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Comparative study of classical and metaheuristic MPPT control of the stand-alone photovoltaic system

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Thankfulness

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Dedication

الحمد لله الذي أنشأ وبرى ... وخلق الماء والثرى

وأبدع كل شيء وضرى ... الرحمان على العرش استوى

والصلاة والسلام على من بكى ... على أمته المبعوث في أم القرى

صلى الله وسلم على الحبيب المصطفى

أما بعد، فإنما طلبنا العلم لوجه الله تعالى ولم نرد بذلك إلا وجه الله وذلك حب الله يؤتيه من يشاء
*وقال تعالى: **{يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنْكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ}** وقد رفعنا الله بذلك، فأسأله أن يرفع مقامنا في الاخرة كما رفعه في الدنيا*

إنما طلبت العلم لوجه الله ثم لأفرح والدي وعائلتي ورفقاء دربي وأساتذتي وجميع من ساهم في نجاحي وتفوقي
فإلى جميع من ساندني وقدم لي يد العون خلال رحلتي، أهدي إليكم هذا العمل المتواضع، ثمرة جهودي ومساعيي

أخيرا، سبحانك اللهم بحمدك أشهد أن لا إله إلا أنت أستغفرك وأتوب إليك

BENGAOUER Chaima

Dedication

{وَآخِرُ دَعْوَاهُمْ أَنِ الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ}

الحمد لله حبا وشكرا وامتنانا، الحمد لله الذي بفضله أدركت أسمى الغايات.

*اهدي بكل حب مذكرة تخرجي الى **نفسي** العظيمة الفتية التي تحملت كل العثرات واكملت رغم كل الصعوبات.*

الى أعظم شخص واعز الناس، داعمي الاول، وسندي وملاذي بعد الله، فخري واعتزازي،
امي وابي
الى من دامت لي اياديهم وقت ضعفي، الى ضلعي الثابت، وامان قلبي،
اخوتي
الى من ساندني بكل حب،
صديقاتي، زملائي وزميلاتي
*الى **اساتذتي** الافاضل، الى كل من اعطاني يد العون من قريب او بعيد وساعدني في هذا المشوار.*

"من قال أنا لها نالها" وأنا لها وإن أبت رغماً عنها أتيت به.

BENKHALED Souad Nour El Houda

Abstract

This dissertation explores optimizing of photovoltaic solar energy, essential in today's climate change context. Due to various internal and external factors, the performance of solar panels can be limited. Maximum power point tracking (MPPT) techniques are used to maximize the power extracted. This work compares two MPPT methods: Perturb and Observe (P&O) and Particle Swarm Optimization (PSO). Using MATLAB Simulink, we evaluate their performance, efficiency, complexity and adaptability to environmental variations. The structure of the dissertation includes the study of stand-alone photovoltaic systems, DC-DC boost converters, the development of simulation blocks, and the comparative analysis of results to determine the most efficient method.

Keywords: Photovoltaic, MPPT, Boost, maximize, Power.

Résumé

Cette thèse explore l'optimisation de l'énergie solaire photovoltaïque, essentielle dans le contexte actuel du changement climatique. En raison de divers facteurs internes et externes, la performance des panneaux solaires peut être limitée. Les techniques de suivi du point de puissance maximale (MPPT) sont utilisées pour maximiser la puissance extraite. Ce travail compare deux méthodes MPPT : Perturbation et Observation (P&O) et Optimisation par Essaims de Particules (PSO). En utilisant MATLAB Simulink, nous évaluons leur performance, leur efficacité, leur complexité et leur adaptabilité aux variations environnementales. La structure de la thèse comprend l'étude de systèmes photovoltaïques autonomes, de convertisseurs DC-DC boost, le développement de blocs de simulation et l'analyse comparative des résultats pour déterminer la méthode la plus efficace.

Mots-clés : Photovoltaïque, MPPT, Boost, Maximiser, Puissance.

ملخص

تدرس هذه الأطروحة تحسين الطاقة الشمسية الكهروضوئية، وهو أمر ضروري في السياق الحالي لتغير المناخ. نظرًا لعوامل داخلية وخارجية مختلفة، يمكن أن يكون أداء الألواح الشمسية محدودًا. ولزيادة الطاقة المستخرجة إلى الحد الأقصى، تُستخدم تقنيات تتبع نقطة الطاقة القصوى (MPPT)

يقارن هذا العمل بين طريقة الاضطراب والمراقبة P&O وطريقة تحسين سرب الجسيمات PSO ويقوم بتقييم أدائهما وكفاءتهما وتعقيدهما وقدرتهما على التكيف مع التغيرات البيئية. يتضمن هيكل هذا العمل دراسة الأنظمة الكهروضوئية القائمة بذاتها ومحولات التيار المستمر-التناوب وتطوير كتل المحاكاة والتحليل المقارن للنتائج من أجل تحديد الطريقة الأكثر كفاءة.

الكلمات المفتاحية: الكهروضوئية، تحسين، الطاقة، MPPT

List of Figures

List of Tables

Table of Contents

General introduction

Photovoltaic (PV) systems have become essential in the global transition towards renewable energy sources. Their ability to convert sunlight directly into electrical energy through photovoltaic cells positions them as an important technology in addressing energy needs and the climate crisis. PV systems can be classified into three main categories: grid-connected, hybrid, and stand-alone or off-grid. Each type has unique configurations and applications, but they all share a common objective: maximizing energy conversion and utilization efficiency.

One of the primary challenges in PV systems is the variability in power output due to changing environmental conditions such as irradiance and temperature. Maximum Power Point Tracking (MPPT) techniques optimize power extraction from PV modules. MPPT ensures that the PV system operates at its optimal power point, where the product of current and voltage is maximized, thereby improving the systems overall efficiency.

This thesis focuses on a comparative study of two prominent MPPT techniques: the classical Perturb and Observe (P&O) method and the metaheuristic Particle Swarm Optimization (PSO) method. The P&O method is widely used due to its simplicity and ease of implementation. However, it often needs help with efficiency and accuracy under rapidly changing environmental conditions. Conversely, the PSO method, inspired by the social behavior of birds and fish, offers a more sophisticated approach by improving a population of solutions to find the optimal power point.

The main objectives of this research are threefold. First, to explore the fundamental principles of the P&O and PSO MPPT techniques. Second, these methods will be implemented and simulated using MATLAB Simulink. Third, to evaluate and compare their performance, efficiency, complexity, and adaptability to varying environmental conditions. By achieving these objectives, this study aims to provide a comprehensive understanding of the strengths and weaknesses of each method, thereby contributing to the development of more efficient and reliable photovoltaic systems.

The structure of this thesis is organized to facilitate a thorough exploration of the topic.

Chapter 1 delves into the fundamentals of PV systems, providing an understanding of photovoltaic conversion, different types of PV systems, and the external factors influencing their performance.

Chapter 2 discusses the role of DC-DC converters in PV systems and introduces various MPPT control methods.

Chapter 3 details the proposed methods, their implementation in MATLAB Simulink, and the setup for the simulation study.

Chapter 4 presents the simulation results, comparing the performance of the P&O and PSO methods under different conditions, including stable environments, slow and sudden changes in irradiance, and partial shading.

The final section, the General Conclusion, summarizes the findings, discusses the results, implications, and suggests future research directions. Through this comparative study, this thesis aims to provide valuable insights into the effectiveness of classical and metaheuristic MPPT techniques. By understanding the strengths and limitations of each method, this research contributes to the development of more efficient and reliable photovoltaic systems, thereby supporting the broader goal of enhancing renewable energy technologies

I. Chapter01: PV Systems Fundamentals

Photovoltaic solar energy is the most abundant source of renewable energy. It comes from directly converting the sun's rays into electrical energy. This energy conversion is carried out by the photovoltaic (PV) cell, based on a phenomenon of the photovoltaic effect.
This chapter explores the essential aspects of this technology, starting with photovoltaic (photoelectric) conversion, the different photovoltaic systems, and the photovoltaic chain. We then move on to the photovoltaic generator (GPV), detailing its specific characteristics and analyzing how external parameters influence these characteristics to understand their impact on the performance and efficiency of solar systems.

I.1 Photovoltaic (photoelectric) conversion

The prefix Photo comes from the Greek "Phos" meaning light. "Volt" comes from the name of the physicist Alessandro Volta[1]. Sunlight comprises photons containing energy corresponding to the different wavelengths of the solar spectrum. When a photon strikes a photovoltaic cell, its power can be transferred to an electron in its semiconductor material. With this extra energy, the electron can escape from its normal position in the atom, creating a "hole," which will become part of a current in an electrical circuit. This is known as the electron-hole pair.[2]

A photovoltaic cell is comprised of two layers of semiconductor material doped so that one conducts negative charges and the other positive charges. This creates a permanent electric field in the cell. Thanks to this diode effect, once the electron-hole pair has been made, the negative charges will be separated from the positive charges. This creates a potential difference between the N and P layers of the cell.[2]

I.2 Photovoltaic systems

Photovoltaic systems can be classified according to functional and operational requirements, component configuration, and connection to other power sources and electrical loads:

- **Grid-connected systems**: they are designed to operate in parallel with the electric utility grid. There are two general types of electrical designs for PV power systems: systems that interact with the utility power grid and have no battery backup capability and systems that interact and include battery backup. The latter system incorporates energy storage as battery to keep “critical load” circuits operating during utility outages.[3]
- **Hybrid Solar PV Systems:** A solar PV system can be combined with other power sources, such as diesel generators, the national grid, or renewable sources like wind, to create a hybrid PV system. The type of converters used in these systems to transform energy into either DC or AC voltage depends on the specific sources integrated with the solar PV panels.[4]
- **Stand-Alone or Off-Grid PV Systems:** This solution is independent of the national grid. Photovoltaic systems are classified into Stand-alone photovoltaic systems with storage or Photovoltaic systems without storage (solar-powered), direct current (DC) systems where the DC-DC converter is directly used to adjust the voltage to an appropriate level, or

alternating current (AC) systems where the inverter converts the DC voltage from the solar panels into AC voltage. [4]

