation: 1000 W/m^2, 900 W/m^2, 800 W/m^2 and 700 W/m^2; we have plotted the corresponding output powers. Then, the statistical data of each curve were obtained over a period of 0.2 s. Results are presented in **Table 4**.

Table 4: Extracted power comparison of the P&O and the MP&O methods.

G	Conventional P&O			Modified P&O			Observations
	<P>(W)	ΔP(W)	$\frac{\Delta P}{<P>}$	<P>(W)	ΔP(W)	$\frac{\Delta P}{<P>}$	The modified P & O method gives a reduced ripple and a high average value compared to the conventional P & O method over a duration of 0.2s, whatever the intensity of irradiation.
1000W/m²	36.26	1.39	3.83%	36.96	0.52	1.41%	
900W/m²	31.88	1.69	5.30%	32.75	0.68	2.08%	
800W/m²	28.65	0.96	3.35%	29.03	0.48	1.65%	
700W/m²	24.74	0.88	3.56%	24.86	0.71	2.86%	

The results analysis leads us to the following observations:

• The ripple of the extracted power is reduced for the modified P & O method; and varies from 0.52 V to 0.71 V. While it varies from 0.88 V to 1.36 V, when the MPPT command is executed by the conventional P & O method.

• The average power extracted by the proposed method is greater than the one produced by the conventional P & O method.

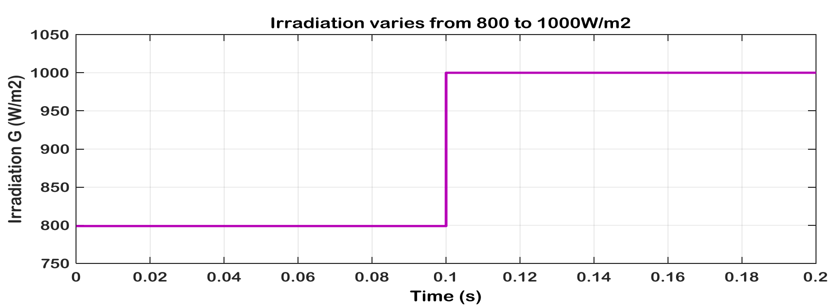
3.3 Varying weather conditions (irradiation varies abruptly from 800 to 1000 m^2)

The introduction of a disturbance (figure 9**a**) shows a rapid response of the modified P & O method, as shown in the circle in figure 9**d**.

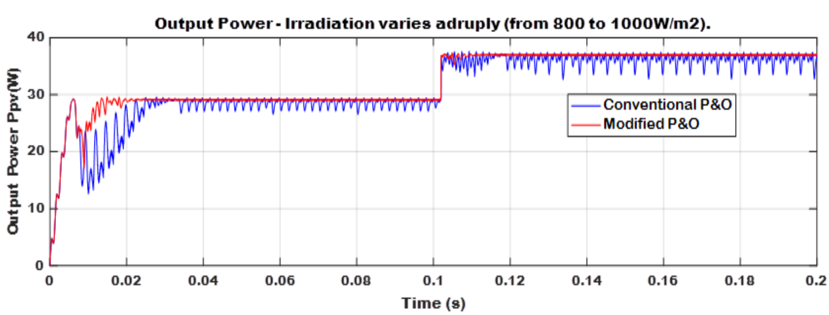
The disturbance occurred at 0.1 s, the irradiation changes abruptly from 800 to 1000W.m^{-2}. Figure 10 below shows clearly the variation of the duties cycles after the sudden change of the irradiation. One can observe that:

-The conventional P&O method reached the steady state after 19 ms;
-Whereas the proposed method reached the steady state after 5 ms.

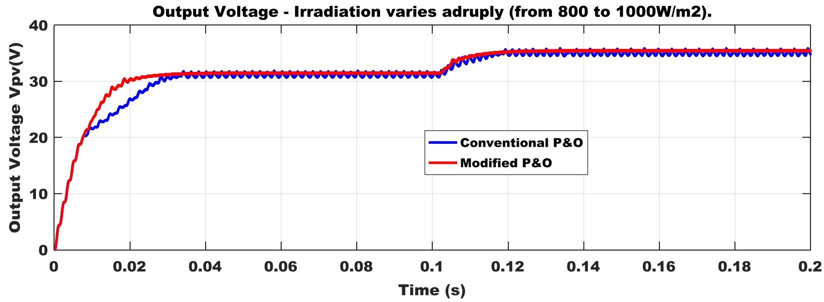
Thus, the modified P&O method is faster than the classical P&O method.



