Validation of the dynamic performance of the perturb and observe type MPPT controller adapted to meteorological variations in the Sahelian region of Chad

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***Abstract*— This article proposes an improved to the perturb and observe (P&O) control method adapted to the climatic conditions of the Sahel region of Chad, specifically for the city of Mongo. This region presents rather severe weather condition in terms of rapid variations in irradiance and temperature, preventing photovoltaic systems from functioning properly. The perturb and observe method was used, the objective is to optimize the tracking of the Maximum Power Point (MPP) of a photovoltaic generator (PVG) subjected to significant variations in irradiance and temperature. The proposed method is first tested using arbitrary meteorological data to evaluate its dynamic performance and stability. Then, the extremum-seeking algorithm was experimentally validated using real meteorological data. The results demonstrated the algorithm's good performance in terms of response time (3 ms), accuracy (98%), and overshoot (6%) under Sahelian conditions in the face of rapid changes in weather condition. These results demonstrated the good efficiency and robustness of the implemented control system, which could also adapt well to weather conditions outside the targeted Sahelian zone of Chad.**

Mots clés— GPV, PPM, Algorithme P&O, Température, Conditions climatiques sahéliennes.

I. INTRODUCTION

In the Sahelian zone of Chad, the climate is characterized by significant variations in solar radiation and temperature [1]. This affects their energy efficiency. To maximize power output, control methods such as perturb-observe, incremental conductance, and intelligent methods are used in recent literature. However, the perturb-observe method remains widely used due to its simplicity of implementation, robustness, and low cost [2]. Nevertheless, few studies have specifically focused on a perturb-observe control adapted to the specific conditions of the Chadian Sahel. The objective of this article is to propose a P&O control system more specifically adapted to the Sahelian conditions of Chad.

II. METEOROLOGICAL CONDITIONS IN THE SAHELIAN ZONE OF TCHAD

This is the transition zone between the desert and the semi-arid tropical climate. It is characterized by high variability in meteorological conditions, particularly significant fluctuations in solar radiation. The study [3] conducted at African stations, including N'Djamena, reveals that conditions in the Sahel are characterized by high temperature amplitudes and significant daily variations in solar radiation. Furthermore, [4] shows that high temperatures, combined with fluctuations in irradiance, continuously alter the current-voltage and power-voltage characteristics of PV modules. The climatic context of the Chadian Sahel necessitates the development of adaptive MPPT controllers capable of reducing oscillations, improving response time, and increasing energy efficiency.

III. MODELING OF THE PHOTOVOLTAIC SYSTEM

A. Modeling of the PV cell.

We present the single-diode model due to its simplicity, short computation time, and good accuracy [5]. Its use allows us to represent the current of a photovoltaic module as a function of the voltage applied to its terminals under various climatic conditions.

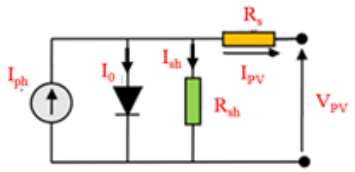

Figure 1: Electrical model of a photovoltaic cell [6]

In the diagram in Fig. 1:
Applying the general electricity laws gives Equation 1 for the current generated by the cell

$$I_{PV} = I_{ph} - I_0 - I_{sh} \quad (1)$$

The photon's photovoltaic current dependent photovoltaic current given by Equation 2 depends heavily on the irradiance and is given by [6]:

$$I_{ph}(T,G) = \frac{G}{1000}(I_{sc} + k_i(T - T_{ref})) \quad (2)$$

The cell's output voltage is given by:

$$V_{PV}(T) = n\frac{KT}{q} ln\left[1 + \frac{I_{ph}(T,G) - I}{I_{0,ref}(\frac{T}{T_{ref}})^3 \exp\left(E\frac{qEg}{nK}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right)}\right] - IR_s \quad (3)$$

With:
I_{ph} : photon stream;
I_0 diode current;
I_{PV}: current supplied by the cell;
R $_{sh}$: shunt resistance;
I_{sh}: current flowing through the shunt resistance;
G: solar irradiance in W/m^2;
I_{sc} : cell short-circuit current;
k_i : short-circuit current temperature coefficient;