I.3 The photovoltaic chain

Stand-alone photovoltaic systems are usually a utility power alternative. They generally include solar charging modules, storage batteries, and controls or regulators, as shown in *Figure I.3*. If AC power is desired, an inverter is also required. [5]

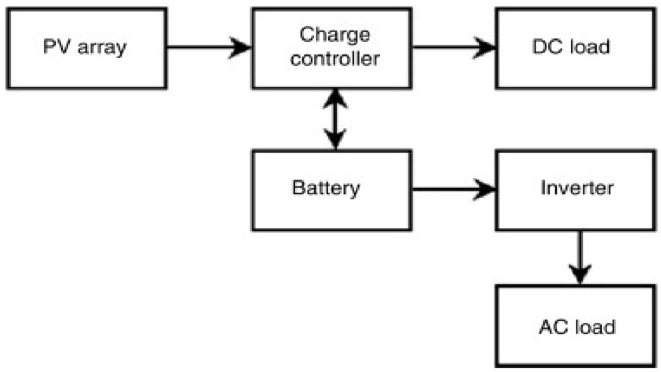


*Figure **Error! Use the Home tab to apply Titre 1 to the text that you want to appear here.**: Stand-alone PV chain [5]*

I.4 The PV generator (GPV)

The elementary photovoltaic cell is a very low-power electrical generator. Photovoltaic generators are, therefore, made by combining a large number of elementary cells. These cells are marketed as photovoltaic modules combining several elementary cells with identical technology and characteristics, generally in series, to raise the voltage.[6]

I.4.1 Characteristics of photovoltaic generator

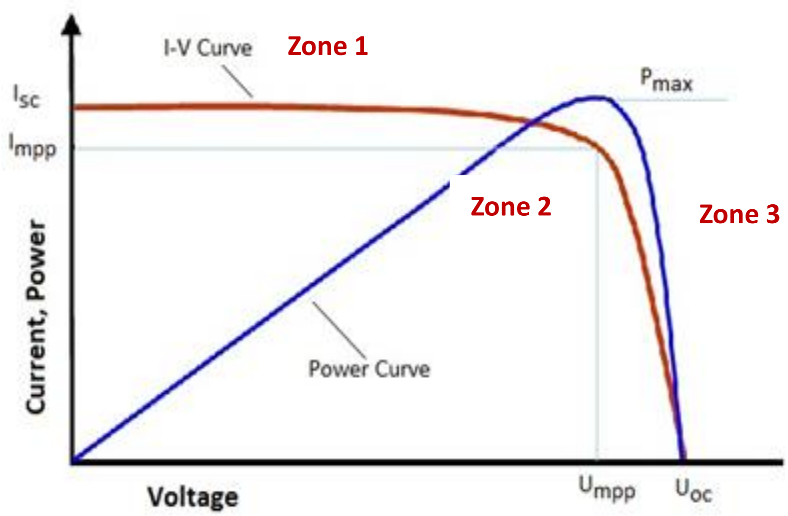


*Figure **Error! Use the Home tab to apply Titre 2 to the text that you want to appear here.**: P(V) and I(V) characteristics of a GPV [7]*

According to the *Figure I.4.1* above, the characteristic can be divided into three different zones:

- **Zone 1:** The solar cell is a current source, so the current is constant and the voltage is variable.[7]
- **Zone 2:** The middle zone between the following two zones, representing the preferred operating zone. The generator can determine the best point [7]
- **Zone 3:** It is the time interval where the solar cell is considered the voltage source because the voltage is constant and the current is variable.[7]

I.4.2 Influence of external parameters on a photovoltaic module

The characteristics of PV cells (P-V characteristics) depend directly on irradiance and temperature, as the following *Figure I.4.2* shows:

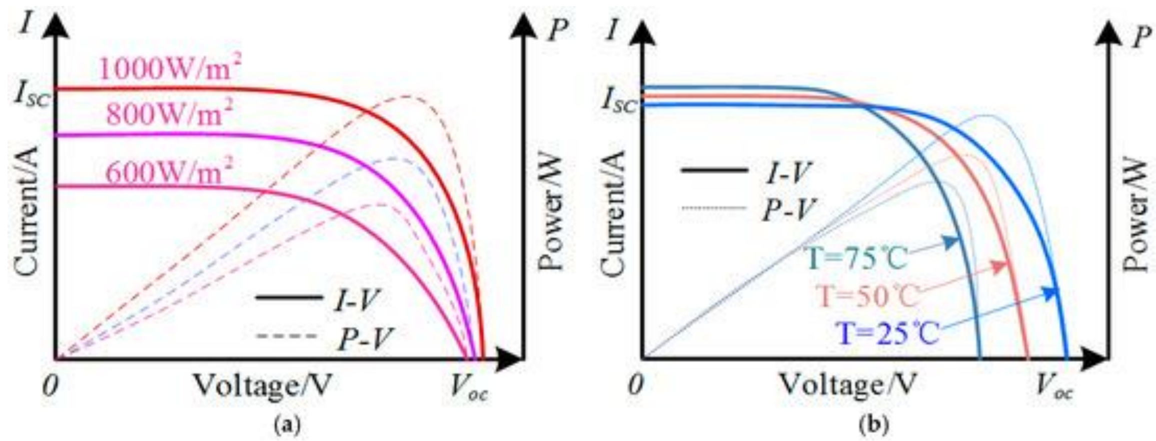


Figure ***Error! Use the Home tab to apply Titre 2 to the text that you want to appear here.****: Influence of irradiation (a) and temperature (b) on P(V) and I(V) characteristics [9]*

- **Influence of the irradiation**
  The short-circuit current (I_{sc}) varies proportionally to the illumination. 10]
  The open-circuit voltage (V_{oc}) changes very little as a function of illumination.[8]
- **Influence of the temperature**
  The open-circuit voltage (V_{oc}) decreases with increasing temperature. 10]
  The influence of temperature on (I_{sc}) can be neglected in most cases.[8]

I.5 Conclusion

This review of external influences on the characteristics of the photovoltaic generator leads us to consider the need for effective control to maximize its performance. Next chapter will examine MPPT control through a DC-DC Boost converter. This approach will enable us to better understand how to adapt the electrical power extracted from the generator to variations in external parameters, thus ensuring the optimum efficiency of photovoltaic systems.

II. Chapter02: DC-DC Boost Converter and MPPT Control

Photovoltaic generators have non-linear (P-V) characteristics and can reach a single optimum operating point under uniform lighting conditions. A matching stage must be inserted between the power supply and the load to operate at maximum power. This may be a DC-DC converter, a power electronics circuit, or an electromechanical device that converts a DC power source from one specified voltage level to another[9]. This chapter presents DC-DC boost converter topologies for designing a power interface.

II.1 DC-DC Converter

DC-DC converters are essential electronic circuits important in modern energy management systems. Their primary function is to convert the voltage of a direct current (DC) source from one level to another, ensuring stable and efficient power supply to various electronic devices and systems[10]. It is used to store photovoltaic energy in batteries or to supply a DC load. In this thesis we will focus on the boost converter.

II.1.1 Boost converter

Also known as step-up choppers, they reduce the components needed to obtain a higher voltage. The DC-to-DC conversion occurs ,so the circuit provides a higher output voltage magnitude than the supply input’s magnitude [11] [12].The ratio between input and output voltages can be expressed as follows: $V_{O=}\frac{V_i}{1-D}$ [12] (1)

Where: V_O, V_i: *the output, input voltage* D: duty cycle

The following *Figure* ***Error! Use the Home tab to apply Titre 2 to the text that you want to appear here.*** shows the chopper structure:

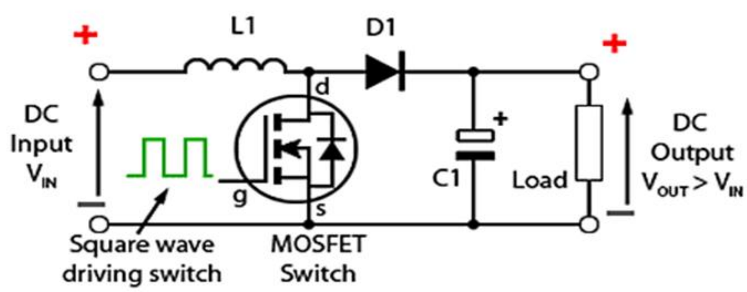


Figure ***Error! Use the Home tab to apply Titre 2 to the text that you want to appear here.*** *:Boost DC-DC enrgy converter [14]*

II.2 MPPT controller and operating principle

An MPPT (Maximum Power Point Tracker) is a principle for tracking the maximum power point of a non-linear electrical generator. By definition, an MPPT control combined with an intermediate adaptation stage enables a GPV to operate in such a way as to constantly produce the maximum power, whatever the weather conditions (temperature and irradiation), the converter control sets the system to the point of maximum .The photovoltaic conversion chain will be optimized by an MPPT control, which varies the static converter's (CS) duty cycle, using an appropriate electrical signal to extract the maximum power the GPV can deliver. [13].

