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Sliding Mode MPPT Controller for Photovoltaic Systems: Performance, Efficiency and Stability Analysis

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Dedication

الحمد لله حمدا كثيرا مباركا فيه، ما سلكنا البدايات إلا بتيسيره، وما بلغنا النهايات إلا بتوفيقه،

أتقدم بإهداء ثمرة جهدي وتعبي إلى من دعموني بلا حدود بحب غير مشروط، إلى من يستمعان إلى ثرثرتي حول تخصصي الذي لا يفقهان فيه شيئا غير اسمه ورغم ذلك يظهران كل الاهتمام، إلى الغاليين على قلبي **أمي وأبي،**

إلى من تسعد عيني برؤية وجهيهما ويفرح فؤادي بسماع رنات ضحكاتهما، إلى من يعيد البسمة على محيّاي إذا ضاقت بي، إليكما يا **أختي وأخي،**

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إلى كل من ساعدني وقدم لي يد العون من قريب أو بعيد في إتمام دراسة سائلة المولى عز وجل أن يجزي الجميع خير الجزاء في الدنيا والآخرة،

وآخر دعوانا أن الحمد لله رب العالمين

CHEURFI Ghada Imane

Dedication

الحمد لله الذي ما تم جهد ولا ختم سعي إلا بفضله الحمد لله الذي وفقنا لتثمين هذه الخطوة في مسيرتنا الدراسية بمذكرتنا

هذه ثمرة الجهد والنجاح بفضله تعالى. وما تخطى العبد من عقبات وصعوبات إلا بتوفيقه

وتعبيرا عن امتناني، أكرس هذا العمل المتواضع لأولئك الذين، مهما كانت الكلمات، لن تتمكن أبداً من التعبير عن حبي

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لأمي الحبيبة وأبي العزيز الكريمين حفظهما الله وادامهما نورا لدربي، اللذين دعماني وشجعاني طوال السنوات الخمس

هذه من الدراسة.

الى العائلة الكريمة التي كانت السند ولا تزال من اخوة واخوات.

الى رفيقات المشوار اللاتي قاسمتني لحظاته رعاهم الله ووفقهم.

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BACHIRI Asma

Abstract

Solar technologies are developing as a possible answer for meeting the rising need for sustainable energy, turning solar energy directly into electricity.

However, the efficiency and profitability of solar power systems are dependent on their capacity to properly absorb and convert solar energy, which is difficult owing to the nonlinear nature of solar generators and the fluctuation of weather conditions. Effective management of this energy source necessitates major technological breakthroughs, particularly in energy conversion and storage.

This emphasizes the crucial necessity of the maximum power point (MPPT), which improves solar panel performance by continually modifying the operating point in response to environmental fluctuations to maximize energy output. In this context, this work proposes a robust MPPT technique using a double integral sliding mode controller (DISMC) for a stand-alone photovoltaic system, whose aim is to design a new sliding surface to improve the transient response and reach MPP quickly under varying conditions. Modeling of the stand-alone photovoltaic system and simulations were carried out using Matlab/Simulink.

Keywords: Photovoltaic, Boost, maximize, Power, Sliding mode, irradiation, MPPT.

Résumé

Les technologies solaires apparaissent comme une solution prometteuse pour répondre à la demande croissante d'énergie propre en convertissant directement l'énergie solaire en électricité.

Cependant, l'efficacité et la rentabilité des systèmes photovoltaïques dépendent de leur capacité à capter et convertir l'énergie solaire de manière optimale, ce qui est un défi en raison de la nature non linéaire des générateurs photovoltaïques et de la variation des conditions climatiques. La gestion optimale de cette source d'énergie nécessite des avancées technologiques significatives, notamment en matière de conversion et de gestion de l'énergie.

C'est là que réside l'importance cruciale du point de puissance maximale (MPPT), qui optimise les performances des panneaux solaires en ajustant continuellement leur point de fonctionnement selon les variations environnementales pour maximiser la production d'énergie. Dans ce contexte, ce travail propose une technique MPPT robuste utilisant un contrôleur mode glissant à double intégral (DISMC) pour un système photovoltaïque autonome, dont le but est de concevoir une nouvelle surface de glissement pour améliorer la réponse transitoire et d'atteindre le MPP rapidement sous l’effet de différentes variantes. La modélisation du système photovoltaïque autonome et les simulations ont été réalisées à l'aide de MATLAB/Simulink.

Mots-clés : Photovoltaïque, Boost, Maximiser, Puissance, mode glissant, irradiation, MPPT.

ملخص

يعد الدمج المتزايد للطاقات المتجددة في شبكات الكهرباء في العالم ركيزة أساسية في الانتقال إلى مستقبل طاقوي مستدام. وفي الجزائر، تزداد وتيرة هذا التحول بفضل المبادرات الهادفة إلى إدماج الطاقات المتجددة، لا سيما من خلال مشاريع الطاقة الشمسية الكهروضوئية الرائدة. تبرز تكنولوجيات الطاقة الشمسية كحل واعد لتلبية الطلب المتزايد على الطاقة النظيفة من خلال تحويل الطاقة الشمسية مباشرة إلى كهرباء.

ومع ذلك، فإن كفاءة ومردودية الأنظمة الكهروضوئية تعتمد على قدرتها على التقاط الطاقة الشمسية وتحويلها على النحو الأمثل، وهو ما يمثل تحديًا بسبب الطبيعة غير الخطية للمولدات الكهروضوئية والتباين في الظروف المناخية. وتتطلب الإدارة المثلى لمصدر الطاقة هذا تقدماً تكنولوجياً كبيراً، لا سيما في مجال تحويل الطاقة وإدارتها.

وهنا تكمن الأهمية الحاسمة لنقطة الطاقة القصوى (MPPT)، التي تعمل على تحسين أداء الألواح الشمسية من خلال تعديل نقطة تشغيلها باستمرار وفقًا للتغيرات البيئية من أجل زيادة إنتاج الطاقة إلى أقصى حد.

في هذا السياق، يقترح هذا العمل تقنية MPPT قوية باستخدام وحدة تحكم في الوضع المنزلق المزدوج المتكامل (DISMC) لنظام كهروضوئي مستقل، والتي تهدف إلى تصميم سطح منزلق جديد لتحسين الاستجابة العابرة والوصول إلى نقطة الانزلاق بسرعة تحت تأثير ظروف متغيرة. تم إجراء نمذجة النظام الكهروضوئي المستقل وعمليات المحاكاة باستخدام Matlab/Simulink

كلمات مفتاحية: الخلايا الكهروضوئية، التعزيز، التعظيم، الطاقة، الوضع المنزلق، الإشعاع، MPPT.

Table of abbreviations

PV	Photovoltaic
GPV	Photovoltaic Generator
I_{sc}	Short Circuit Current
V_{oc}	Open Circuit Voltage
P_{max}	Maximum Power (W)
V_{pv}	Voltage generated by the panel
I_{pv}	Current generated by the panel
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
V_{mpp}	Voltage of the PV module at the Maximum Power Point
I_{mpp}	Current of the PV module at the Maximum Power Point
SMC	Sliding Mode Control
DISMC	Double Integration Sliding Mode Control
P&O	Perturb and observe

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General introduction

Renewable energies play an important role in the global energy transition because of their ability to reduce dependence on fossil fuels and reduce greenhouse gas emissions. Among these energy sources, photovoltaic (PV) energy has gained in popularity due to its abundant availability, non-polluting nature, and falling production costs. Many nations, including Algeria, have adopted strategies to generate energy from alternative sources, as outlined in the National Renewable Energy Program 2011-2030.

Renewable energies are a key component of Algeria's energy and economic strategies, particularly through the large-scale development of solar energy. Modern technologies have made it possible to set up and use these solar power plants. One of these advanced technologies is maximum power point tracking (MPPT).

Maximum Power Point Tracking (MPPT) is an essential technique for regulating the operation of PV panels and aims to continuously adjust the operating point of the PV array to maximize its power output. This technology is particularly important as photovoltaic systems are exposed to rapid and unpredictable variations in solar irradiance and temperature, which can impact their efficiency and stability.
A variety of MPPT algorithms exist each with its advantages and disadvantages, starting with conventional methods such as Perturb and Observe (P&O) and Incremental Conductance (INC) that have long dominated the MPPT field, but they present limitations in terms of rapid convergence and robustness in the face of complex environmental variations. To overcome these challenges, more advanced solutions such as the Sliding mode controller and especially Double Integral Sliding Mode (DISMC) algorithms have been developed.

Sliding Mode Control (SMC) is a robust control technique well suited to non-linear and uncertain systems such as photovoltaics systems. SMC offers several advantages, including increased robustness to disturbances and parameter variations, and simplicity of design. However, traditional SMC has certain drawbacks, such as the phenomenon of chattering, which can lead to undesirable oscillations and premature wear of system components. To overcome these limitations, variants of the SMC have been developed, among which the Double Integrated Sliding Mode Controller (DISMC) stands out for its ability to reduce steady-state errors and mitigate chattering, often encountered with traditional techniques.

This thesis proposes to explore and develop an MPPT method based on double integrated sliding mode controller.

The purpose of this thesis is to investigate and develop a Maximum Power Point Tracking (MPPT) method using a double integration sliding mode controller. This will involve studying the Double Integral Sliding Mode Controller (DISMC) for photovoltaic systems, creating a mathematical model of the photovoltaic system to use as a basis for controller design and analysis, simulating the proposed model in the MATLAB/Simulink environment, and analyzing the results to determine the advantages and limitations of the proposed method.

This thesis is structured into four chapters, each addressing a specific aspect of the research, starting with the first chapter, which serves as a literature review of MPPT for PV systems, double integrated sliding mode control, and related work, with a justification of the choice of the double integrated sliding mode.

The second chapter is devoted to the presentation of the mathematical model of the PV system and the theoretical design of the double-integrated sliding mode controller (DISMC), explaining the fundamental principles of this approach.

In the third chapter, the DISMC controller is implemented and simulated in MATLAB/Simulink under various scenarios to evaluate the performance of the DISMC in terms of robustness, stability, and efficiency.