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T: operating temperature of the reference cell;
n: diode ideality factor;
K: Boltzmann constant (1.380649. 10^{-23}J/K);
q: elementary charge (q=1.6 10^{-19} C) ;
R_{sh}: shunt resistance;
E_g : Gap energy;
T_{ref} : Reference temperature ($T_{ref} = 25°C$) ;

B. *Boost Converter Modeling*

Known as a voltage booster (see Fig. 2), this converter has two operating sequences. It operates according to the following principle:
In the first-time interval from 0 to αT , the switch represented by the transistor is closed, and the current in the inductor increases. The inductor is storing energy. In the second period, from αT to T, the switch opens and the inductor releases the energy to the load through the diode [7].

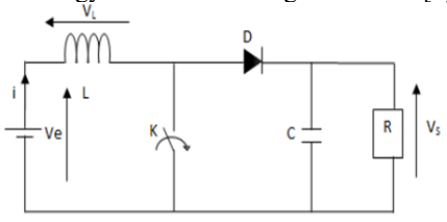

Figure 2: Boost Converter

In steady state, the voltage across the inductor is zero. Therefore:

$$V_s = \frac{V_e}{1-\alpha}$$

And so, the gain is:

$$\frac{V_s}{V_e} = \frac{1}{1-\alpha} \quad (5)$$

The gain is greater than 1, which grants this converter the booster function.
While this converter increases the voltage, it conversely decreases the current according to the following relationship:

$$I_s = (1-\alpha)I_e \quad (6)$$

IV. .INFLUENCE OF IRRADIANCE AND TEMPERATURE ON THE PV

A. *Influence of irradiance*

Solar irradiance is the predominant factor that strongly influences the electrical behavior of photovoltaic cells. Recent studies consistently show that short-circuit current and maximum power vary almost linearly with irradiance, as demonstrated experimentally in [8], indicating a strong correlation between light intensity and power output. [9] shows that at low irradiance, the P-V curve flattens out, making the MPP less pronounced and more difficult to detect. However,[10] demonstrates that High irradiance causes a vertical shift in the curve I-V, with a significant increase in the maximum power point. but also lead to internal losses due to resistances introducing non-linearity in the I-V [11]. Furthermore, [12] specifies that under variable irradiation, the MPP shifts slightly but maintains relative voltage stability, while its power value fluctuates significantly. Thus, irradiation acts primarily as a vertical scaling factor for power, with a limited impact on the location of the MPP.

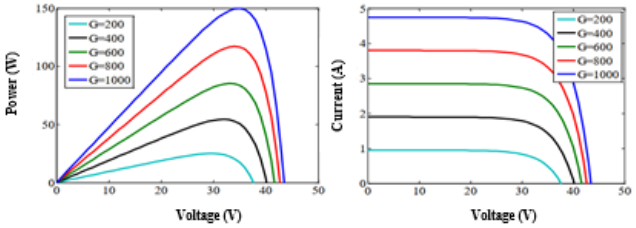

Figure 3: Influence of irradiation on power and current [11]

Figure 3 shows that as irradiance increases, the current rises sharply. In contrast, the voltage varies little. This promotes maximum power.

B. *Influence of température*

Temperature is a factor that limits the efficiency. Recent studies also show that rising temperature leads to a significant decrease in open-circuit voltage and thus in maximum power [14]. This decrease is attributed to the increase in the diode's saturation current and a reduction in the semiconductor's energy gap, explained by[15]. Furthermore, [16] indicates that the overall efficiency decreases by 0.45%/°C. Conversely, the short-circuit current increases slightly. Finally, [17] shows a distortion of curve I-V characterized by a shift to left and sharp reduction in efficiency. Thus, temperature appears to be a critical parameter degrades photovoltaic performance, particularly in hot environments.

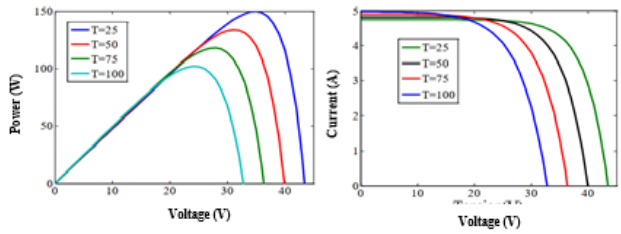

Figure 4: Influence of temperature on power and current [13]

Figure 4 clearly shows that as the temperature increases, the current varies little while the voltage decreases significantly. This negatively affects the maximum power.