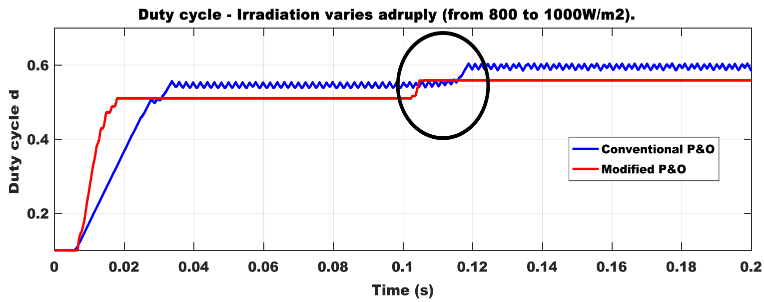
(**a**): Irradiation



(**b**): Ouput power P_{PV} (W)



(**c**): Output voltage V_{PV} (V)



(**d**): Duty cycle

Fig. 9: Simulation results in changing weather conditions

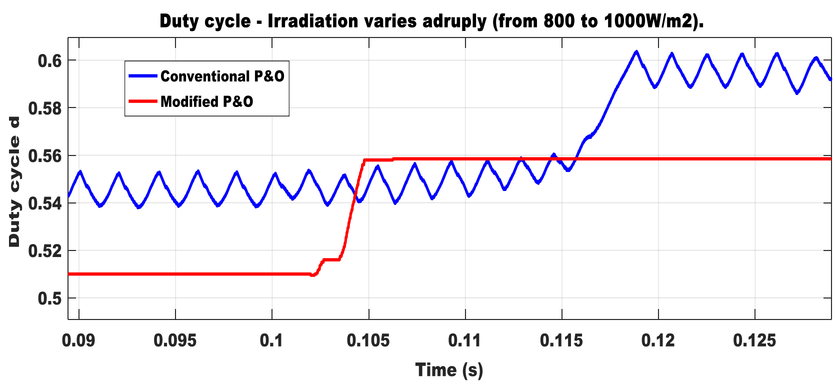


Fig. 10: Zoom on the circle

3.4 The effect of the step variation of the duty cycle deltaD

The values 0.0001, 0.0002, 0.0003 and 0.0005 are assigned to the step size, for the conventional P & O method (figure 11) and the proposed method (figure 12).

Once can deduce by observing the different curves of figures 11 and 12 the following facts:

With regard to the classical P&O method:

- the higher the step size of the duty cycle, the higher the oscillation magnitude;
- the higher the step size of the duty cycle, the faster the tracking speed.

Concerning the modified P&O method:

- The higher the step size of the duty cycle, the faster the tracking speed;

- The values of the duty cycle's step size haven't any influence on the oscillation magnitude.

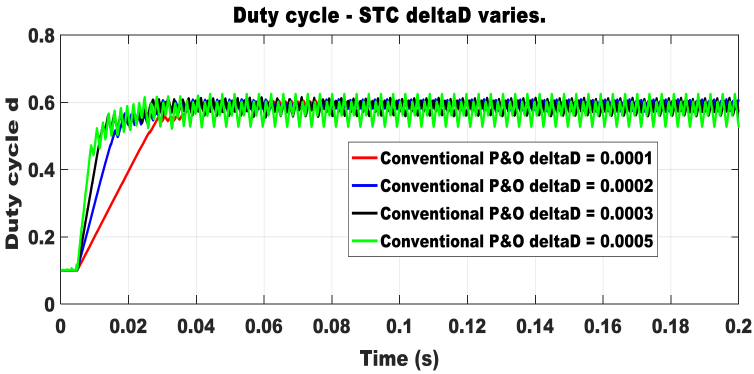


Fig. 11: Duty cycle curves for different step sizes (P&O)