The fourth chapter is dedicated to the analysis and interpretation of the simulation results. It compares the results of DISMC with those of other control techniques, highlighting its advantages and limitations. The practical implications of the results are also discussed, and suggestions for further research are offered.

I. Chapter01: Solar Photovoltaic Energy

On a global scale, solar photovoltaic (PV) energy has not just emerged, but has firmly established itself as a vital component of sustainable energy solutions. The significant improvements in solar technology, driven by the growing global demand for clean and renewable energy sources, have made it more accessible and efficient. This chapter delves into the fundamentals of solar photovoltaic energy, including the photovoltaic effect, the different types of solar panels, and the variables and factors affecting their performance. It also underscores the crucial role of an adaptation phase in maximizing the dependability and efficiency of solar energy systems, thereby emphasizing the global impact of the audience's work in this field.

I.1. Photovoltaic Energy and Power Generation Principle

Photovoltaic energy converts light into electricity using semiconducting materials exhibiting photovoltaic effects. This process is the physical basis for converting light energy into electricity in solar cells, an important clean energy source.[2]

During photon-electron interaction in a photovoltaic cell, the photon's energy causes the separation of an electron from a silicon atom, generating opposite electrical charges and the photovoltaic effect. The negatively charged electrons move to the N-zone, while the positively charged atoms migrate to the P-zone, creating an electrical voltage between the two zones. Conventional current flows from zone N to zone P, following the electric field. When a photon encounters an electron in the space charge zone, it causes the electron to separate from the atom, generating a direct current flow, with the positively charged atoms moving toward the N zone and the electrons toward the P zone.

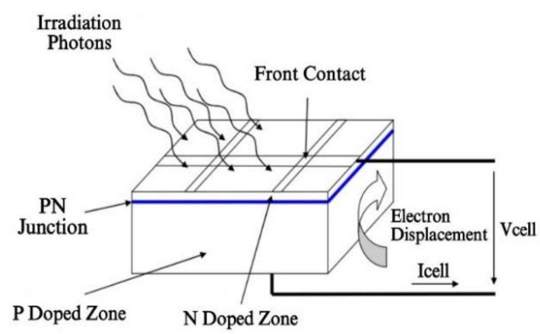

Figure 1: Transversal cut of a typical PV cell

I.2. Types of solar photovoltaic panels

The different types of PV panels are shown in the following table:

Table 1: Types of PV panels

Type	Description	Color	Efficiency	Application

Monocrystalline 	• Made from a single pure crystal of silicon. • highly efficient • More expensive to produce.	Black or dark blue	15-22%	• Residential commercial rooftops
Polycrystalline 	• Made from silicon crystals melted together. • Less uniform appearance.	Blue with a mottled appearance	13-18%	• Residential commercial rooftops
Thin-Film (Amorphous Silicon) 	• Uses silicon in non-crystalline forms deposited on a substrate.	Dark grey to almost black	10-13%	• Large-scale installations, portable applications

I.3. Factors affecting the performance of PV panels

I.3.1. Influence of external parameters on a PV cell

I.3.1.1. Influence of the Irradiation

Irradiance is the parameter that most influences the performance of the PV panel. There is a proportional relationship between irradiance and photon-generated current, significantly affecting the short-circuit current (ISC) of the (V-I) characteristic curve. As irradiance increases, leading to a higher ISC. This consequently increases the overall power output of the PV panel.

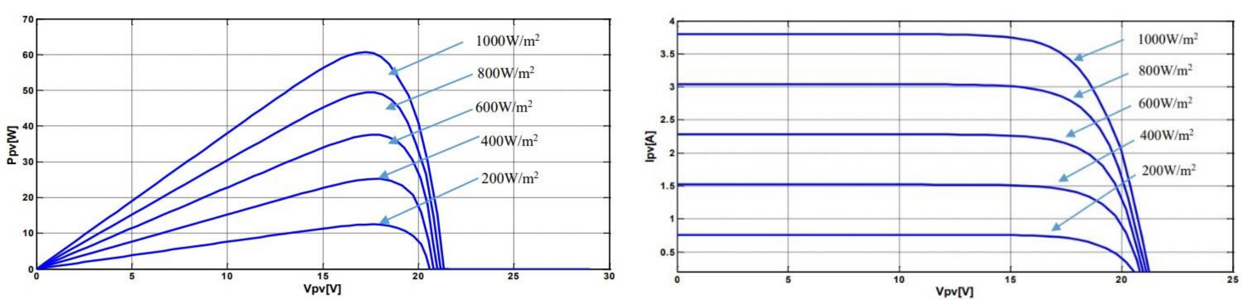

Figure 2: (P/V) and (I/V) characteristics of solar panel for canstant temperature and variable irradiation

I.3.1.2. Influence of the Temperature

Temperature is a critical parameter in the operation of photovoltaic panels because the electrical properties of a semiconductor are susceptible to temperature variations. An increase in temperature harms the open-circuit voltage V_{oc}. V_{oc} dramatically drops with the temperature increase, resulting in a decrease in total power output.

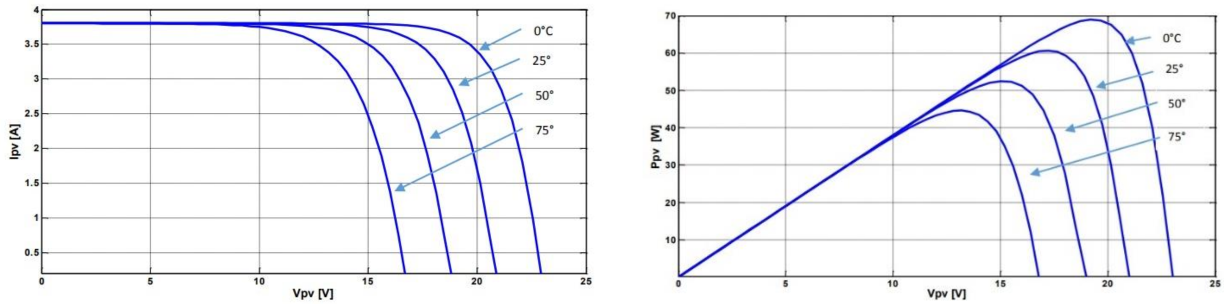

Figure 3:(P/V) and (I/V) characteristics of solar panel for variable temperature and constant irradiation

I.3.2. Influence of internal parameters on a PV cell

I.3.2.1. Influence of series resistance (R_s)

Series resistance is the cell's internal resistance; it does not affect I_{cc} or V_{oc} but it does cause a decrease in the slope of the (I-V) and (I-P) curves near the area where the panel operates as a voltage source. The value of (R_s) has a negative effect on power; as series resistance increases, power will decrease.

I.3.2.2. Influence of shunt resistance (R_{sh})

The shunt resistance represents part of the leakage current losses. As R_p decreases, the V_{oc} voltage decreases, as does the slope of the (I-V) and (I-P) curves.

An adaptation stage is necessary to address the variability in performance due to these factors. This stage involves monitoring and adjusting the system to optimize efficiency under different conditions. The modules' electrical operating point is continuously adjusted by the MPPT controller to guarantee that, in a variety of scenarios, they function at their MPP.

I.4. Conclusion

The implementation of MPPT is not just a recommendation, but a necessity to maximize the performance and efficiency of solar PV systems. The optimization of solar energy conversion requires a deep understanding of the maximum power point tracking techniques, different types of controllers, and the MPPT principle. Each MPPT method has its own set of benefits and drawbacks, and the best approach will depend on the specific needs of the system and the surrounding circumstances. This chapter will provide an up-to-date overview of MPPT technology, highlighting the most recent developments, patterns in research, and inventions in the area, thereby emphasizing the importance of the audience's research in this crucial area.

II. Chapter02: State of the art

The importance of photovoltaic (PV) systems in producing renewable energy has sparked a wave of research into optimizing their performance. Among these techniques, Sliding Mode Control (SMC) for Maximum Power Point Tracking (MPPT) has emerged as a robust and effective method, thanks to its ability to handle system nonlinearities and uncertainties. This chapter reviews the recent advances and the various approaches adopted to implement SMC in PV systems, thereby highlighting the exciting progress in the field and the audience's role in it.

II.1.Basic principle of MPPT Controller

MPPT, a maximum efficiency tracker, is a technique used in photovoltaic systems to maximize the power extracted from solar panels. The basic principle of an MPPT controller is to place the system at the maximum operating point (V_{mpp} andI_{mpp}) regardless of weather conditions. [3]

MPPT control varies the duty cycle of the static converter, using an adapted electrical signal to extract the maximum power that the GPV can deliver. Generally, it is based on the variation of the static converter duty cycle as a function of the evolution of its input parameters (I and V, and consequently of the GPV power) until it reaches the MPP. [3] [1]

II.2.Classification of the MPPT Controllers

II.2.1. Classification of the MPPT Controls according to input parameters

II.2.1.1. MPPT controllers based on the input parameters of static converter

Several MPPT controllers track the MPP according to the variation of the power delivered by the GPV. These algorithms use the value of the energy generated by the GPV to apply an appropriate control action to monitor the MPP. The advantages of all these controls are their precision and speed of reaction. [1]

II.2.1.2. MPPT controllers based on the output parameters of static converter

In the literature, there are also algorithms based on the output parameters of static converters. In all systems using output parameters, P_{max} is approximated by the converter efficiency. In short, the better the converter stage, the more valid this approximation. In general, however, all single-sensor systems need to be more accurate. [1]

II.2.2. Classification of the MPPT Controllers by search type

II.2.2.1. Indirect MPPT

This type of MPPT controller uses the link between measured variables (V_{oc} andI_{sc}), which can be easily determined, and the approximate position of the MPP. These controllers have the advantage of being simple to implement. [4]

II.2.2.2. Direct MPPT

This type of MPPT control determines the optimum operating point (MPP) from the currents, voltages, or powers measured in the system. The maximum power curve is determined without interrupting operation, and to achieve this, the operating point voltage is incremented at regular intervals. If the output power is more significant, the search direction is maintained for the next step. Otherwise, it is reversed. The actual operating point then oscillates around the MPP. [4]

II.3.Classic MPPT Techniques

II.3.1. Perturb & Observe (P&O) Method

The principle of this command is to generate perturbation by reducing or increasing the duty cycle D and to observe the effect on the power delivered by the PV generator; if, following a voltage perturbation, PV power increases, the perturbation direction is maintained. Otherwise, it is reversed to resume convergence towards the new MPP.