V. STATE OF THE ART ON THE PERFORMANCE OF THE PERTURB AND OBSERVE CONTROL

The performance of the perturb and observe control, as demonstrated in recent studies, summarized in the table below.

Tableau1: Summary of some previous work

Authors	Response time	Overshoots	Accuracy	Méthods
[18]	3ms	-	99%	P&O adaptif
[19]	100ms	-	97,8%	P&O adaptif
[20]	-	3 à 5%	99,98%	P&O adaptif
[21]	-	6,4%	-	P&O adaptif +PI
[22]	-	4%	-	P&O adaptif +PI

These results show that the performance of the P&O controller (response time, overshoot and accuracy) is acceptable but can be improved.

VI. PROPOSED PERTURB AND OBSERVE TECHNIQUE

In the conventional perturb and observe method, the duty cycle often starts with an arbitrary fixed value. The proposed control introduces an adaptive estimation of the duty cycle based on the photovoltaic current. This current I_{pv} is used to calculate an initial value D_{init} through the PI corrector, which improves the system's speed and convergence toward the maximum power point, particularly under rapid variation in irradiance.

$$D_{initial} = \frac{I_{pv} \times D}{k} \quad (7)$$

Where D is the duty cycle used for the Boost converter's sizing and k is a constant.

A. Diagram of the Perturbe et observe control

The perturb and observe technique involves studying of the relationship between the PV output power and its voltage. As shown in Fig. 5, when the PV module's operating point is to the left of the curve ($\Delta P/\Delta V > 0$), the PV module voltage disturbance must be increased towards the MPP. When this operating point is on the right side of the curve ($\Delta P/\Delta V < 0$), the voltage offset must be reduced to reach the MPP.

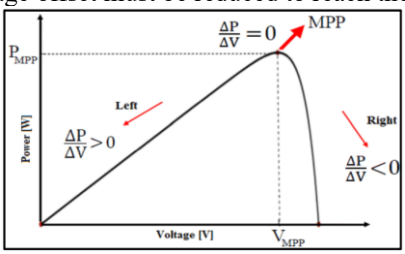

Figure 5: Finding the maximum power point

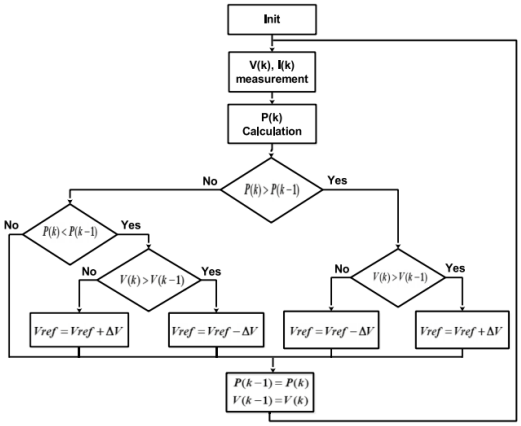

Figure 6: Classic P&O Diagram

B. System diagram in Matlab Simulink

The system consists of a PV module with a current of $I_{mp} = 0{,}89A$ and voltage of $V_{mp} = 8{,}8V$. The maximum power is $P_{mp} = 7{,}83W$, whose characteristic curves P(V) and I(V) are shown in Fig. 7. The Boost converter, composed of an inductance L=165µH, two capacitors $C_1 = 2.2\mu F$, and $C_2 = 15\mu F$ operating at a frequency of 200 kHz.