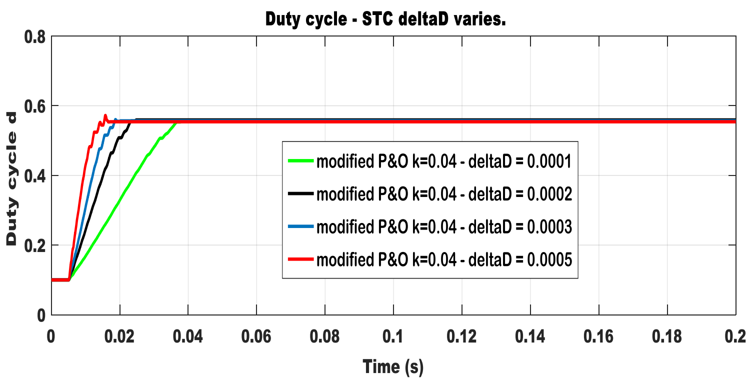


Fig. 12: Duty cycle curves for different step sizes (MP&O)

3.5 Influence of the parameter K on the duty cycle

By maintaining the PV system under standard conditions, one can assign to parameter K, the following values: 0.04, 0.045, 0.06, 0.1, 0.135 and 0.14.

The curves depicted in figure 13 represents the duty cycle variations for a fixed value of K and the duty cycle variations when K varies, under standard tests conditions.

One can find out that the proposed MPPT command reaches the MPP at $d = 0.55$ in the range of the interval] 0.04 , 0.145 [. As soon as K no longer belongs to this range, the duty cycle is different from 0.55 (the cases of $K = 0.04$ and $K = 0.145$).

Therefore, the operating point "leaves" the MPP and is no longer optimal. The dynamic performance of the PV system increases while the parameter K is varying decreasingly in the interval] 0.04 , 0.14 [.

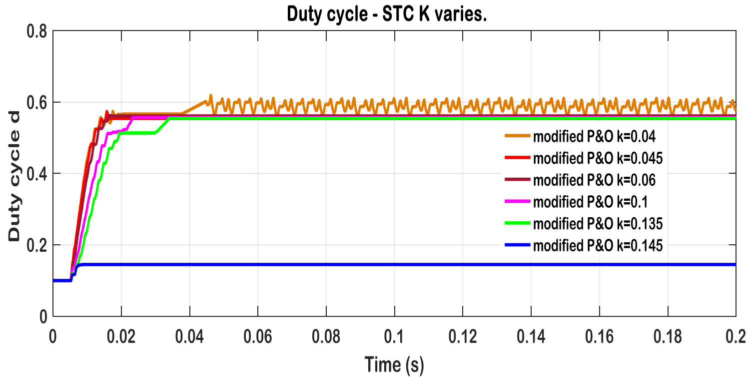


Fig. 13: Duty cycle curves for different values of K (MP&O)

4. CONCLUSION

This paper presented a modified Perturb and Observe method (MP&O). The proposed method had been simulated on Matlab / Simulink / Sympowers System / Simelectronics.

In fact the results analysis depended of the both optimization parameters:

- ➢ the optimization parameter K;
- ➢ the step size of the duty cycledeltaD.

The judicious choices of deltaD and K parameters enable the system to track accurately and efficiently the MPP in dynamic state as in steady state. One can observe these phenomenon:

- In dynamic state:
  - ✓ The higher the step of the duty cycle, the higher the speed;
  - ✓ The lower the parameter K, the faster the tracking speed;
- In steady state:
  - ✓ The higher the variation step size deltaD, the higher the magnitude of the ouput power oscillations with the conventional P&O method;
  - ✓ The variation step size of the duty cycle has no influence on the power extracted for the modified P & O method.

The results obtained show good performances of the PV system with the proposed method by choosing judiciously the values of K and deltaD.

In fact, the proposed method is faster in achieving the MPP. Once the optimum operating point is reached, the duty cycle remains almost constant. This has the effect of getting an extracted power with a much reduced oscillation around the MPP compared to the P&O method.

Oscillations around the point of maximum power are reduced significantly. However, in spite of these improvements observed by the proposed method, there is a major drawback: instability when sudden weather variations occurred.

Then others methods as pattern search methods or the slide mode control (SMC) can improve the results.

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