- If $\frac{dP_{PV}}{dV_{PV}} > 0$ increases the voltage, this induces an increase in the duty cycle.

$$D\ (k)\ = D\ (k-1) + \Delta D.\Delta D$$

- If $\frac{dV_{PV}}{dV_{PV}} < 0$, the voltage is reduced, which means a decrease in the duty cycle.

$$D\ (k)\ = D\ (k-1) - \Delta D$$

II.3.2. Incremental Conductance method

The INC algorithm detects the slope of the P-V curve and tracks the MPP by searching the peak of the P-V curve. It uses the instantaneous conductance I/V and the incremental conductance $\frac{dI}{dV}$ for MPPT.[5]

$$\frac{\boldsymbol{dP_{pv}}}{\boldsymbol{dV_{pv}}} = \boldsymbol{I_{pv}} + \boldsymbol{V_{pv}}\,.\frac{\boldsymbol{dI_{pv}}}{\boldsymbol{V_{pv}}} = \boldsymbol{0} \ \ => \frac{\boldsymbol{dI_{pv}}}{\boldsymbol{dV_{pv}}} = \ -\frac{\boldsymbol{I_{pv}}}{\boldsymbol{V_{pv}}}$$

- If $\frac{\boldsymbol{dI_{pv}}}{\boldsymbol{dV_{pv}}} > -\frac{\boldsymbol{I_{pv}}}{\boldsymbol{V_{pv}}}$, the operating point is to the left of the MPP, so the voltage must be increased to reach MPP.
- If $\frac{\boldsymbol{dI_{pv}}}{\boldsymbol{dV_{pv}}} < -\frac{\boldsymbol{I_{pv}}}{\boldsymbol{V_{pv}}}$, the operating point is to the right of the MPP, so the voltage must be decreased to reach MPP.

II.4.Limitations of Classic MPPT Techniques

Although conventional MPPT techniques are widely used, they have certain limitations, including reduced performance under rapidly changing environmental conditions and increased complexity in practical implementation. In addition, some of these methods can lead to oscillations around the maximum power point, reducing overall efficiency.

II.5. State-of-the-art Sliding Mode Control (SMC) and Double Integral Sliding Mode Control (DISMC)

II.5.1. Sliding Mode Control (SMC)

SMC achieves robustness by driving the system state to a predefined sliding surface and maintaining it there, effectively handling model uncertainties and external disturbances (Utkin, 2004). The primary challenge of SMC is the chattering phenomenon, which is mitigated through techniques like higher-order sliding modes (Nouri et al., 2017).

II.5.2. Double Integral Sliding Mode Control (DISMC)

DISMC incorporates a double integral of the error term in the sliding surface, significantly reducing steady-state errors and improving performance under persistent disturbances (Chen & Kuo, 2017).

DISMC addresses chattering through optimized sliding surface design and adaptive control elements, ensuring smoother control actions (Pradhan & Subudhi, 2016).

DISMC is applied to maximum power point tracking (MPPT) in photovoltaic systems, enhancing performance by addressing issues such as chattering and slow transient responses (Pradhan & Subudhi, 2016). In brushless DC motor control, DISMC integrates adaptive PID observers to adjust control gains online, reducing tracking errors (Chen & Kuo, 2017).

II.6. Conclusion

This chapter has comprehensively reviewed the literature on MPPT techniques, sliding mode control, and the dual sliding mode integrator. DISMC systems offer significant advantages over conventional methods and simple sliding-mode controllers. The following chapter will detail the research methodology adopted for this study, including modelling, simulation, and practical experiments of DISMC-based MPPT techniques.

III. Chapter03: Modeling and Description of Maximum Power Point Tracking (MPPT) algorithm

The sliding mode control method is particularly effective for maximum power point tracking (MPPT) in PV systems, where irradiance and temperature conditions vary rapidly. Among the Various forms of sliding mode control, the double-integration sliding mode stands out for its ability to improve the robustness and accuracy of control. It combines integral sliding mode control (ISMC) with additional integral terms to design a new sliding surface, which improves transient response and reduces chattering.[6]

In this chapter, we explore the modeling of a Maximum Power Point Tracking (MPPT) controller based on Double Integration Sliding Mode Control on a PV system; the implementation and simulation steps were conducted using MATLAB/Simulink.

III.1. Design of the MPPT controller using Double integration sliding mode control

III.1.1. Introduction to DISMC MPPT

DISMC (Double Integral Sliding Mode Control) is an advanced sliding mode control variant that monitors the maximum power produced by a solar panel. Its role is to impose on the chopper the exact duty cycle (D) required to maintain the photovoltaic generator (GPV) at its maximum power.[7]

III.1.2. Double Integration Sliding Mode Control

The design of the control system can be carried out in three main stages, which are highly dependent on each other:

- Establishing the existing conditions
- Defining sliding surface.
- Determination of the control law. [7]

III.1.2.1. Determination of the control law:

The fundamental concept of sliding mode control is initially to attract the system states into a suitably selected region and then to design a control law to keep the system in that region.

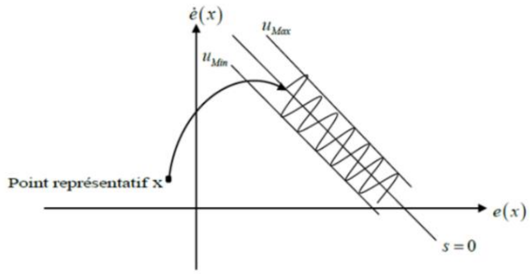

Figure 4: Sliding mode

This control is divided into two parts:

The first part deals with the equivalent control quantity u_{eq}, which maintains the operating point in the switching surface and moves it back to the origin, and the second is a discontinuous control depending on the sign of the sliding surface u_n.[6]

$$u = u_n + u_{eq} \tag{1}$$

We defined u_n

$$u_n = -k.sign(s) \tag{2}$$

Where: k is a positive gain.

III.1.2.2. Defining sliding surface

In general, for a defined system it is given by:

$$\dot{x} = f(x) + g(x)u \tag{3}$$

Where:

$x = (x_1, x_2, \dots, x_n)^T$: A differentiable variety

u : The command of the system

f and g : are vector fields that are defined on X.

The sliding surface for a system of order n is defined as follows:

$$S(x) = \left(\frac{\partial}{dt} + \lambda\right)^{r-1} e(x) \tag{4}$$

Where:

$$e(x) = X_{ref} - X \tag{5}$$

$e(x)$: The error or the deviation of the variation to be adjusted

λ: Positive constant that characterizes the bandwidth of the desired control.

r: Relative degree, equal to the number of times the output must be differentiated to make the control appear.

Then, selecting the surface "S", the control vector "u, "where each component experiencing u_i a discontinuity at $Si(x) = 0$, is given by**:**

$$\begin{cases} u_i(x) = u_i^{+} \;\; if \;\; S_i(x) > 0 \; for \; i = 1,2, \dots\dots m \\ u_i(x) = u_i^{-} \;\; if \;\; S_i(x) < 0 \; for \; i = 1,2, \dots\dots m \end{cases} \tag{6}$$

This shows that the change in the value of the control vector u depends on the sign of the surface $S(x)$. [8]

III.1.2.3. Existing conditions:

The conditions to ensure convergence towards the sliding surface are:

$$S(x).\dot{S}(x) < 0 \text{[8]} \tag{7}$$

III.2. Modeling of the pc system:

Accurate modeling of the photovoltaic system is essential for designing an efficient controller.

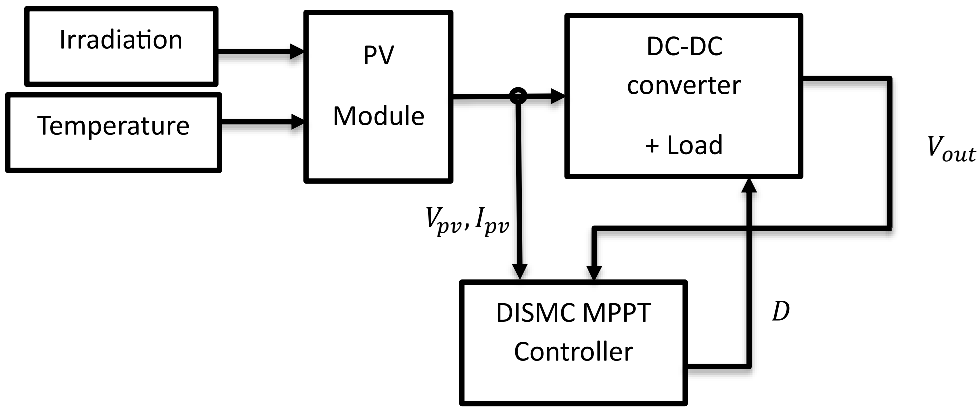

Figure 5:Structure of the general control of MPPT system

III.2.1. Modeling of the PV array:

The mathematical model of a PV system comprises several non-linear equations representing the behavior of photovoltaic cells. The current-voltage relation of a photovoltaic cell can be described by the following equations (the diode equivalent model equations for the non-linear I-V characteristics of the PV cell shown in the figure (6) are as follows:[9]

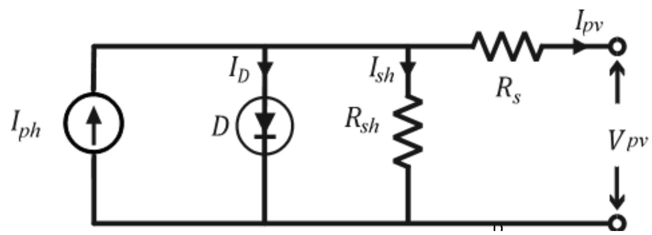

Figure 6: The equivalent circuit of a PV cell (5 parameters model) [9]

$$I_{pv} = I_{ph} - I_D - I_{sh} = I_{ph} - I_0 \left[exp\left(\frac{(V_{pv}+I_{pv}R_S)}{nV_T} \right) - 1 \right] - \frac{V_{pv}+IR_S}{R_p} \tag{8}$$

The equations of the diode current:

$$I_D = I_0 \left[exp\left(\frac{(V_{pv}+I_{pv}R_S)}{nV_T} \right) - 1 \right], V_T = \frac{KT}{q} \tag{9}$$

Where:

- I_{pv} : PV cell output current.
- I_{ph} : Photo-current(A).
- I_0 : Reverse saturation current(A).
- V_{pv} : PV cell output voltage (V).
- R_s : Series resistance(Ω).
- R_{sh} : Shunt resistance(Ω).
- n: Ideality factor.