II.2.1 Classification of MPPT methods

II.2.1.1. Classic (conventional)

- **Basic idea:** Based on the perturbation, relation, and comparison of panel characteristics. They perform best under constant irradiance. [14]
- **Advantages:**
  - Easily implemented[14]
  - Less complexity algorithm and not expensive [16]
- **Disadvantages:**
  - The loss of power (rapid oscillations) [15]
  - Neglecting the effect of partial shading[14]

II.2.1.2. Metaheuristic (optimized/bio-inspired)

- **Basic idea:** Based on the iterative improvement of a single or population of solutions and the study of natural evolution and swarming behavior of living organisms, randomization is mainly used to solve an optimization problem. [15]
- **Advantages:**
  - Independence of system knowledge. [16]
  - Track GMPP without requiring the temperature and irradiation sensors. [14]
  - High tracking speed.[14]
- **Disadvantages:**
  - No guarantee of accuracy or optimality.[15]
  - Difficulty adjusting parameters.[15]

II.2.1.3. Intelligent

- **Basic idea:** These methods use soft computing techniques to perform MPPT.[14] and more advanced use of adaptive algorithms or methods based on artificial intelligence[16] .These techniques are intended for dynamic weather changing conditions with the utmost accuracy.
- **Advantages:**
  - Fast tracking speed.[15]
  - High efficiencies and accuracy[17]
  - No need for additional parameters[17]
- **Disadvantages:**
  - Huge control circuit complexity. [18]
  - Big data processing and high cost[18]

II.2.1.4. Hybrid

- **Basic idea:** Combination between classical with intelligent or optimal MPPTs. The tracking methodology is done in 2 steps: making the set point close to MPP by the classical, then this set point is made to reach the actual MPP using the advanced techniques. [15]
- **Advantages:**
  - Tracing accuracy [19]

- High ability to track under PSCs. [19]
- High efficiencies[19]

- **Disadvantages:**
  - High cost.[15]
  - More complex. [19]

Example: This diagram shows examples of each type:

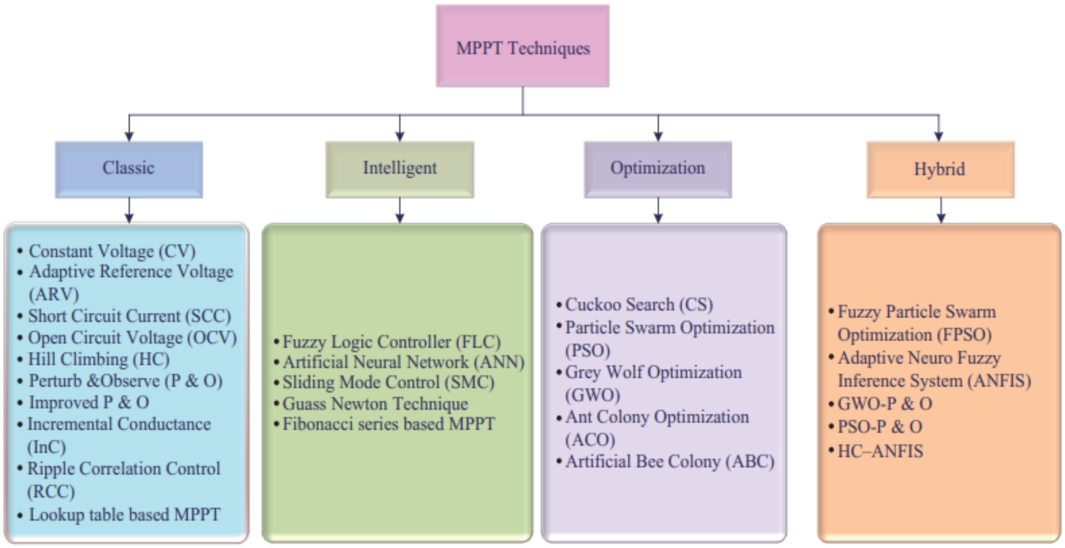


*Figure **Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.**: Example of MPPT methods [18]*

II.2.2 Other classification

MPPT controls can be broadly classified according to the type of control (conventional, metaheuristic, intelligent or hybrid). However, it is more interesting to classify them according to the kind of search they used to the input parameters of the MPPT control [20], as the ***Table II.2.2*** shows :

*Table **Error! Use the Home tab to apply Titre 2 to the text that you want to appear here.**: Classification of MPPT methods by input/output parameters and by search type*

Classification of MPPT control by input or output parameters.[20]	**Input parameters:** based on proportionality relationships characterizing the MPP (V_{opt} and I_{opt}) and the characteristic parameters of the PV module (V_{oc} and I_{sc}).[20]
	Output parameters: based on output current maximization, and the converter efficiency approximates the Pmax.[20]
Classification of MPPT Control by Search Type[21]	**Indirect method:** taking into account only the variations in cell temperature measured by a sensor.[21]
	Direct method: uses the link between the variables (I_{sc} or V_{oc}) and the approximate position of the MPP.[21]

II.3 Conclusion

This chapter has explored the different approaches to maximum power point tracking (MPPT) in photovoltaic systems, focusing on boost converters and conventional, metaheuristic, hybrid and intelligent MPPT techniques. Each method has distinct advantages and disadvantages, influencing their applicability in specific scenarios. The next chapter looks at two popular MPPT techniques, Perturb and Observe (P&O) and Particle Swarm Optimization (PSO), exploring their fundamental principles and implementation in a stand-alone PV system.

III. Chapter03: PSO and P&O Based MPPT Control Study and Simulation

This chapter focuses on two proposed control algorithms for maximum power point tracking (MPPT) in PV systems: Perturb and Observe (P&O) and Particle Swarm Optimization (PSO). It starts by presenting the fundamental principles of these methods, highlighting their crucial role in improving the performance of PV systems.

Secondly, it will explore the implementation of these algorithms in a stand-alone PV system simulated using MATLAB Simulink. This simulation will enable us to evaluate and compare their effectiveness and robustness under different conditions.

III.1 The proposed methods

III.1.1 Perturb and Observe method

III.1.1.1. The basic concept of the P&O algorithm

The P&O method is the most widely used due to its simplicity and ease of use. As its name suggests, this method works by disturbing the system and observing the impact on the power output of the GPV[22]. The number of perturbations made in one second is called the frequency of perturbation, which can also be called the frequency of the MPPT[14]. If we analyze the *Figure III.1.1.1*, if the operating voltage is disturbed in a specific direction, we will have the following situations:

- If the power increases and $\frac{dP}{dV} > \mathbf{0}$, the P & O algorithm will **continue** to perturb the voltage in the same direction (On the **left** of MPP)
- If the power decreases and $\frac{dP}{dV} < \mathbf{0}$, the P & O algorithm will **reverse** the direction (on the **right** of MPP)
- If $\frac{dP}{dV}$**=0**, it is the **MPP**

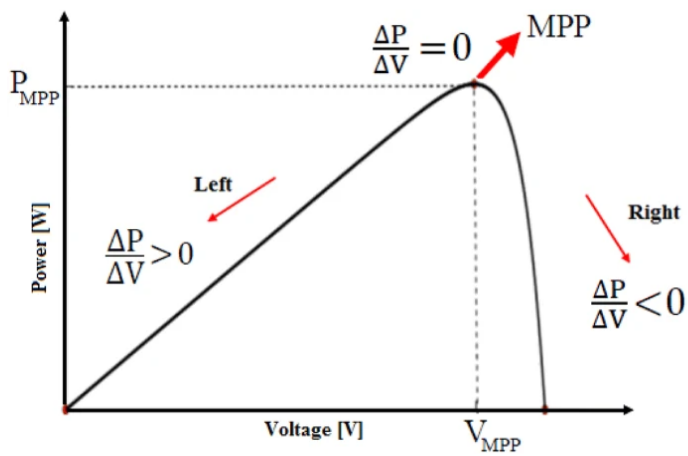


Figure ***Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.****:*
Graphical representation of the P&O method

III.1.1.2. Flow chart of the general P&O algorithm

P&O algorithm is summarized as follows:

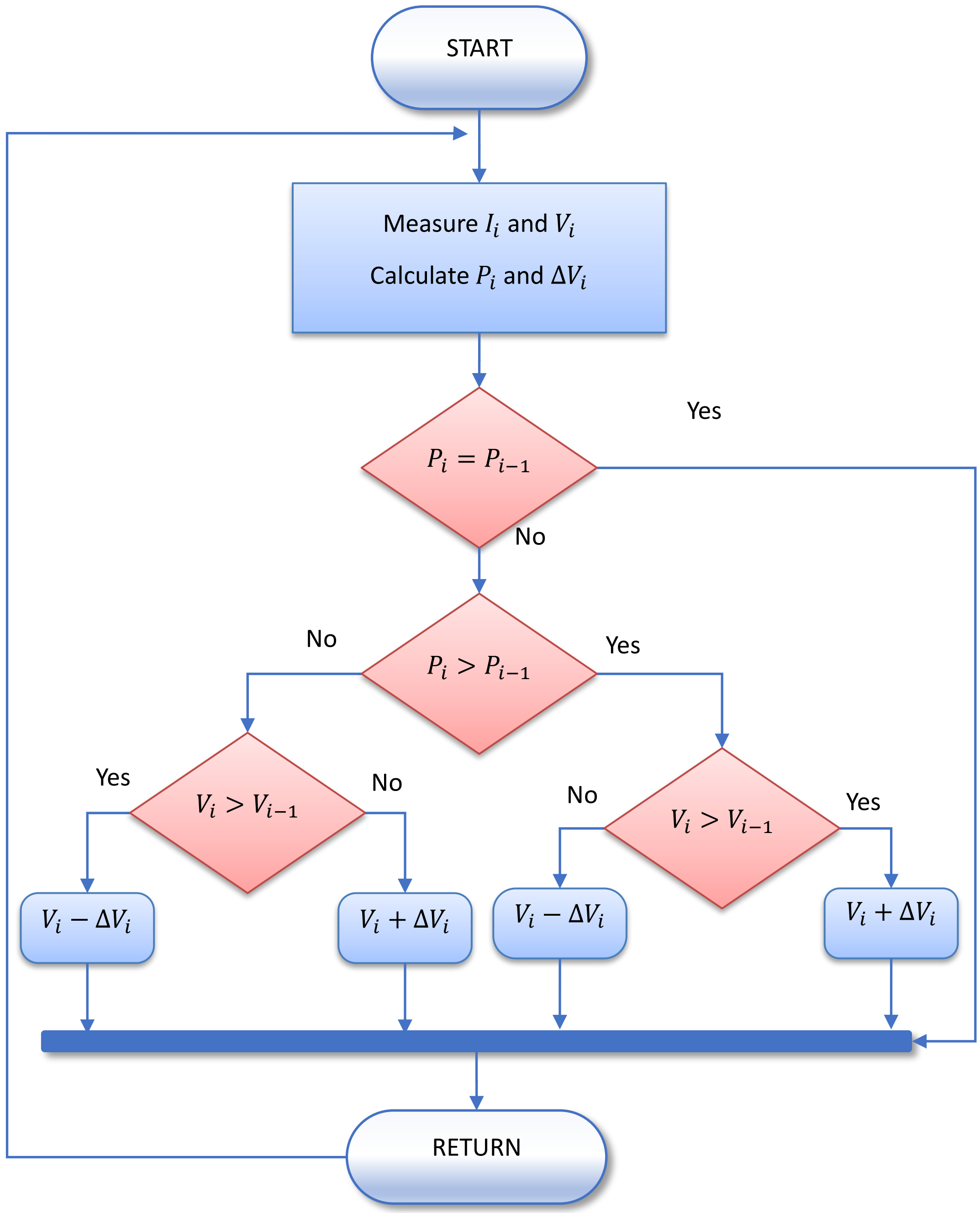


Figure ***Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.****: Flow chart of the P&O method*