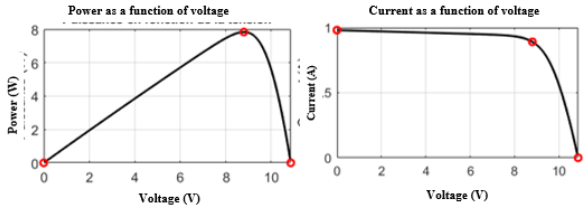

Figure 7: Characteristics of the PV module

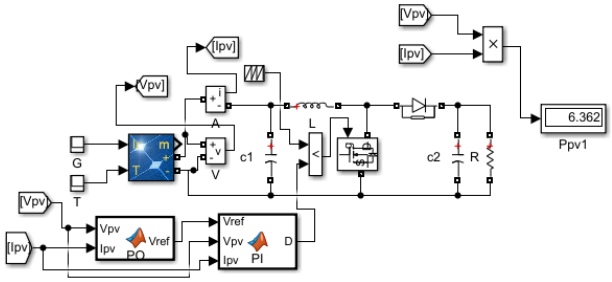

Figure 8: PV-Boost System

VII. SIMULATION RESULT AND DISCUSSION

Simulations are performed for various scenarios to illustrate possible real-world data. The results will be discussed considering existing work in the scientific literature.

A. standards Conditions (1000W/m² et 25°C)

In these simulations, the objective will be to evaluate the system's performance using the following criteria which are: response time to 5% of the final value, stability and accuracy.

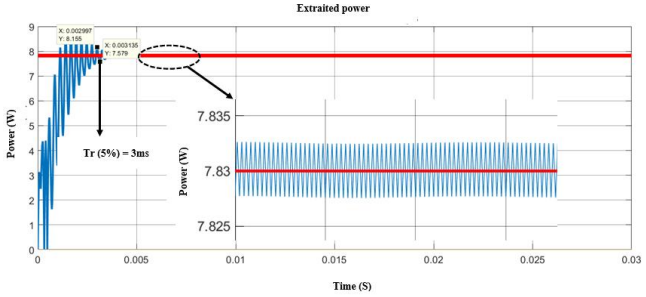

Figure 9:Power extracted under standard conditions

The proposed control method has a response time of 3 ms and an efficiency of approximately 99%, which is slightly higher than the results reported [20], which proposed a variable-step P&O method with an efficiency of 98.8% under standard conditions but a convergence response time of approaching 5 ms .In Comparison to [18], which reports an efficiency of 99.2% and a response time of 3.1 ms. The proposed method has a shorter response time (2.3 ms) while maintaining similar efficiency. For [19], it achieved an accuracy of approximately 99.98% with a convergence time close to 100 ms. Similarly, [23] introduces a variable-step P&O method that reduces oscillations but still has a response time greater than 10 ms. In contrast, the classic implementation, as presented by [24], has an efficiency of approximately 98.7% and remains limited by a trade-off between speed and accuracy. However, in these studies, oscillations around the MPP may persist in steady state condition. Overall, the model offers a good trade-off between speed and accuracy, consistent with the performance reported in the literature.

B. Irradiation and temperature variations

The objective of this simulation is to evaluate the robustness, and therefore the overshoot of the control, under rapid variations in irradiance.

- ✓ Rapid changes in irradiance and temperature

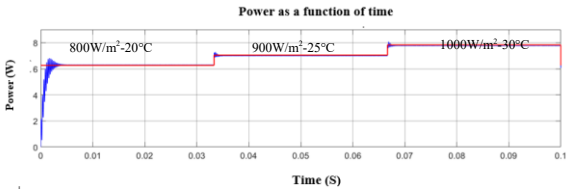

Figure 10:power extracted under non-standard conditions

✓ Irradiance change from 800 à 900W/m²

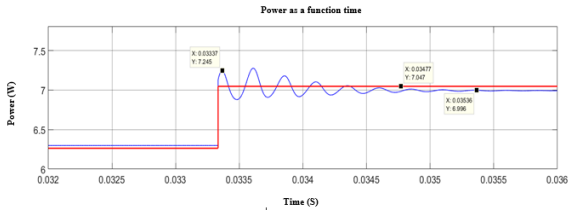

Figure 11: zoom1 on the varying power

The rapid change in irradiation from 800 to 900 W/m² caused oscillations as the control system is searching for the maximum point again. This overshoot is estimated:

$$D_p(\%) = \frac{P_{max} - P_{stable}}{P_{stable}} = 2{,}8\% \qquad (8)$$

✓ Irradiance change from 900 à 1000W/m²

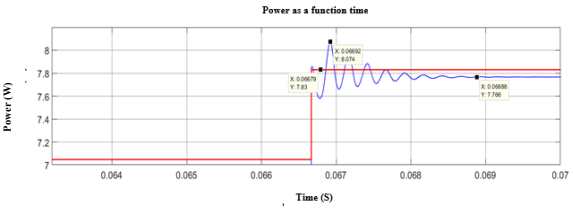

Figure 12: zoom2 on the varying power

In the second variation, the overshoot is around 3% with 99% accuracy, which is comparable to the work by [27] showing a variable-step P&O with an overshoot of 3 to 5% during rapid irradiance transitions. Furthermore, [21] shows a P&O yielding an overshoot of 6.4% for a large irradiance variation from 400 to 1000 W/m². Finally, [22] also presents an improved P&O associated with a PI corrector that offers an overshoot of 4%. The results obtained by the proposed control method are therefore acceptable and superior to those of some studies, indicating better transient stability of the control under variable weather conditions. This make it a particular technique suited to the Sahelian zone of Chad, which is characterized by sudden variations in irradiance and temperature.

C. Cloudy conditions

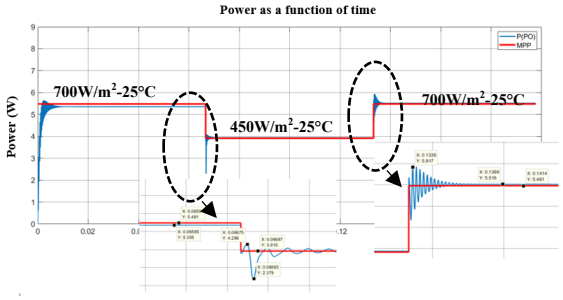

Figure 13: Power output during cloud passage

This case illustrates the rapid passage of clouds, and we see good adaptation with an initial accuracy of 97.6%, and an overshoot of around 6%.

VIII. EXPERIMENTAL VALIDATION

. As a reference for this work, we will consider meteorological data from Mongo city

The experimental results were obtained on March 7, 2025, from 7:41 AM to 4:41 PM at the Polytechnic University of Mongo (Longitude: 18.7° Latitude: 12.15°). The SM 206 Solar Pyranometer, with an accuracy of 5%, was used to measure solar irradiance at 1.5 m above ground level. A TORANGE PM8229 multimeter and a MAX6675 sensor were used to measure ambient temperatures and cell, respectively.

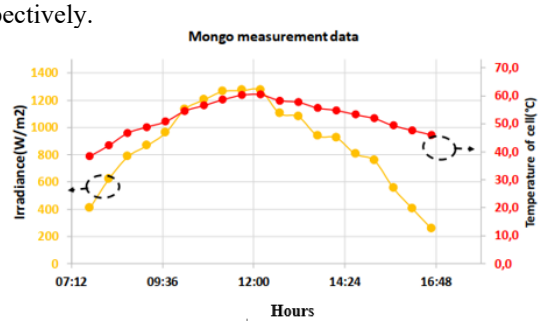

Figure 14: Measurement data from Mongo

Actual meteorological data for the city of Mongo show severe conditions for MPP tracking, with the sharpest rise in irradiance of 214 W/m² observed between 7:00 AM (406 W/m²) and 8:00 AM (620 W/m²) , and the steep decline of 202 W/m² observed at 3:00 PM, from 756 to 554 W/m². The greatest instantaneous temperature variation observed was only 2°C.

The average irradiance is 878W/m² and the temperature is around 37°C. This indicates an environment with high solar potential but one that is thermally challenging for photovoltaic generators.

A. Experimental results using real-word data from Mongo

The meteorological data acquired for the city included several measurements. However, we did not consider all measurements in the simulations to avoid data redundancy in certain data. Nevertheless, representative data points, including phases of rapid increases, sudden drops, and stabilization of meteorological parameters, were simulated to evaluate the robustness and dynamic performance of the proposed control system.