- V_T: Thermal voltage(V).
- K : Boltzman constant ($K = 1.38 \times 10^{-23} J/K$).
- q : Electron charge ($q = 1.60 \times 10^{-19}\ C$)
- T : Operating temperature of the cell.

For a photovoltaic module composed $of\ N_S$ of PV cells in series and N_P PV cells in parallel, the output current is given by the following equation:

$$I_{pv} = N_P I_{ph} - N_P I_0 \left[exp\left(\frac{q(N_S V_{pv} + (N_S/N_P) I_{pv} R_S)}{N_S nKT}\right) - 1\right] - \frac{N_S V_{pv} + (N_S/N_P) I_{pv} R_S}{(N_S/N_P) R_p} \quad (10)$$

III.2.2. Modeling of the Chopper:

DC/DC converters are distinguished by their ability to efficiently convert a direct current (DC) voltage to another voltage level (buck, boost, buck-boost). For our photovoltaic system, we have selected a boost converter to efficiently convert the DC voltage generated by the solar panels to a higher output voltage. This allows for better adaptation to the energy storage or load requirements.

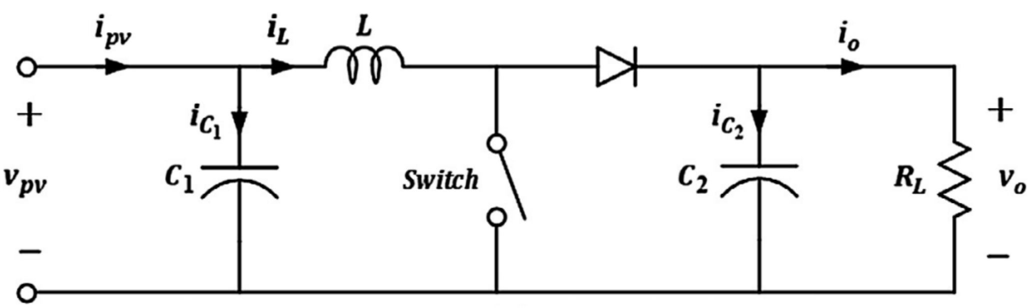

Figure 7:Boost converter schematic

The Boost converter depicted in Figure (07), comprises an inductor (L) that stores and releases energy to elevate the output voltage. A diode (D) that rectifies the current. An input capacitor (C1) that stabilizes the voltage applied to the switch. An output capacitor (C2) that attenuates voltage ripples, and a switch, which can be a transistor or a thyristor, that regulates the current flow.

When the switch is in the ON state, the diode is reverse-biased (blocked). Inductance L stores energy and the current flowing through the source increases progressively. In this first case, a set of equations is represented as follows:

$$\frac{dV_L}{dt} = \frac{i_{C1}}{C_1} \quad With \quad i_{C1} = i_{pv} - i_L \quad (11)$$

$$\frac{dV_0}{dt} = \frac{i_{C2}}{C_2} \quad With \quad i_{C2} = -\ i_o \quad (12)$$

$$\frac{dI_L}{dt} = \frac{V_L}{L} \quad With \quad V_L = V_{pv} \quad (13)$$

When the switch is OFF, the diode becomes forward-biased and conducts current. This allows the inductor to discharge its stored energy, which is transferred through the diode to the load and the capacitor. As a result, the output voltage increases.

$$\frac{dV_{pv}}{dt} = \frac{i_{C1}}{C_1} \quad With \quad i_{C1} = i_{pv} - i_L \quad (14)$$

$$\frac{dV_o}{dt} = \frac{i_{C2}}{C_2} \qquad With \qquad i_{C2} = i_L - i_o \tag{15}$$

$$\frac{dI_L}{dt} = \frac{V_L}{L} \qquad With \quad V_L = V_{pv} + V_o \tag{16}$$

Based on the equations drawn from two phases, it is possible to conclude and establish the expression of the duty cycle as follows:

$$V_o = \frac{1}{1-D} \cdot V_{pv} \quad (17) \quad With \quad D \in [\,0\,,1\,]$$

III.2.3. Design of the proposed adaptive DISMC-MPPT:

Before we start presenting the modeling of the DISMC MPPT, we should notice that the equilibrium condition of the system is:

$$\left(\frac{\partial P_{pv}}{\partial I_{pv}}\right) = 0 \tag{18}$$

The design of DISMC, as we have said, is divided into 2 main parts:

- **The first is defining the sliding surface** [6]**:**

The sliding mode $S(t)$ is defined with the following:

$$S(t) = \{x \backslash S(x,t) = \dot{S}(x,t) = 0\} \tag{19}$$

In our case, the selected one should be designed to maximize power extraction in the output panel. The sliding surface is defined by:

$$\left(\frac{\partial P_{pv}}{\partial I_{pv}}\right) = 0, \left(\frac{\partial P_{pv}}{\partial I_{pv}}\right) = I_{pv}\left(\left(\frac{\partial V_{pv}}{\partial I_{pv}}\right) + \left(\frac{V_{pv}}{I_{pv}}\right)\right) \tag{20}$$

The sliding surface is as follows:

$$S(t,x) = \left(\left(\frac{\partial V_{pv}}{\partial I_{pv}}\right) + \left(\frac{V_{pv}}{I_{pv}}\right)\right) \tag{21}$$

For the controller design, the tracking error e is given as:

$$S(x) = e(x), e(x) = e(x_1) + e(x_2), \tag{22}$$

$$e(x_1) = \int \left(\frac{\Delta P}{\Delta I}\right) dt\,, e(x_2) = \int \left\{\int \left(\frac{\Delta P}{\Delta I}\right) dt\right\} dt, \begin{Bmatrix} \Delta P = P_{pv}(k) - P_{pv}(k-1) \\ \Delta I = I_{pv}(k) - I_{pv}(k-1) \end{Bmatrix} \tag{23}$$

So:

$$S(x) = e(x_1) + e(x_2) = \int \left(\frac{\Delta P}{\Delta I}\right) dt + \int \left\{\int \left(\frac{\Delta P}{\Delta I}\right) dt\right\} dt \tag{24}$$

- **The second is: Control law**[6]**:**

Before we design the control law or the switching function u, we have to calculate the first part of it, the equivalent control u_{eq} that should ensure the stability condition:

$$\begin{cases} S(x) = 0 \\ \dot{S}(X) = 0 \end{cases} \Rightarrow u \cong u_{eq} \tag{25}$$

By solving the algebraic equation:

$$\dot{S} = [ds/dx]^T,\ \dot{x} = [dS/dx]^T.\left(f(x) + g(x)u_{eq}\right) = 0 \tag{26}$$

$$u_{eq} = -([dS/dx]^T f(x))/([dS/dx]^T g(x)) = 1 - (K_1 \int S + V_{pv})/V_s \tag{27}$$

By taking into account that discontinuous control can ensure the Lyapunov stability criterion, which is given by: $S(x).\dot{S}(x) < 0$

The second part of the law control is given by:

$$u_n = K_2|S|^{\alpha}.sign(S) \qquad 0 < \alpha < 1 \tag{28}$$

$$\begin{cases} sing(s) = 1 & if \;\; S(x) > 0 \\ sing(s) = 0 & if \;\; S(x) = 0 \\ sing(s) = -1 & if \;\; S(x) < 0 \end{cases} \tag{29}$$

The control law for a DC/DC boost converter is as follows:

$$u = u_{eq} + u_n = \left[1 + K_2|S(x)|^{\alpha}.sign(s) - (K_1 \int S(x)dx + V_{pv})/V_s\right] \tag{30}$$

Where: K_2 and K_1 are positive constants.

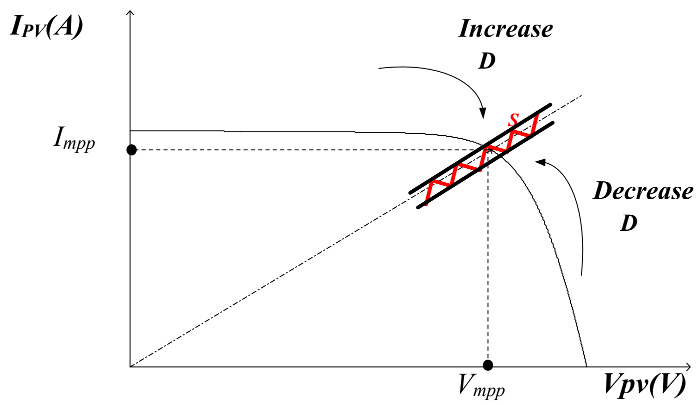

Figure 8: Sliding surface while finding MPP[10]

III.3. Implementation and simulation

Following this mathematical development, a simulation of the proposed DISMC was developed using the MATLAB/Simulink environment to evaluate this command's performance and robustness under different irradiation and temperature conditions.

The studied system consists of a PV array of 1200W (three parallel strings, each string has two series-connected modules) supplying a DC-DC boost converter connected to a resistive load.