III.1.2 Particle swarm optimization method

III.1.2.1. The basic concept of the PSO algorithm

Particle swarm optimization is a population-based swarm intelligence algorithm. It was initially proposed by Kennedy et al. to simulate the social behavior of social organisms such as bird flocking and fish schooling[23]. The PSO is used to solve some optimization problems; parameters called particles are used in the algorithm implementation, and each particle is defined by its position (P_i) (a solution) and its velocity (V_i). These particles are objects or entities randomly dispersed in the search space and searched for the best position to be optimized. Each particle controls its motion by combining the history of its current and previous best fitness locations with other groups or members of the swarm in random perturbation of the search space[24], the graphical representation is as follows:

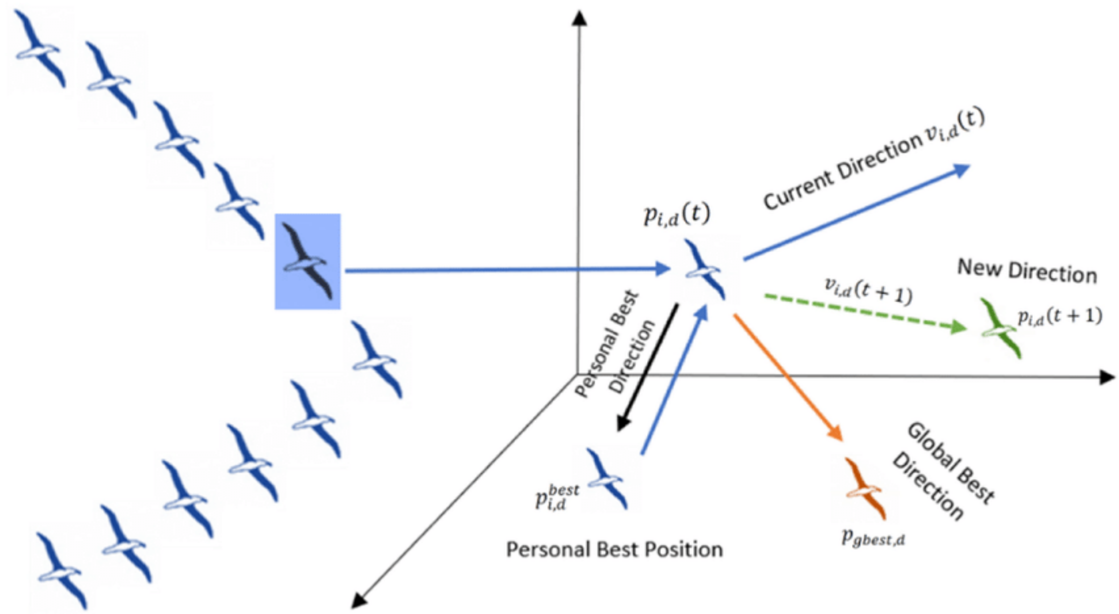


Figure ***Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.****: Graphical representation of the PSO method [28]*

III.1.2.2. The different steps of the PSO algorithm

In this study, we based on the following steps:

1) Defining the total number of particles and the maximum iteration number.

2) Declaration of persistent variables: These variables persist between function calls.

3) Initialization: If empty variables, they are initialized with default values (zeros or constants).

- P: Stores the power calculated for each particle (or population)
- D: Stores current duty cycle values for each particle (or population)
- velocity: Stores current velocities for each particle (or population)]
- current_dutycycl: Stores the current duty cycle for each particle (or population)
- current_power: Stores current power for each particle (or population)
- local_best_power: Stores the best local power for each particle (or population)
- local_best_dutycycl: Stores the best local duty cycle for each particle (or population)

- j / k: Counters for iterations and populations
- count: Global iteration counter
- global_best_power: Stores the best global power found
- globl_best_dutycycl: Stores the best global duty cycle found
- Initializing of W to 0

4) Initialization phase (W=0):

- Initialize current_dutycycl(i)
- Initialize velocity
- Calculate power
- Update best local and global results
- Setting of W to 1

5) Main **calculation phase (W=1):**

- **PSO algorithm parameters:**
  - **w:** Inertia factor
  - **c1, c2**: cognitive coefficient, social coefficient respectively
  - **R1, R2**: Random numbers between 0 and 1
  - Var_{min}: Minimum duty cycle limit
  - Var_{max}: maximum duty cycle limit
- **For each particle:**
  - **Calculating velocity:**

$$velocity(i) = w \times velocity(i) + c1 \times R1 \times (local\_best\_dutycycl(i) - current\_dutycycl(i)) + c2 \times R2 \times \left(global\_bes\_dutycycl(i) - current\_dutycycl(i)\right) \quad (2)$$

  - **Updating the duty cycle:**

$$current\_dutycycl(i) \; = \; current\_dutycycl(i) \; + velocity(i) \quad (3)$$

  - **Duty cycle limitation:**

$$current\_dutycycl(i) \; = max(min(current\_ dutycycl(i), VarMax), VarMin) \quad (4)$$

  - **Power calculation:**

$$P(i) = V_{PV} * I_{PV} \quad (5)$$

  - **Compare and update the best local and global results**

III.1.2.3. Flow chart of the general PSO algorithm

P SO algorithm is summarized as follows:

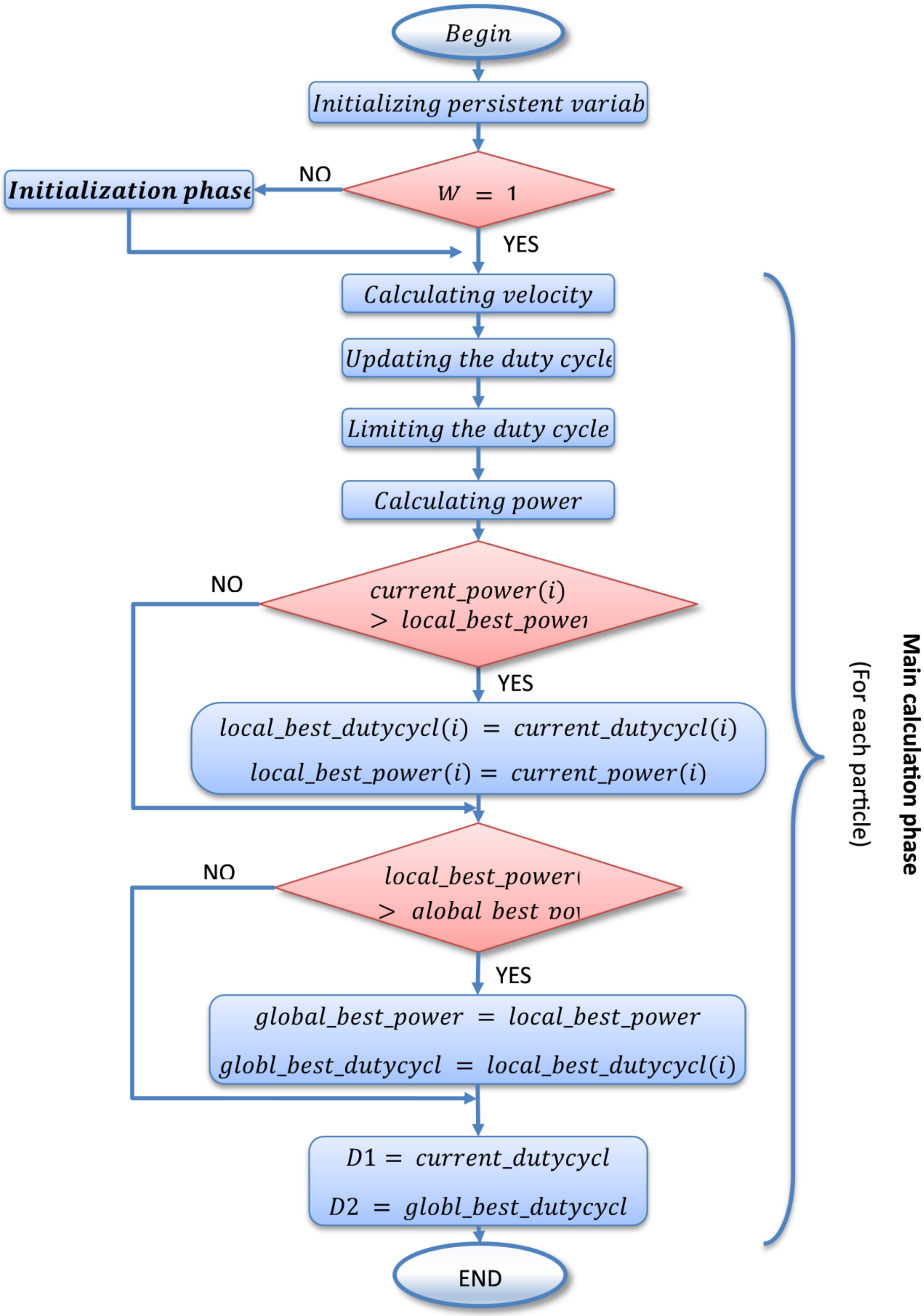


Figure ***Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.****: Flow chart of the PSO method*

III.2 Stand-alone system simulation

For this study, the simulation was carried out using MATLAB Simulink. The proposed photovoltaic system model consists of a 3x1 array, a boost converter, MPPT command block (PSO and P&O), and a resistive load.