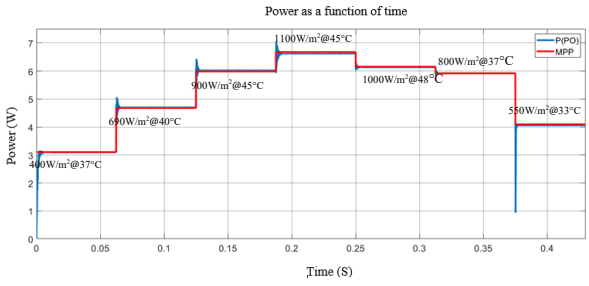

Figure 15: Simulation results based on actual data

B. Analysis of experimental simulation results

Although the technique has been compared to results in the literature, its application to real-world data is a very important step. The same evaluation criteria will allow for the definitive validation of the proposed method.

- Start-up response time

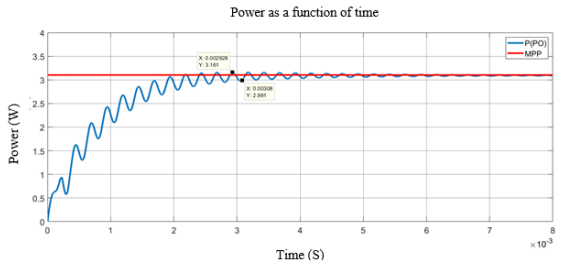

Figure 16: Zoom on response time

The system reached its maximum point in 3 ms and remained more stable for the rest of the remainted of the time before the change in meteorological data. This demonstrates a significant speed compared to the previous study.

- Overshoot during the transition phase and data drop

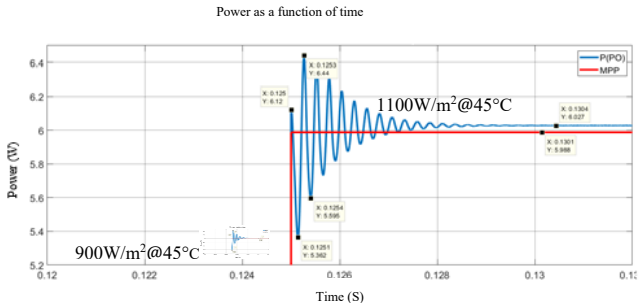

Figure 17: Zoom1 on the overshoot

The maximum value $P_{max} = 6{,}44W$ and its steady-state value $P_{stable} = 6{,}027W$, resulting in an overshoot of 6.5%. The difference between its steady-state value and the setpoint $P_{mpp} = 5{,}988W$ is 0.04W, an error of less than 1%, therefore an accuracy of 99%.

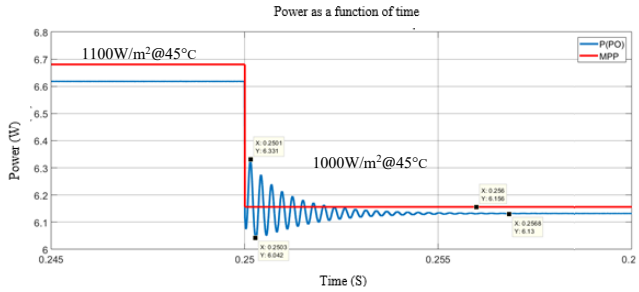

Figure 18: Zoom2 on the overshoot

For the drop, the deviation is around 3.3% with an accuracy of 99.5%. Response times are less than 5ms, and the system remains stable otherwise. This demonstrates acceptable and valid performance of the adaptive perturbe and observe technique for meteorological conditions in the Sahelian zone of Chad.

Conclusion

This work has enabled the proposal of an improvement to the perturb and observe MPPT (Maximum Power Point Tracking) control to adapt it to the climatic conditions of the Chadian Sahel, particularly those of the city of Mongo. The proposed strategy was first evaluated using synthetic meteorological data and then with real data from local measurements. The results obtained show an improvement in the performance of the photovoltaic system. The proposed control method is fast with a convergence time of 5 ms, accurate of 99%, and overshoot of 6% under unstable conditions. This translate consistent efficiency and robustness in the face of Sahelian weather conditions. Nevertheless, the method exhibits minimal oscillations around the maximum power point (which could lead to losses). The control system should therefore be further improved to reduce these oscillations, test it using other meteorological data from the sub-region and to implement the proposed control under real-world conditions.

ACKNOWLEDGMENT

The authors thank the laboratory of Polytechnic University of Mongo for his technical support

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