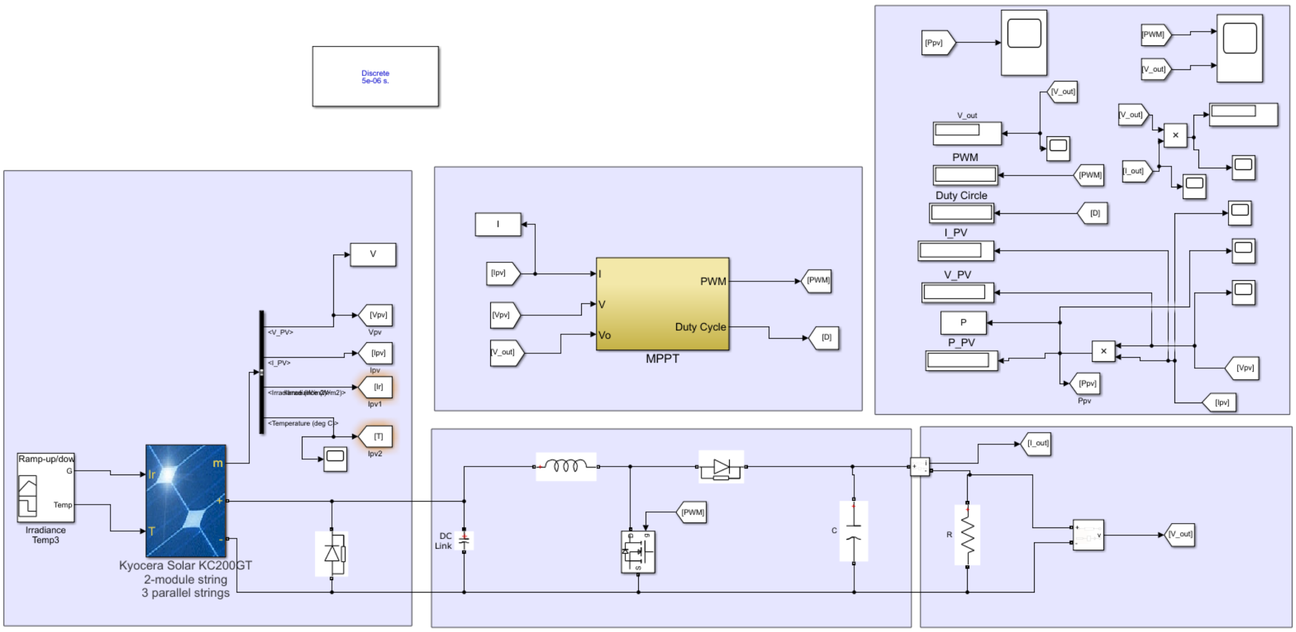

Figure 9 : MATLAB/Simulink Block Diagram of PV Panel Controlled by DISMC

- The data of the used module Kyocera solar KC200GT is shown in the table below:

Table 2: KC200GT Data Sheet for STC Conditions

Number of series cells per module (N_S)	54
Maximum power(P_{mpp})	200.143 (w)
Short-circuit current (I_{sc})	8.21 (A)
Open-circuit voltage (V_{oc})	32.9 (V)
Voltage at MPP (V_{mpp})	26.3 (V)
Current at mpp (I_{mpp})	7.61 (A)

The Panel characteristics under the standard test condition ($\mathbf{1000\ W/m^2\ and\ 25}$℃) and other different irradiations and temperature conditions are presented in the figures below:

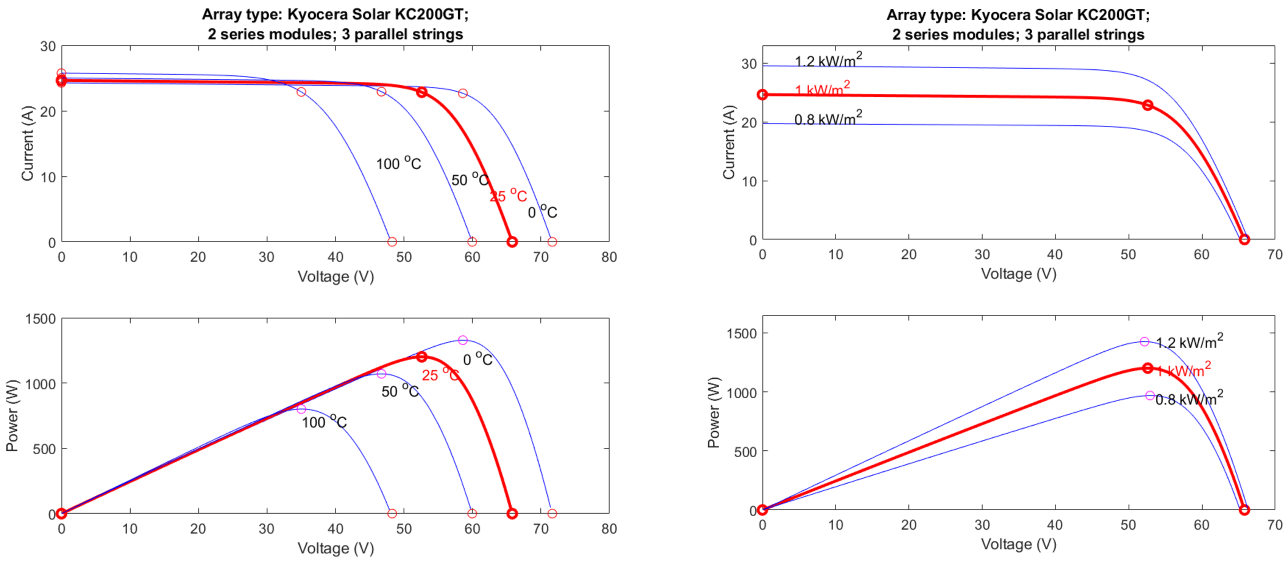

Figure 10 (P/V) and (I/V) characteristics under variable temperature and irradiation

For the boost converter, the table below contains its parameters:

Table 3: Boost Converter Parameters

C_{in} **and** C_{out}	$1200.10^{-6}(F)$
L	$26.3\ (V)$

For the load:

RLC: $R = 120\ \Omega$ With a nominal voltage of $V_n = 50\ V_{rms}$

III.4. Conclusion:

In this chapter, we have discussed the modeling of the photovoltaic system and the design of the doubly integrated sliding mode controller in detail. The implementation in MATLAB/Simulink enables us to simulate and evaluate the system's performance under various conditions, including its robustness in responding to sudden changes in irradiance and its ability to quickly stabilize with a fast transient response.

IV. Chapter04: Results and Discussion

This chapter presents the simulation results of the double integration sliding control on a PV system. We will use the parameters listed in the table in the previous chapter, to confirm its functionality and resilience to climate change.
The main objective of this study is to determine the controller's robustness to abrupt changes in temperature and sun irradiation, as well as its response time and ability to mitigate undesired oscillations caused by the regulator or the DC/DC converter switching.
We will illustrate the benefits and drawbacks of our method by comparing the performance of DISMC with alternative control strategies.

IV.1. Simulation Results

A number of simulation scenarios are planned in order to assess DISMC's performance. Among these are:

- Changes in solar irradiation, both sudden and gradual.
- Temperature variations.

IV.1.1. Standard Test Conditions Scenario

In this, case the irradiation is $1000\ w/m^2$ and the temperature $T = 25$°C.
According to the theoretical values in Table 02 in Chapter 03 and the simulation, we have summarized the obtained output of the PV array values including current, voltage, and rated power in Table 4 and presented the variations of them in **Figure 11**:

Table 4: Output of the PV array at STC Conditions

	Calculated	**Measured**
$I_{pv}(A)$	$3 \times 7.61 = 22.83$	22.52
$V_{pv}(V)$	$2 \times 26.3 = 52.6$	53.13
$P_{pv}(W)$	$200.143 \times 3 \times = 1200.858$	1196.4876

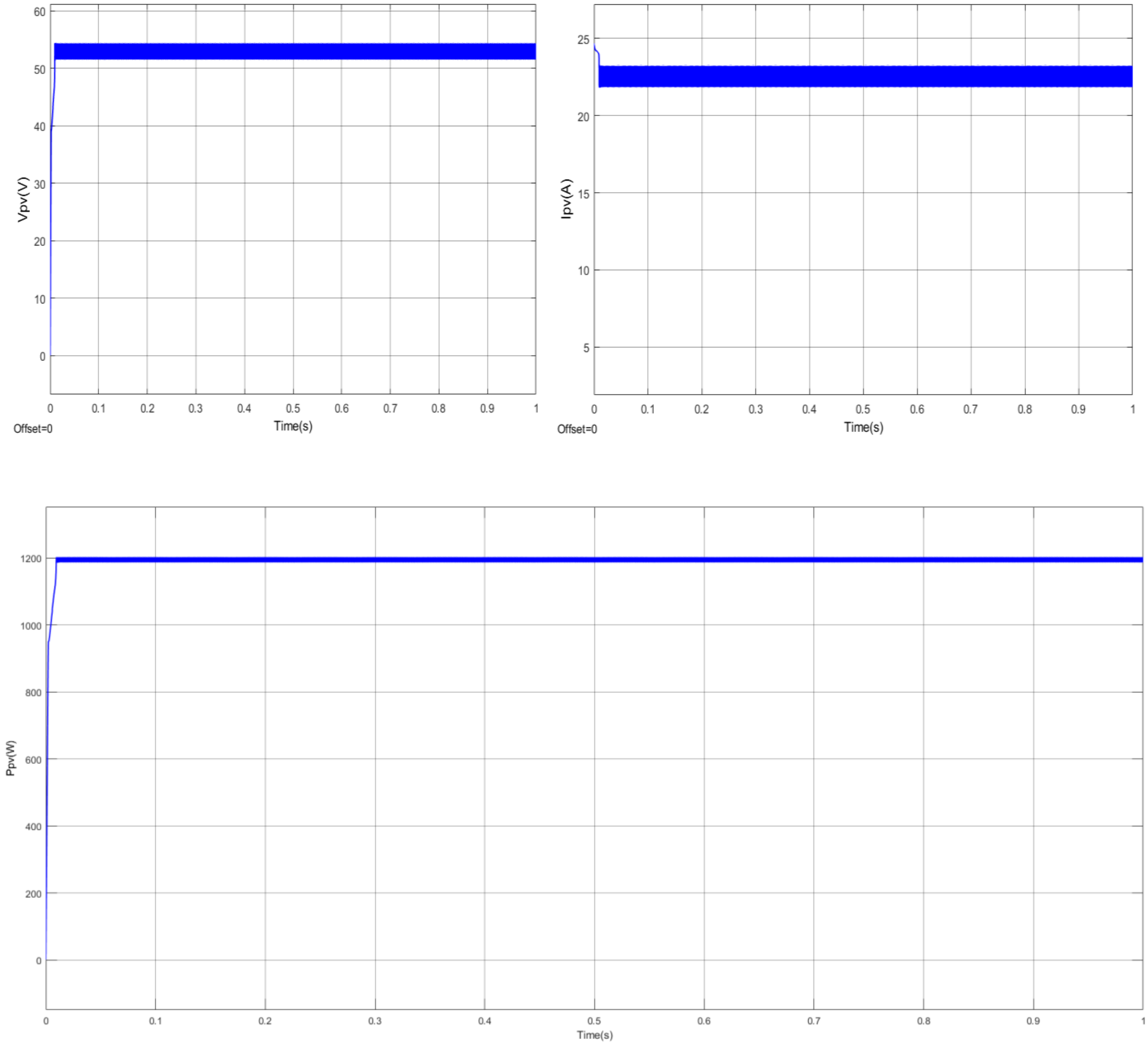

Figure 11: V(t), I(t) and P(t) under STC

According to Figure 11, we observe that with the proposed DISMC algorithm, the system rapidly responds in $0.010\ s$ to locate and maintain the maximum power point, and it stabilizes quickly with a very low oscillation.