III.3 MATLAB Simulink

MATLAB Simulink is a block diagram environment for multidomain simulation and Model-Based Design. It supports system-level design, simulation, automatic code generation, and continuous testing and verification of embedded systems. [29]

III.3.1 Model simulation

III.3.1.1. P&O model

The block diagram of the complete chain with MPPT controlled by the P&O method is shown in the following figure:

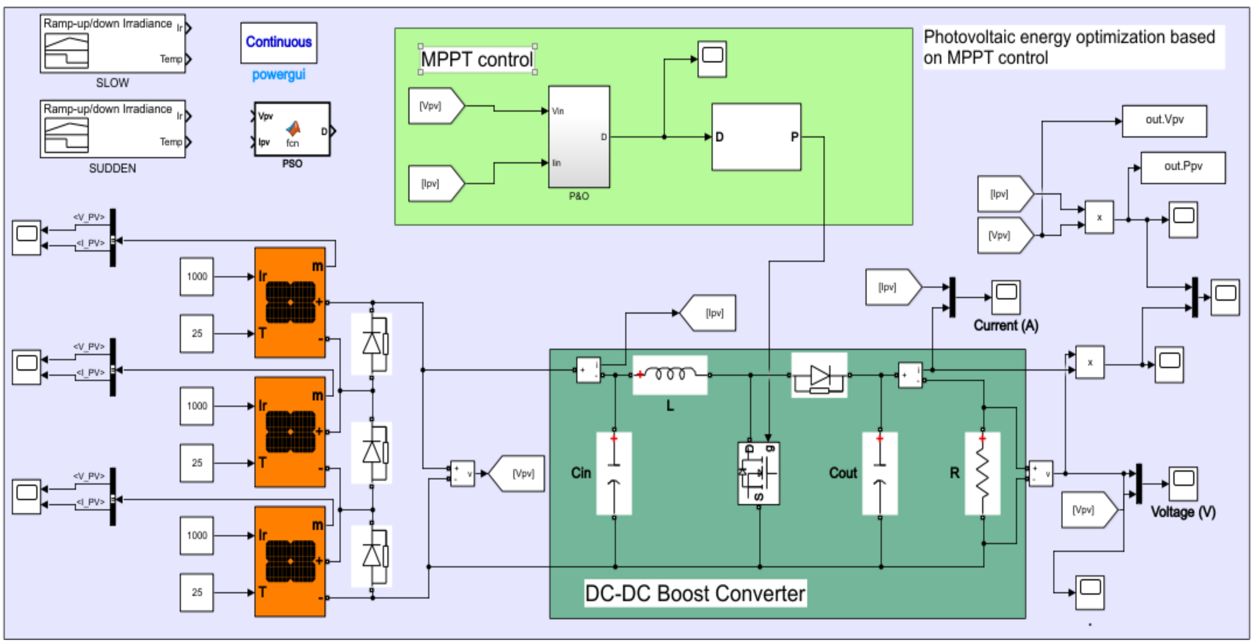


*Figure **Error! Use the Home tab to apply Titre 3 to the text that you want to appear here..**:*
Simulation of the stand-alone PV chain using the MPPT command P&O

III.3.1.2. PSO model

The block diagram of the complete chain with MPPT controlled by the PSO method is shown in the following figure:

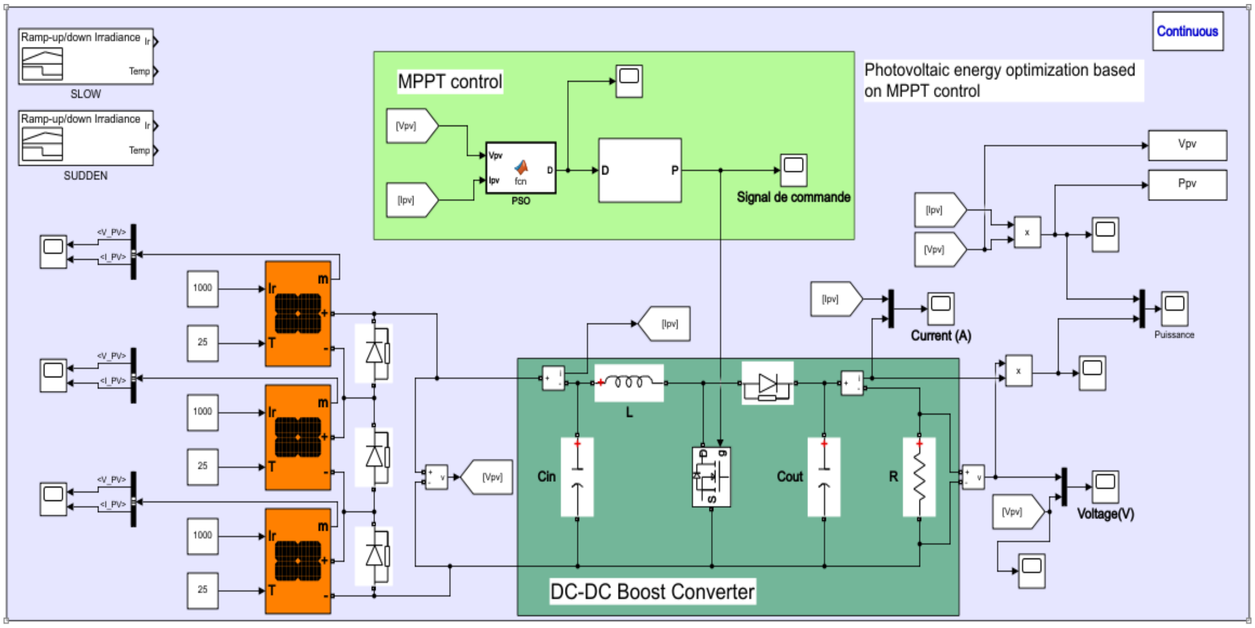


Figure ***Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.****.: Simulation of the stand-alone PV chain using the MPPT command PSO*

III.3.1.3. Identification of the parameters

To conduct this simulation, we will use the following parameter values:

Table ***Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.****.1: PV array parameters used in the simulation*

PV array	
Type of module	Yingli Energy (China) YL250P-29b
Number of series	8
Number of shunts	182
Number of modules	3 Series
Isc	8,79 A
Voc	38,4 V
Output power	$\sim$1,09 MW

Table ***Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.****.2: Boost converter parameters used in the simulation*

Boost converter

Cin/cout	$5000.10^{-6}\ F$
L	$1{,}875.10^{-6}\ H$
Diode	default setting
Mosfet	To be controlled by its duty cycle

*Table **Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.**.3: Load parameters used in the simulation*

Load parameters	
Resistive load	10 Ω

*Table **Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.**.4: P&O method parameters*

P&O algorithm parameters	
D_{max}	0,9
D_{min}	0,1
D_{init}	0,4
Delta D	10^{-3}

*Table **Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.**.5: PSO method parameters*

PSO algorithm parameters	
w	0,4
c1	0,8
C2	1,2
R1	0,25
R2	0,25
Var_{min}	0,4
Var_{max}	0,95
Count (number of iteration)	10
Number of populations	3

Comparison criteria

III.3.2 Speed

Speed is defined by the system's response time to an amplitude step, i.e. the time it takes for the system to reach saturation. The lower a system's response time, the faster it is. The *Figure III.4.1* shows the difference between a fast and a slow system:

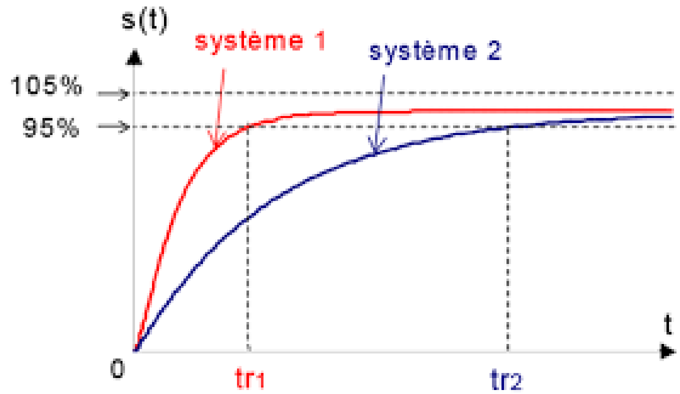


Figure ***Error! Use the Home tab to apply Titre 2 to the text that you want to appear here.****:*
Graphic representation of speed criteria [30]

III.3.3 Accuracy

The accuracy of a system response is the error it can make in order to reach more or less the exact theoretical value. It can be studied in terms of absolute or relative error. Absolute error is calculated by subtracting the absolute value of the exact value from the experimental value, while relative error is the quotient of absolute error and the exact value, which can be expressed as a percentage using the following equation:

$$Er = \frac{|approached\ value - theorical\ value|}{theorical\ value} \times 100 \qquad (6)$$

III.4 Conclusion

This chapter presents an overview of each method (PSO and P&O) used to find the MPP and summarizes their steps in flowcharts. To compare the performance of the two methods, a simulation of a stand-alone PV system with P&O and PSO MPPT was performed using MATLAB Simulink. The results and interpretation of the simulation results will be shown in the following chapter.

IV. Chapter04: Results and Discussion

A simulation of stand-alone PV string was prepared to compare the efficiency of a metaheuristic and classical method. The main objective of this chapter is to study the response of the two (02) methods presented in the previous one using a simulation block of the stand-alone PV system to determine the maximum power point MPP operating in different situations.

