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Dynamic Analysis of Single-Ended Primary Inductor Converter Topology for Photovoltaic Applications

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ملخص

يركز هذا البحث على المحاكاة والاختبار التجريبي لخوارزمية تتبع نقطة الطاقة القصوى للتطبيقات الكهروضوئية ويستخدم النظام محول ، والذي تم اختياره بسبب قدرته على العمل في وضعي التباعد والتعزيز ، وبالتالي التحكم في خرج الجهد تحت مجموعة واسعة من ظروف التشغيل .الهدف من الدراسة هو تقييم أداء خوارزمية الاضطراب والمراقبة في ظل حجمين من خطوات الاضطراب - الكبيرة والصغيرة - في ظروف الأحمال الثابتة والمتغيرة .تم تطوير نموذج المحاكاة والنموذج الأولي للأجهزة لتحليل الاستجابة الديناميكية للنظام والكفاءة في التتبع والاستقرار .تكشف النتائج أنه على الرغم من أن حجم الخطوة الكبيرة يضمن تقاربًا أسرع ، إلا أنه يزيد أيضًا من تموج الحالة المستقرة ، بينما يحقق حجم الخطوة الصغيرة دقة أفضل على حساب الاستجابة البطيئة .لوحظ أن محول يوفر تنظيمًا فعالاً للجهد أثناء انتقالات الحمل .توفر النتائج إرشادات لتحسين أداء في الأنظمة الكهروضوئية في العالم الحقيقي من خلال اختيار حجم الخطوة المناسب وتكامل المحول.

الكلمات المفتاحية:

الأنظمة الكهروضوئية ، ، الاضطراب والمراقبة ، محول ، الحمل المتغير ، عملية باك-بوست ، المحاكاة الكهروضوئية ، التحقق التجريبي.

Abstract

This research is focused on the simulation and experimental test of the Perturb and Observe (P&O) maximum power point tracking (MPPT) algorithm for photovoltaic (PV) applications. The system employs a SEPIC (Single-Ended Primary Inductor Converter) which was chosen because of its ability to work in both buck and boost modes, thus voltage output control under a vast set of operating conditions. The study's objective is to evaluate the performance of the P&O algorithm under two sizes of disturbance step large and small in fixed and variable load conditions. The simulation model and hardware prototype are developed to analyze the dynamic response of the system, efficiency in tracking and stability. Results reveal that although a large step size ensures faster convergence, it also increases steady-state ripple, while a small step size achieves better accuracy at the cost of slow response. Results provide guidelines for optimizing MPPT performance in real world PV systems through appropriate step size selection and converter integration. It is observed that the selected converter has demonstrated its ability to operate effectively in the two Buck and Boost modes adapting to load variations

Keywords:

PV systems, MPPT, P&O, SEPIC converter, variable load, Buck-Boost operation, PV simulation, experimental validation.

Résumé

Cette étude se consacre à la simulation et le test expérimental de l'algorithme Perturb et Observe (P&O) de suivi du point de puissance maximale (MPPT) pour les systèmes photovoltaïques (PV). Le système utilise le convertisseur SEPIC, qui a été choisie en raison de sa capacité à fonctionner à la fois en modes buck et boost ce qui permet de contrôler la tension de sortie. L'objectif de l'étude est d'évaluer les performances de l'algorithme P&O pour deux pas de perturbations grande et petite sous une charge variable. Le modèle de simulation et le prototype sont réalisés pour analyser la réponse dynamique du système, l'efficacité du suivi et la stabilité. Les résultats révèlent que pour une grande taille de pas assure une convergence plus rapide elle augmente également l'ondulation en régime permanent tandis qu'une petite taille de pas permet d'obtenir une meilleure précision au prix d'une réponse lente. On observe que le convertisseur SEPIC a démontré sa capacité à fonctionner efficacement dans les deux modes buck et boost en s'adaptant aux variations de la charge.

Mots-clés

Systèmes PV, MPPT, P&O, convertisseur SEPIC, charge variable, fonctionnement Buck-Boost, simulation PV, validation expérimentale.

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Our first thanks go to Allah, the Almighty, who gave us the strength and wisdom to reach this stage in our studies. A special thank you goes to our families who supported us throughout our studies and who always encouraged us in every step forward.

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To all those who have contributed to our training from near and far.

Dedications

In the Name of Allah, the Beneficent, the Merciful.

All the Praise is Due to Allah the Sustainer of all the Worlds.

Above all*, we sincerely dedicate this work to* ***Allah****, the most gracious for the wisdom, strength, and understanding He has given us.*

To my sweet and loving parents ***my mother Malika*** *and* ***my father Amraoui****, the reason of what I become today. Thanks for your great support and continuous care and for being always there for me. You share me all my happiness and my saddest moments.*

To ***my sister Rahma****, I am really grateful to have you in my life. You have been my inspiration and my soul mate; I really appreciate that you were there for me in every single process of my work, I wish for you all the best in your life and to achieve all of your dreams.*

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All in all, "Every challenging work needs self-efforts as well as my guidance

especially those who are very close to our heart" I dedicate this work to my family, my friends and my classmates along with all hard working and respect to my lovely teachers.

Thank you all

Atallah Rayenne

Dedications

بِسْمِ اللهِ الرَّحْمنِ الرَّحِيمِ

قال تعالى: يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنْكُمْ والَّذِينَ أُوتُوا الْعِلْمَ دَرَجاتٍ واللَّهُ بِما تَعْمَلُونَ خَبِير

I dedicate this magnificent work...