IV.1.2. Response to Sun irradiation changes

IV.1.2.1. Rapid change Scenario

In order to evaluate the performance of the algorithm under sudden changes we applied the irradiation profile below (Figure 12) and we kept a constant temperature $T = 25°C$. The results presented in the figures.

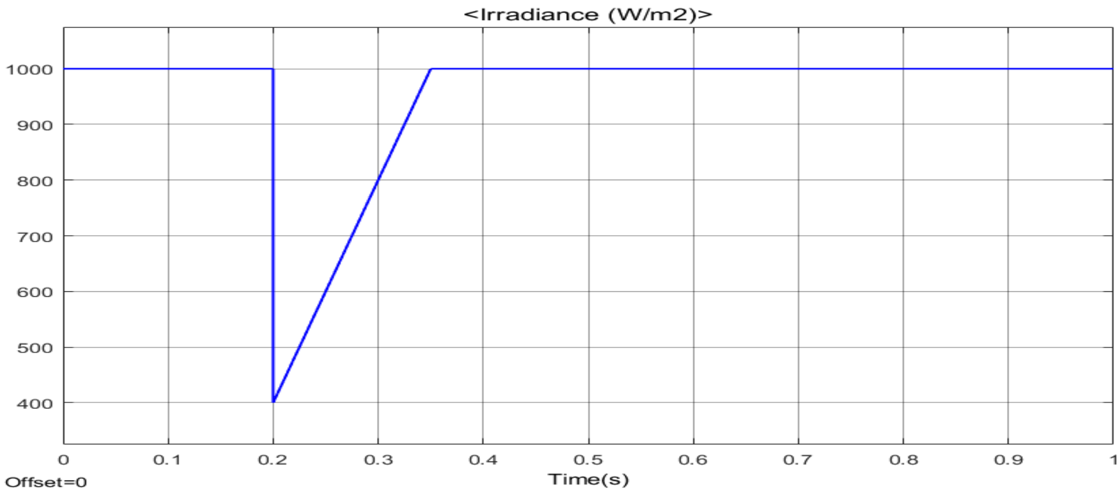

Figure 12: Irradiation Profile

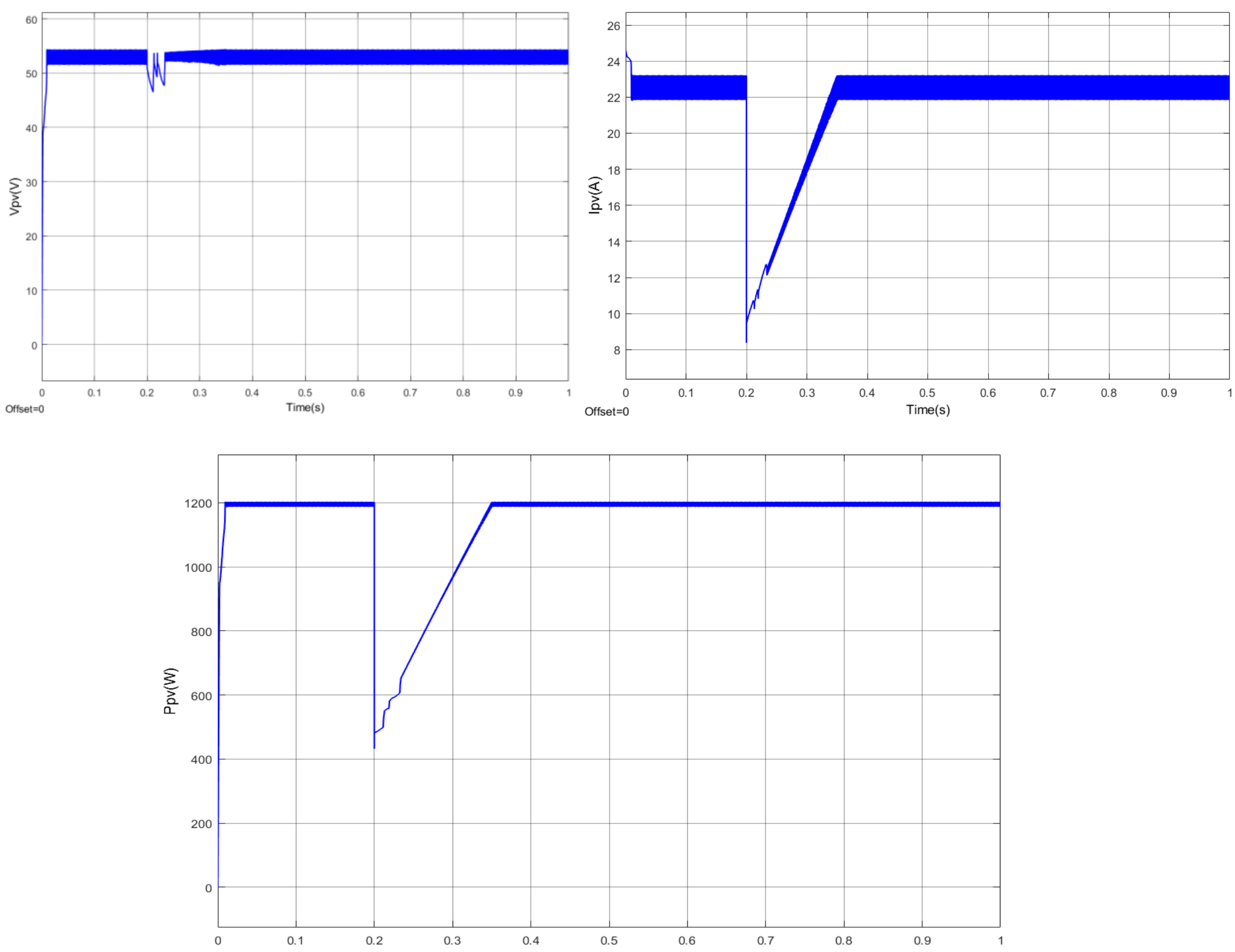

Figure 13: V(t), I(t) and P(t) under sudden irradiation changes

In the figure 13, we visualize the output of a PV panel in terms of current, voltage, and power. We applied a sudden change in irradiation from $1000\ w/m^2$ to $400\ w/m^2$ at $0.2\ s$, demonstrating an environmental disturbance, and we notice rapid drop in the output power of the photovoltaic panel as the irradiation decreased. The controller detected the changes and started adjusting the operating point to the new maximum power point (MPP) corresponding to the reduced irradiation.

IV.1.2.2. Gradual change Scenario

In this scenario we kept a constant temperature $T = 25°C$ and we changed the irradiation gradually as shown the Figure 14. The simulation results are presented in the figure.