IV.1 PSO algorithm VS P&O algorithm

The algorithms are implemented as MATLAB functions to be called by the MPPT control simulation block. To study the performance of each algorithm according to two (02) comparison criteria (speed and accuracy), we will simulate the different MPPT methods in 4 different situations:

- ► Stable environnement (Irr=1000W/m2, T=25°C).
- ► Slow, linear change in irradiance.
- ► Sudden change in irradiance
- ► Partial shading (2 maximums in the P-V characteristic)

IV.1.1 Stable environment

In this part, an irradiance of 1000W/m2 and a temperature of 25°C were given as input for the panels.

IV.1.1.1. P-V characteristic

Under STC conditions, from the panel output power P_{pv} and the panel output voltage V_{pv} , it is possible to plot the power versus voltage obtaining the P-V characteristic shown in the following figure:

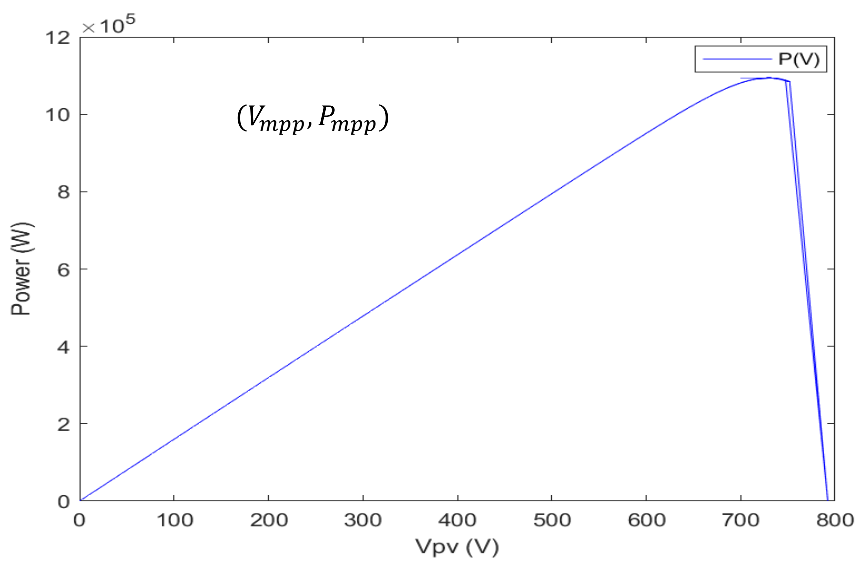


*Figure **Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.**: P(V) characteristic under STC conditions*

According to the figure above, the maximum output power P_{mpp} , equal to the power created by the panel under STC conditions, is obtained from the pair (V_{mpp}, I_{mpp}). One of the roles of the DC-DC converter is to ensure that this P_{mpp} is achieved through MPPT control.

IV.1.1.2. Criteria 1: Speed (response time)

To compare the response speed of the two (02) MPPT controls; PSO and P&O; under STC conditions, a zoom is made on the graph of the output power resulting from the simulation of the two methods which is illustrated in the following figure:

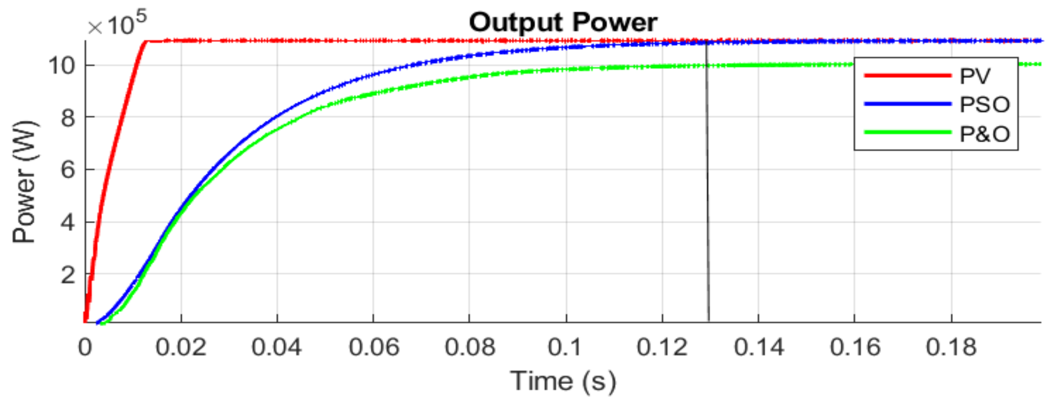


*Figure **Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.**: Curves representing the power Ppv, Ppso and Pp&o under STC conditions*

According to the figure above, the response time of the two methods until saturation is estimated at:

- **PSO:** $t1 \approx 0.13s$ with reaching the desired power.
- **P&O:** $t2 \approx 0.13s$ without reaching the desired power.

Both methods have approximately the same response time, but not the same response; the PSO method achieved the desired power, i.e., the power delivered under STC conditions. However, the P&O method was unable to achieve it.

IV.1.1.3. Criteria 2: Accuracy (relative error)

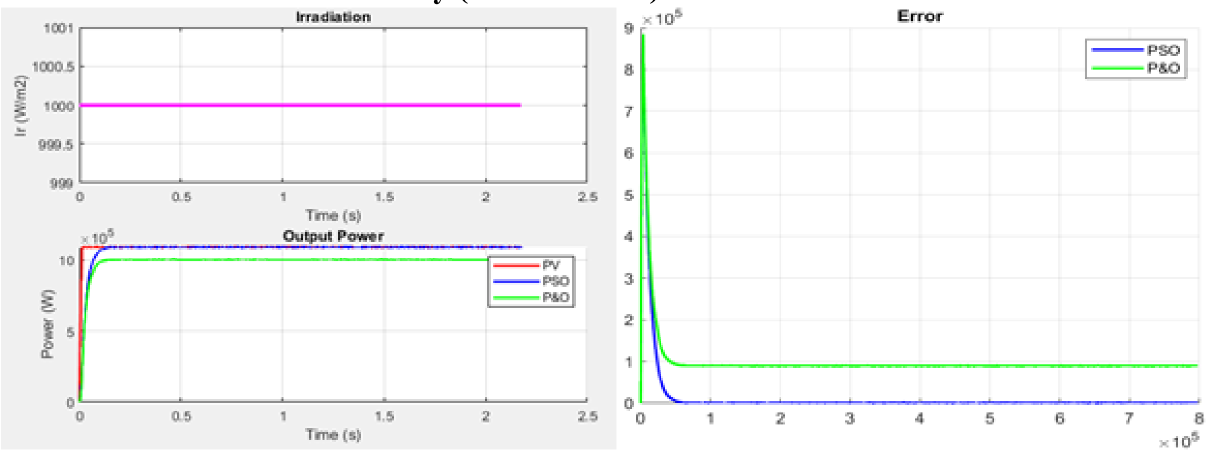


Figure ***Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.****:*
Curves representing the power Ppv, Ppso, P&O and the error under STC conditions

- **PSO:** With a relative error of $E_{r1} = \frac{|P_{pv} - P_{pso}|}{Ppv} = \mathbf{7.24\%}$
- **P&O:** With a relative error of $E_{r2} = \frac{|P_{pv} - P_{p\&o}|}{Ppv} = \mathbf{11.24\%}$

The PSO method has a smaller relative error than the P&O method under STC conditions, which means that the PSO method can achieve the desired power with a small margin compared to the P&O method.

IV.1.2 Slow, linear change in irradiance

In this part, an irradiance signal representing a linear change from 1000W/m2 to 600W/m2 and a slow change from 0.5s to 2s was given as input for the panels.

IV.1.2.1. Criteria 1: Speed (response time)

To compare the response speed of the two (02) MPPT controls; PSO and P&O; under a constant temperature of 25°C and a slow linear change in irradiance, a zoom is made on the graph of the output power resulting from the simulation of the two methods which is illustrated in the following figure:

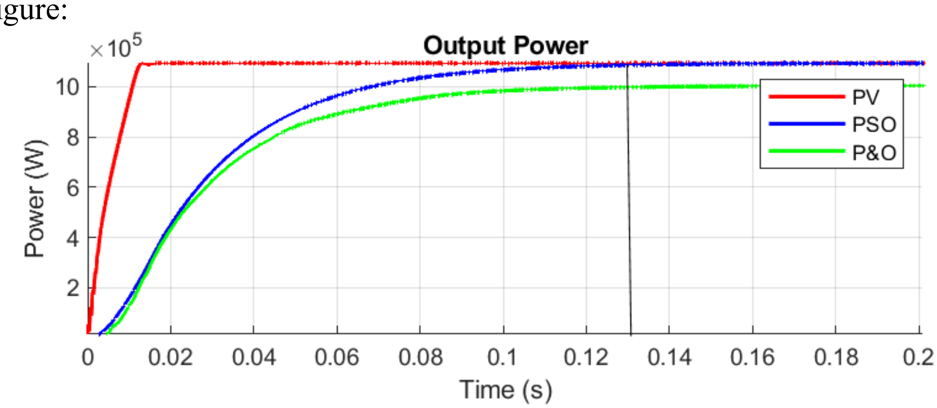


Figure ***Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.****:*
Curves representing the power Ppv, Ppso and Pp&o under slow linear change in irradiance

According to the figure above, the response time of the two methods until saturation is estimated at:

- **PSO:** $t1 \approx 0.13s$ with higher power output.
- **P&O:** $t2 \approx 0.13s$ with lower power output.

Both methods have approximately the same response time; but not the same response; the PSO method achieved a higher power than the P&O method when reaching the desired power, i.e., the power delivered by the panels under a slow linear change in irradiance. However, the P&O method was unable to get it.