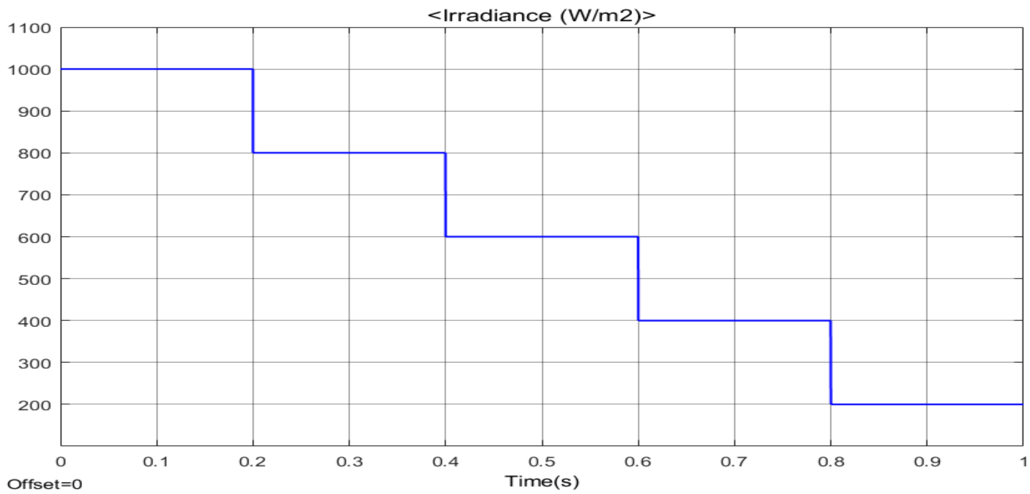

Figure 14: The gradually changing irradiation

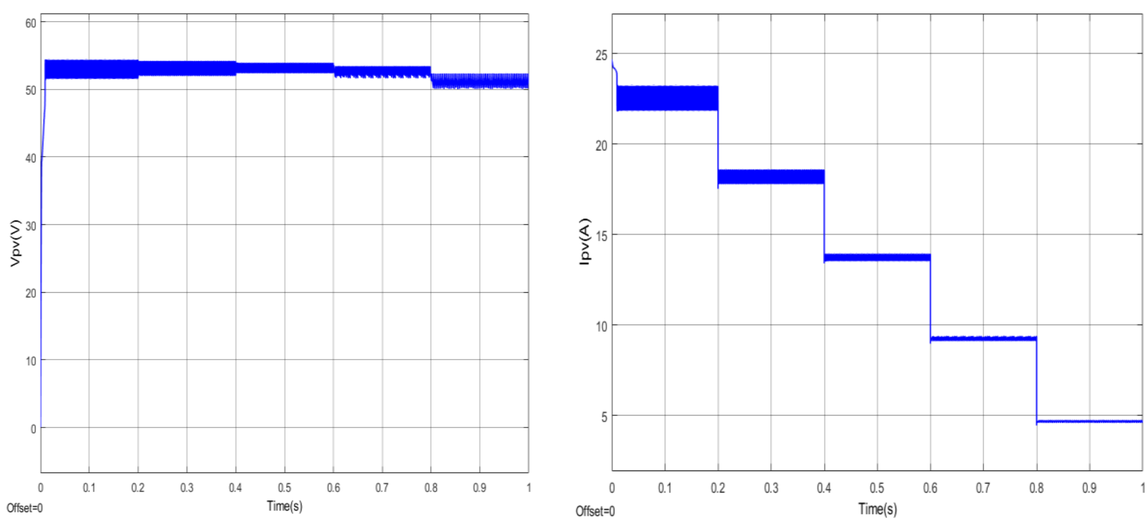

Figure 15: V(t), I(t) and P(t) under sudden irradiation changes

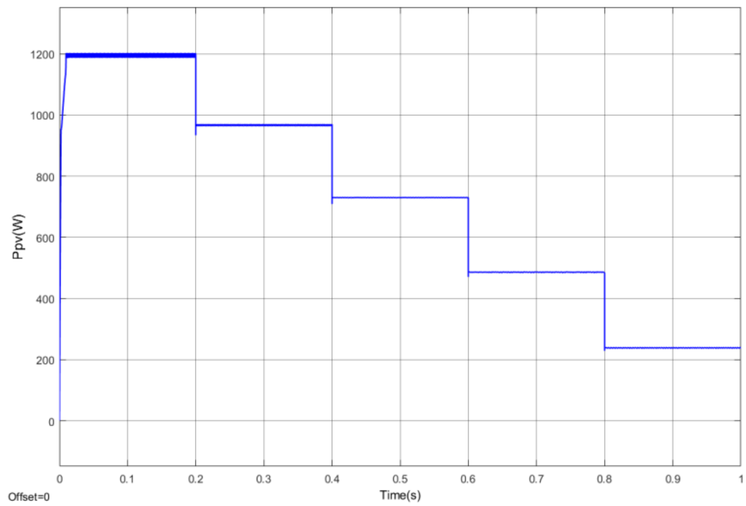

Figure 16: The power

In the case of testing the non-rapid irradiation, during the interval of $t = [0\,,0.2](s)$, and by keeping the temperature constant in 25℃ and the irradiation at $1000\ w/m^2$ the current, voltage, and PV power are at their nominal values. Consequently, a sudden decrease in irradiation to $G = 800\ w/m^2$ at t = [0.2, 0.4] (s), causes a decrease in I_{pv}, P_{pv}, and a few increasing in V_{pv}, and so on for the other level of variating irradiation. This can be explained by the negative effect of the decreasing irradiation on the current and power level of the PV output and positively the PV voltage (Fig.15, 16).

IV.1.3. Response to Temperature changes

In this case, we changed the temperature to analyze its effect on the panels' output by the temperature values shown in the figure 17:

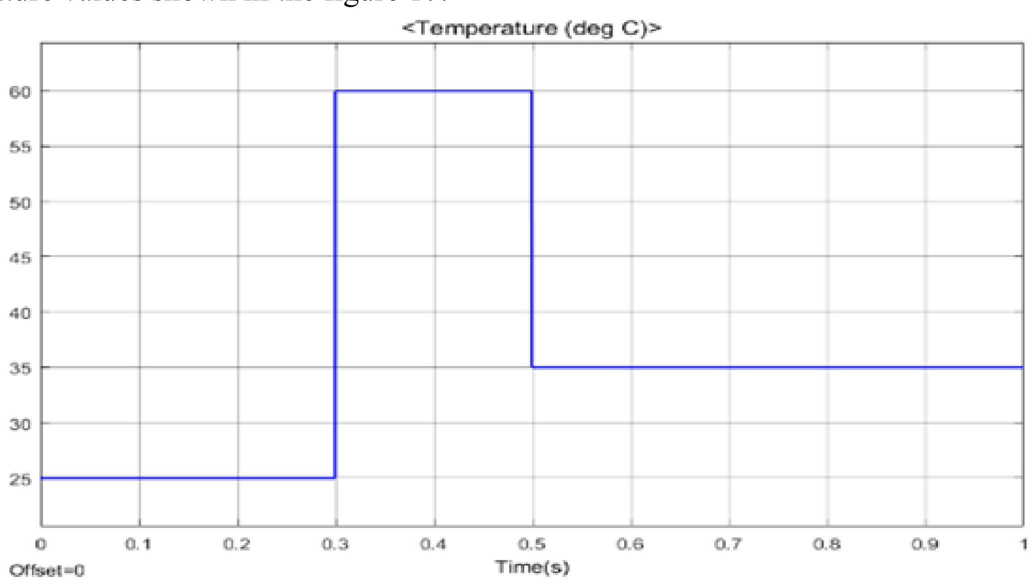

Figure 17: Temperature variation

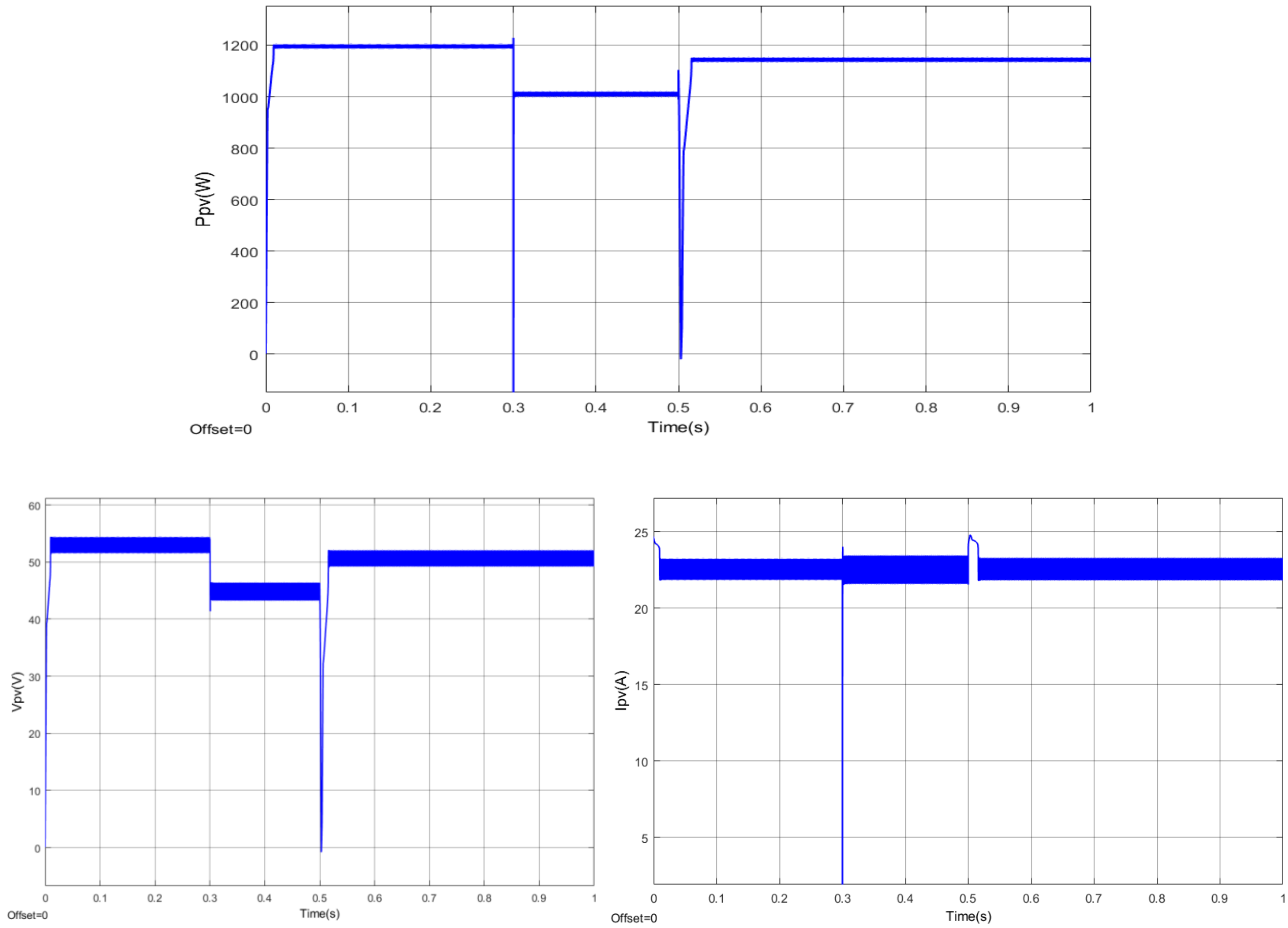

Figure 18: Vpv, Ipv, Ppv under the temperature variation

In the case of the temperature robustness test, during the interval of $t = [0\,,0.3](s)$, with the irradiation of 1000 $w/m^2$and the temperature level is 25°C the current, voltage, and PV power are at their nominal values as standard scenario case. Consequently, a sudden increase in temperature $T = 60$°C at t = [0.3, 0.5] (s), causes a drop in V_{pv}, I_{pv}, P_{pv}, (Fig.18), and therefore, it can be concluded that increasing the temperature above the reference value 25°C effects the efficiency of the solar panels, causing a decreasing in PV power. However, because of the DISMC MPPT control the pc power remains below the nominal value. In addition, decreasing in temperature as in the interval t = [0.5, 1] (s) reward increasing in the PV power at the rated power

IV.2. Performance analysis

To evaluate the performance of the proposed double integrated sliding mode control we have compare it to a classic and popular method which is the **P&O** under a different profile of irradiation and temperature.