IV.1.2.2. Criteria 2: Accuracy (relative error)

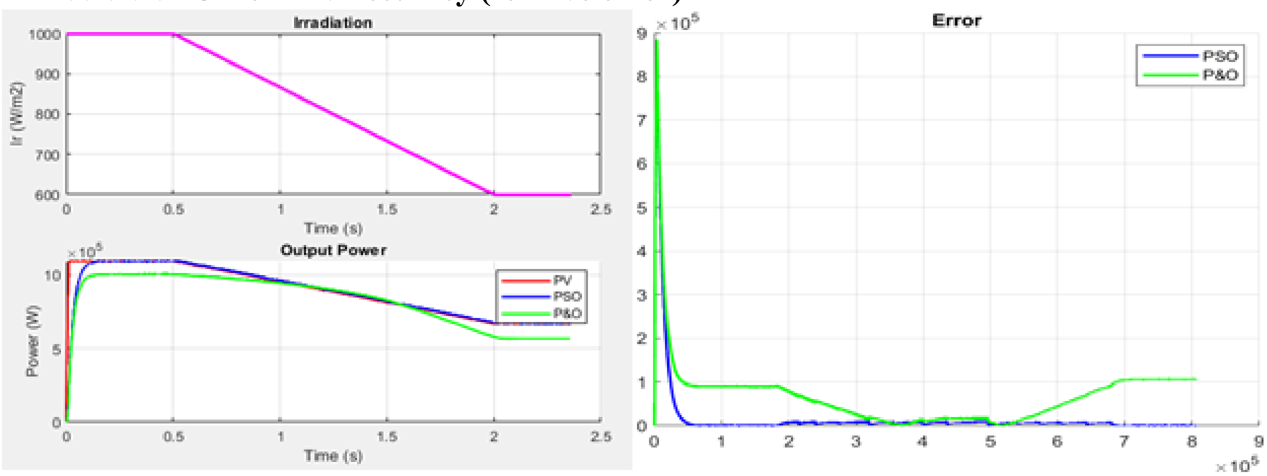


*Figure **Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.**:Curves representing the power Ppv, Pps, Pp&o and error under slow linear change in irradiance*

- **PSO:** With a relative error of $E_{r1} = \frac{|P_{pv} - P_{pso}|}{Ppv} = \mathbf{8.72}\%$
- **P&O:** With a relative error of $E_{r2} = \frac{|P_{pv} - P_{p\&o}|}{Ppv} = \mathbf{11.91}\%$

The PSO method has a smaller relative error than the P&O method under slow linear change in irradiance, which means that the PSO method can achieve the desired power with a small margin compared to the P&O method.

IV.1.3 Sudden change in irradiance

In this part, an irradiance signal representing a sudden change from 1000W/m2 to 600W/m2 from 0.5s to 0.6s was given as input for the panels.

IV.1.3.1. Criteria 1: Speed (response time)

To compare the response speed of the two (02) MPPT controls; PSO and P&O; under a constant temperature of 25°C and a sudden change in irradiance, a zoom is made on the graph of the output power resulting from the simulation of the two methods which is illustrated in the following figure:

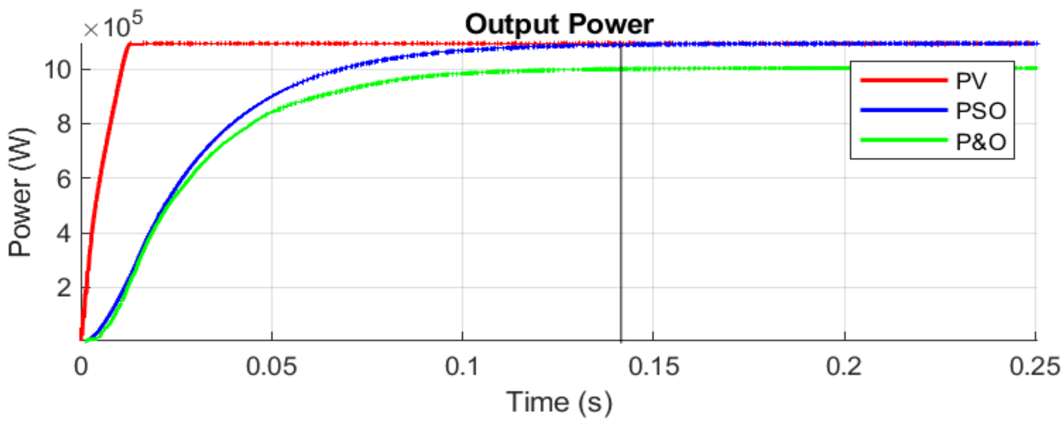


*Figure **Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.**:Curves representing the power Ppv, Ppso and Pp&o under sudden change irradiance*

According to the figure above, the response time of the two methods until saturation is estimated at:

- **PSO:** $t1 \approx 0.14s$ with higher power output.
- **P&O:** $t2 \approx 0.14s$ with lower power output.

Both methods have approximately the same response time, but not the same response; the PSO method achieved a higher power than the P&O method reaching the desired power, i.e., the power delivered by the panels under a slow linear change in irradiance. However, the P&O method was unable to get it.

IV.1.3.2. Criteria 2: Accuracy (relative error)

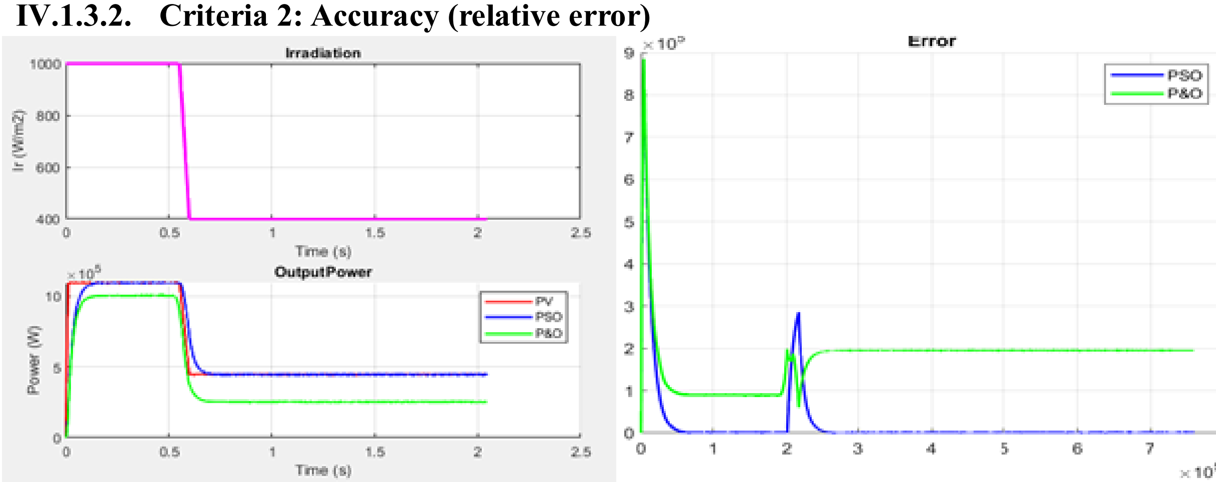


*Figure **Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.**: Curves representing the power Ppv, Ppso, Pp&o and the error under sudden change in irradiance*

- **PSO:** With a relative error of $E_{r1} = \frac{|P_{pv}-P_{pso}|}{Ppv} = \mathbf{12.88\%}$
- **P&O:** With a relative error of $E_{r2} = \frac{|P_{pv}-P_{p\&o}|}{Ppv} = \mathbf{28.08\%}$

The PSO method has a smaller relative error than the P&O method under STC conditions, which means that the PSO method can achieve the desired power with a small margin compared to the P&O method. Due to poor monitoring during this sudden change the P&O method has a slow convergence to the maximum power point

IV.1.4 Partial shading

In this part, to simulate partial shading, different irradiances were given to the different panels (3 PV array), as shown in the following table:

Table ***Error! Use the Home tab to apply Titre 2 to the text that you want to appear here.****: Partial shading parameters*

PV array number	Irradiance (W/m2)
1	1000
2	500
3	800

IV.1.4.1. P-V characteristic

Under partial shading conditions [1000W/m2 800W/m2 500W/m2], from the panel output power P_{pv} and the panel output voltage V_{pv} , it is possible to plot the power versus voltage obtaining the P-V characteristic shown in the following figure:

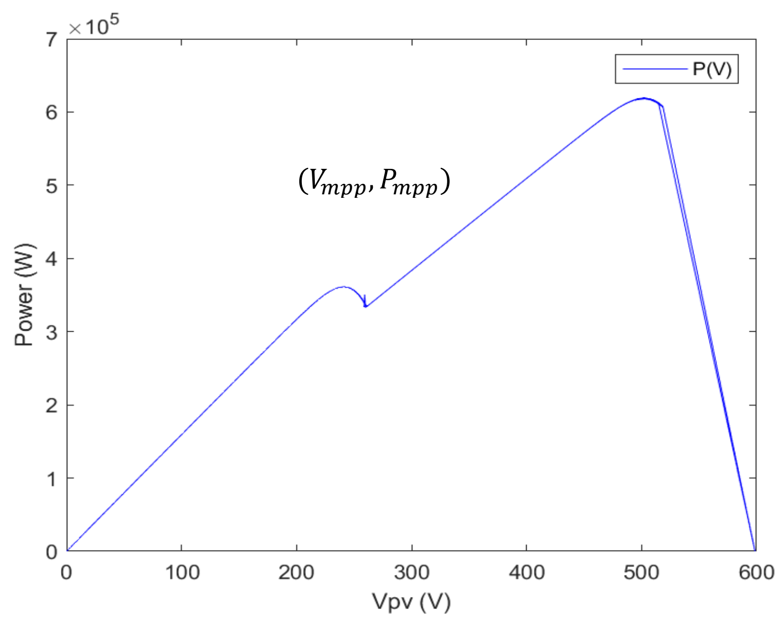


Figure ***Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.****: P(V) characteristic under partial shading*

According to the figure above, two (02) maximum output power is due to partial shading conditions. One of the roles of the DC-DC converter is to ensure that the global power is achieved through MPPT control.

IV.1.4.2. Criteria 1: Speed (response time)

To compare the response speed of the two (02) MPPT controls, PSO and P&O, under a constant temperature of 25°C and a change in irradiance (partial shading), a zoom is made on the graph of the output power resulting from the simulation of the two methods which is illustrated in the following figure:

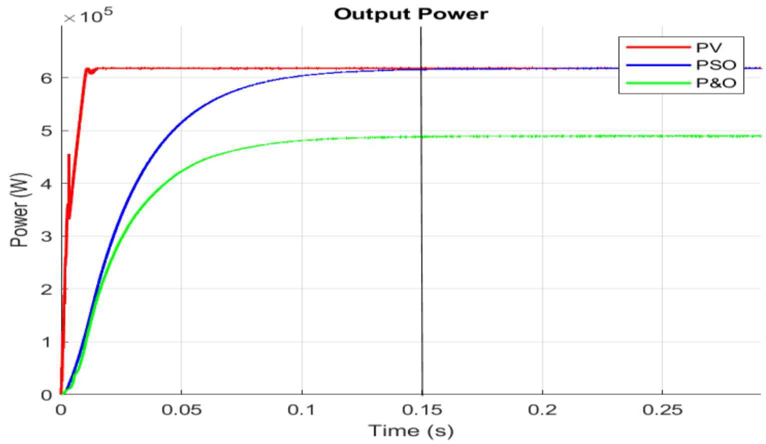


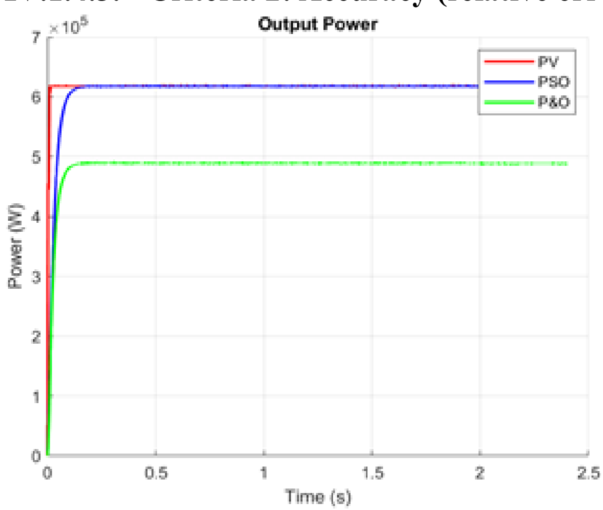
*Figure **Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.**: Curves representing the power Ppv, Ppso and Pp&o under sudden change in irradiance*

According to the figure above, the response time of the two methods until saturation is estimated at:

- **PSO:** $t1 \approx 0.15s$ with reaching the desired power.
- **P&O:** $t2 \approx 0.15s$ without reaching the desired power.

Both methods have approximately the same response time; but not the same response; the PSO method achieved the desired power, i.e., the power delivered under partial shading conditions. However, the P&O method was unable to achieve it.

IV.1.4.3. Criteria 2: Accuracy (relative error)



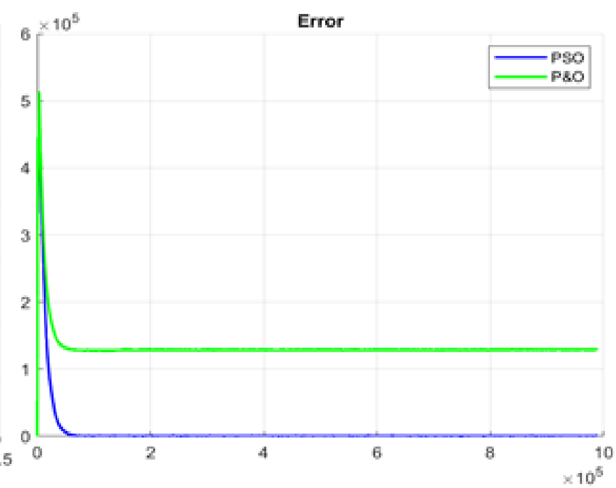


*Figure **Error! Use the Home tab to apply Titre 3 to the text that you want to appear here.**: Curves representing the power Ppv, Ppso, Pp&o and error under partial shading*

- **PSO:** With a relative error of $E_{r1} = \frac{|P_{pv} - P_{pso}|}{Ppv} = \mathbf{6.92}\%$
- **P&O:** With a relative error of $E_{r2} = \frac{|P_{pv} - P_{p\&o}|}{Ppv} = \mathbf{22.14}\%$

The PSO method has a smaller relative error than the P&O method under partial shading conditions, which means that the PSO method can achieve the desired power with a large margin compared to the P&O method.

IV.1.5 Other case of partial shading

In this part, to simulate other case of partial shading, a variable irradiance signal has been applied to the panels (3 PV array), as shown in the following figure:

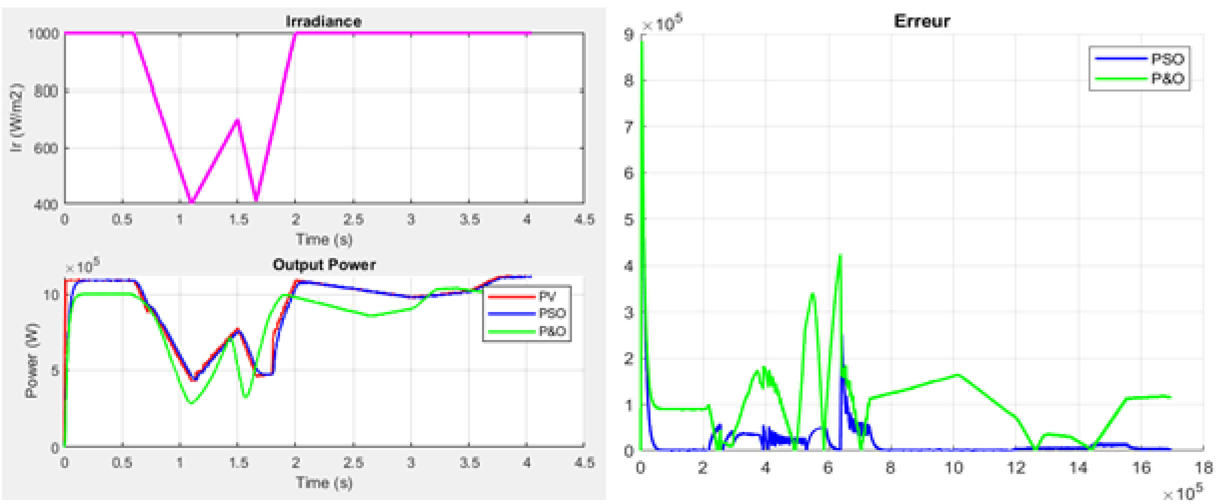


Figure ***Error! Use the Home tab to apply Titre 2 to the text that you want to appear here.****:*
Curves representing the power Ppv, Ppso, Pp&o and error under partial shading

In the context of partial shading conditions, the Particle Swarm Optimization (PSO) algorithm demonstrates superior performance over the Perturb and Observe (P&O) algorithm for a photovoltaic (PV) system with a large margin of error:

- **PSO:** With a relative error of $E_{r1} = \mathbf{6.30}\%$
- **P&O:** With a relative error of $E_{r2} = \mathbf{13.26}\%$

As shown in the comparative graph, the PSO algorithm maintains a more stable and higher output power despite the fluctuating irradiance, effectively tracking the global maximum power point (GMPP). In contrast, the P&O algorithm exhibits greater instability and struggles to efficiently manage the multiple peaks in the power-voltage (P-V) curve caused by partial shading, resulting in reduced power output. This highlights the effectiveness of PSO in enhancing the efficiency and reliability of PV systems under non-uniform shading conditions.

IV.2 Conclusion

In this chapter, the MPPT control algorithm based on the particle swarm optimization technique and the perturb and observe technique has been developed according to previously defined situations. The two methods generate a proportional relationship between changes in power and irradiance. In different conditions, the PSO method always shows a minor error compared to the

P&O method but with approximately the same response time. Under partial shading, the metaheuristic PSO method, which can reach the global maximum power point[31], presents a better response than the classic P&O method, which always converges towards the first optimum it encounters.[32]

General conclusion

This master's thesis has explored the comparative performance of two prominent Maximum Power Point Tracking (MPPT) techniques used in photovoltaic (PV) systems: the classical Perturb and Observe (P& O) method and the metaheuristic Particle Swarm Optimization (PSO) method. This study aimed to identify which technique offers better performance in terms of efficiency, reliability, and adaptability to varying environmental conditions, ultimately contributing to improving PV system operations. The study began with a thorough review of PV system fundamentals, emphasizing the importance of optimizing energy conversion due to the impact of factors such as irradiance and temperature. The necessity of MPPT techniques in maximizing the efficiency of PV systems was underscored, highlighting their role in adjusting the system to operate at its optimal power point.

The P&O method is known for its simplicity and ease of implementation, making it widely used. However, it has limitations, particularly under rapidly changing environmental conditions. In contrast, the PSO method, inspired by the social behavior of organisms like birds and fish, offers a more complex but potentially more practical approach by improving a population of solutions to find the optimal power point.

Using MATLAB Simulink, both methods were implemented and tested under various conditions, including stable environments, slow and sudden changes in irradiance, and partial shading. The simulation results provided a clear comparison of their performance. The PSO method consistently outperformed the P&O method in terms of accuracy and efficiency, particularly in dynamic conditions where the P&O method struggled to achieve the desired maximum power point. However, the P&O method, with its simplicity and lower computational requirements, still presents a viable option for more stable applications.

This thesis has demonstrated that while the PSO method offers significant advantages in accuracy and adaptability, the P&O method remains useful for more straightforward, more stable environments. The insights gained from this study can guide the selection of MPPT techniques for different PV system applications, balancing complexity and performance.
Future work could explore hybrid MPPT approaches that combine the strengths of both P&O and PSO methods, potentially offering a balance between simplicity, efficiency and rapidity, further optimization of the PSO method to reduce its computational complexity could enhance its practical applicability

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