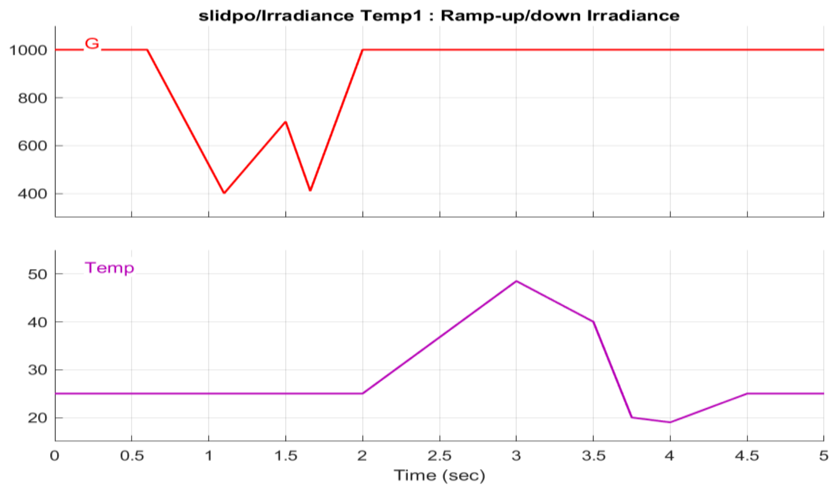

Figure 19: Irradiation and temperature

The provided graph illustrate the performance comparison between the Double Integral Sliding Mode Control (DISMC) and the Perturb and Observe (P&O) algorithm in the photovoltaic (PV) system.

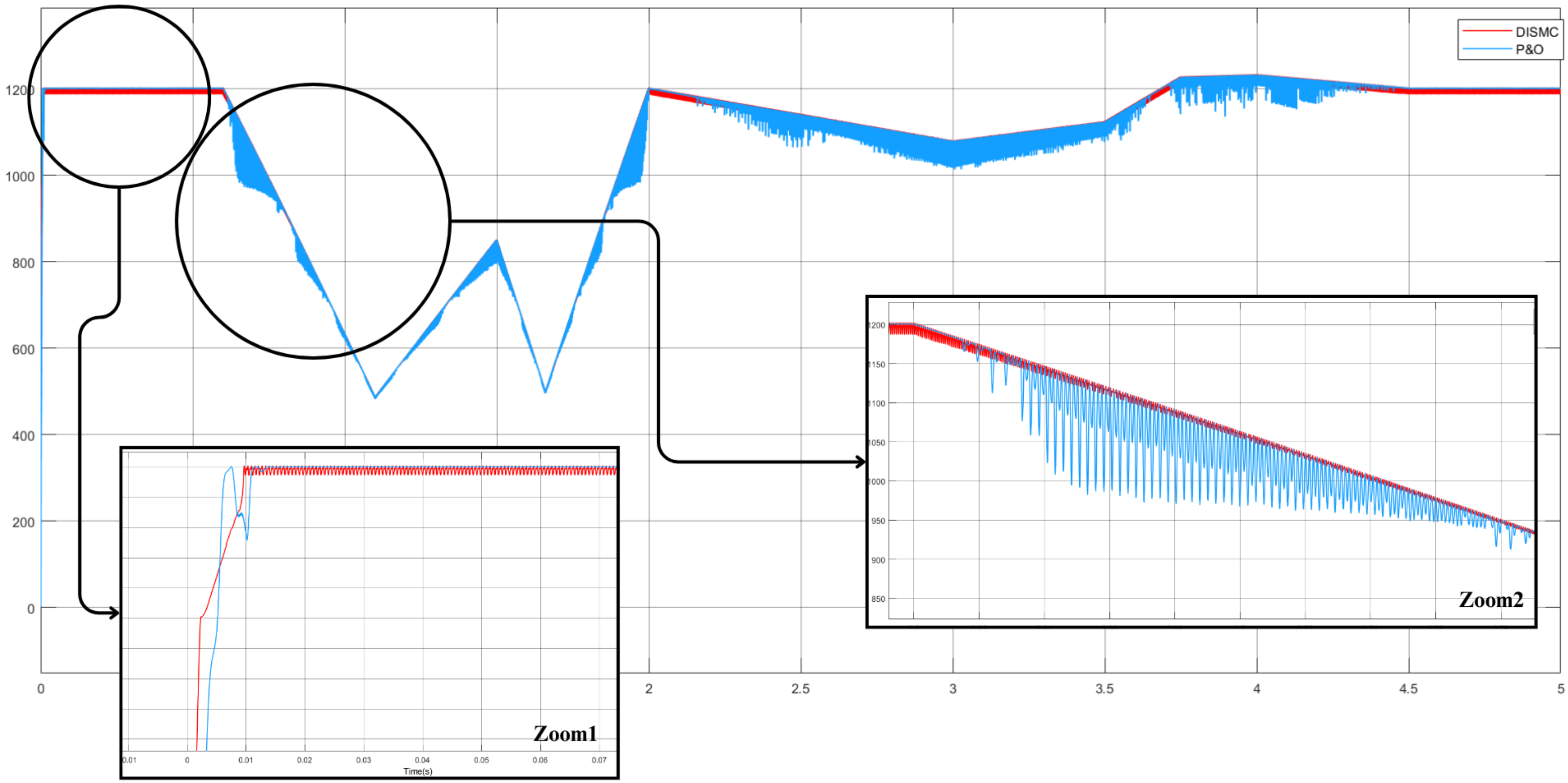

Figure 20: Comparaisonof power output between P&O algorithm and DISM controller

Comments

- To fluctuating irradiance conditions. The first set of graphs (Fig.19) presents the irradiance (G) and temperature (Temp) profiles over time, showcasing significant variations in irradiance that simulate partial shading conditions, while the temperature also exhibits less intense fluctuations.
- The second set of graphs (Fig.20) compares the output power of the PV system when using the DISMC (red line) and P&O (blue line) algorithms. Notably, two zoomed-in sections, Zoom 1 and Zoom 2, provide a detailed view of the algorithms responses to specific irradiance changes. Zoom 1 highlights the initial response to a change in irradiance, where the DISMC algorithm demonstrates a rapid and stable adjustment, quickly reaching the maximum power point with minimal oscillation. In contrast, the P&O algorithm shows pronounced oscillations and a slower stabilization, indicating its inefficiency in quickly adapting to new irradiance levels.
- Zoom 2 focuses on a segment with a steep decline in irradiance, revealing further insights into the algorithms' performance. During these rapid irradiance changes, the DISMC algorithm maintains a relatively smooth and stable power output, effectively managing the fluctuations. Conversely, the P&O algorithm experiences significant power oscillations and instability, struggling to track the changing maximum power point accurately. This comparison underscores the superior capability of the DISMC algorithm in handling rapid and dynamic changes in irradiance, ensuring a more reliable and consistent power output.
- Throughout the fluctuating irradiance scenario, DISMC consistently outperforms P&O in maintaining higher and more stable power output. The superior performance of DISMC can be attributed to its advanced control strategy, which is better suited for managing the dynamic and non-linear characteristics inherent in partial shading conditions. This comparison demonstrates the effectiveness of DISMC in providing stable and efficient maximum power point tracking (MPPT), making it a preferable choice over the P&O algorithm for PV systems operating under variable and challenging environmental conditions.

IV.3. Conclusion

The simulation results validate the effectiveness and robustness of the double integration sliding mode control (DISMC) for photovoltaic (PV) systems under varying environmental conditions. The DISMC demonstrated rapid response and minimal oscillations, effectively maintaining maximum power point tracking (MPPT) even with abrupt changes in solar irradiation and temperature. Compared to the traditional Perturb and Observe (P&O) method, DISMC consistently outperformed in terms of stability, efficiency, and quick adaptation to environmental disturbances. These findings confirm that DISMC is a highly reliable and efficient control strategy for PV systems, ensuring optimal performance in dynamic and challenging climates.

General conclusion

This thesis investigated the application of Double Integrated Sliding Mode Control (DISMC) for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems. The primary objective was to enhance the efficiency and reliability of PV systems by addressing the challenges posed by environmental variability and inherent system nonlinearities.

The research successfully implemented a DISMC-based MPPT algorithm tailored specifically for PV systems. The inclusion of dual integral terms in the control law significantly improved the system's ability to track the maximum power point (MPP) with greater accuracy and robustness. Extensive simulations and experimental validations demonstrated that the DISMC-based MPPT algorithm outperformed conventional MPPT methods. Key performance indicators such as tracking speed, efficiency, and stability under rapidly changing environmental conditions and partial shading scenarios showed notable improvements.

Furthermore, the DISMC approach effectively mitigated the issues of chattering and slow convergence that are commonly associated with traditional sliding mode control. This led to smoother and more reliable operation of the PV system, reducing oscillations and enhancing overall energy yield. The comparative analysis highlighted the advantages of the DISMC-based MPPT over commonly used methods such as Perturb and Observe (P&O), with the DISMC algorithm consistently outperforming these methods in terms of response time and steady-state accuracy.

The findings of this research have significant implications for the field of renewable energy, particularly in optimizing the performance of PV systems. By improving MPPT efficiency, the DISMC-based approach can contribute to higher energy yields and better economic returns for solar installations. Additionally, the robustness and reliability of DISMC can enhance the operational lifespan of PV systems, reducing maintenance costs and downtime.

While the research has demonstrated the potential of DISMC-based MPPT, there are several avenues for future exploration. Further research could focus on the hardware implementation of the DISMC algorithm in real-world PV systems to validate its performance under actual operating conditions. Investigating the integration of DISMC with other advanced control strategies, such as artificial intelligence and machine learning, could further enhance MPPT performance and adaptability. Exploring the application of DISMC in other renewable energy systems, such as wind turbines and fuel cells, could extend the benefits of this control strategy to a wider range of technologies. Conducting long-term performance studies to assess the durability and reliability of the DISMC-based MPPT under various climatic and operational conditions would provide valuable insights for large-scale deployments.

In conclusion, this thesis has successfully demonstrated the viability and advantages of Double Integrated Sliding Mode Control for MPPT in photovoltaic systems. By addressing the limitations of traditional methods and leveraging the strengths of DISMC, this research contributes to the advancement of renewable energy technologies. The outcomes of this study lay a strong foundation for future innovations in MPPT techniques, promoting the broader adoption and effectiveness of solar energy systems in the global pursuit of sustainable energy solutions.

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