To Almighty Allah: *Thank you for giving me everything I need to succeed in life and for guiding me towards that goal.*

To the first man I ever knew, ***My dear father****, I cannot find the words to express his support and encouragement throughout my journey; he was always by my side.*

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1. Introduction

PV systems are devices that convert solar radiation directly to electricity by virtue of the unique properties of special semiconducting materials. Unlike thermal systems, which convert power through mechanical means, PV systems are solid-state and require minimal maintenance, making them applicable for urban and remote installations. With the future in clean sources of energy, solar PV excels because it is capable of being modular, scalable, and climate-friendly. In this chapter, we introduce the fundamental principles of how PV systems work, delve into solar cell physics, and observe how the individual modules are packaged and housed in practical application [1].

2. Photovoltaic effect

As one might see from **Figure 1.1**, photovoltaic effect is the general mechanism by which solar cells have the ability to convert sun light directly into electricity. When it hits a semiconductor like silicon, high-energy photons excite electrons bound, so they bounce out from inside the atomic structure. Free charge carriers thus created are driven by an electric field within, generating continuous current. Complemented by voltage established across junction, this creates useful electrical power [2].

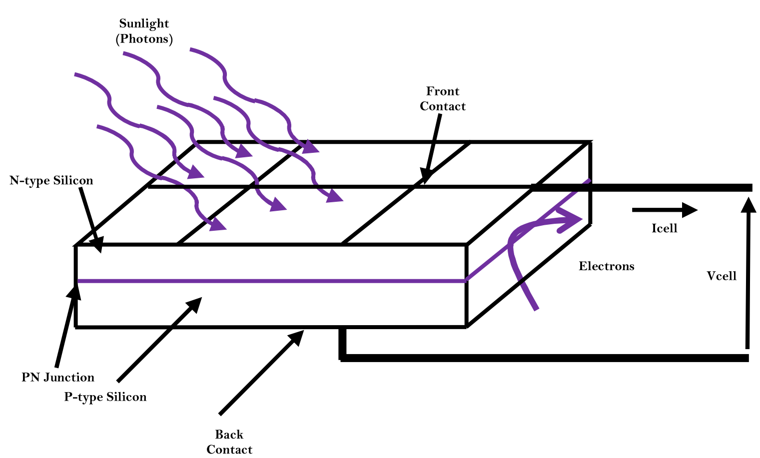

Figure 1.1. Photovoltaic Effect.

3. Photovoltaic Panel Modeling

Exactly modeling the electrical response of PV panels is essential to effective design, simulation, and optimization of solar energy systems. Of all the possible models, the **five-parameter single-diode model** presented in **Figure 1.2** has been chosen for its ability to achieve an optimal compromise between physical representativeness and mathematical simplicity. The model is widely recognized as being a pragmatic and reasonable approximation of the electrical characteristics of a solar cell.

The equivalent circuit with a single diode approximates a real PV cell with a structure made of a light-generated current source, a diode, and two resistive components: series and shunt resistances. The model's performance is based on five significant parameters **[3]:**

- **Photocurrent (I_{ph}):** Refers to the current generated by incident solar radiation. Directly proportional to irradiance, with some temperature dependence.
- **Diode Saturation Current (I_o):** A small reverse-bias leak current across the diode, highly temperature sensitive and important in defining the open-circuit voltage behavior.
- **Series Resistance (R_s):** Balances resistive losses in the cell materials and interconnects, affecting the slope of the I-V curve at or close to the open-circuit voltage.
- **Shunt Resistance (R_{sh}):** Describes internal leakage paths through the junction. Greater values are better, since poor shunt resistance can significantly reduce power output, particularly under low illumination.
- **Ideality Factor (n)**: A parameter that describes the diode's departure from perfect behavior, normally between 1 and 2, and depending on the cell's recombination processes and material quality.

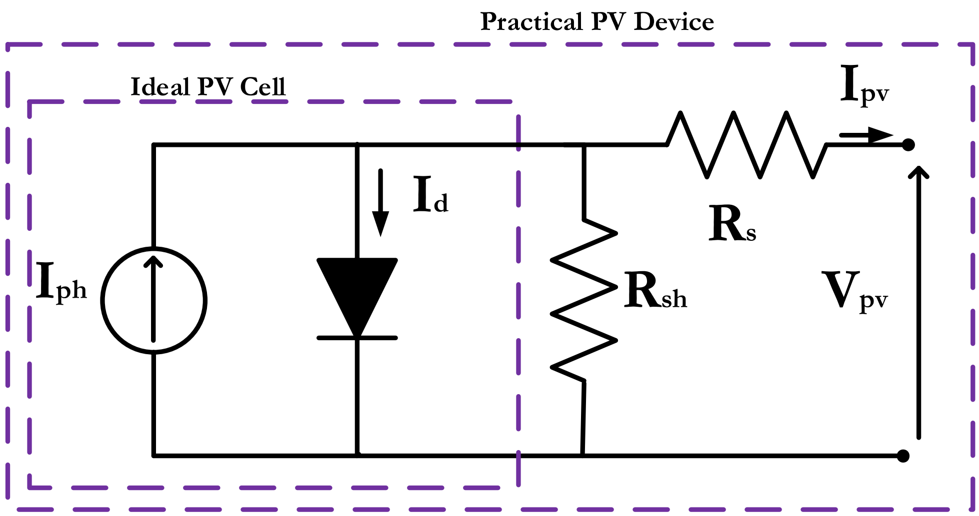

Figure 1.2. The five parameters PV cell model.

The output PV current I_{pv} is given by:

$$I_{pv} = I_{ph} - I_o\left[exp\left(\frac{q\left(V_{pv} + I_{pv}R_s\right)}{nkT}\right) - 1\right] - \frac{V + I_{pv}R_s}{R_{sh}} \qquad (1.1)$$

4. Photovoltaic Panel Characteristics

It is necessary to understand the electrical performance of an individual PV panel in order to evaluate its operating behavior and efficiency. Such a performance can normally be characterized using significant electrical parameters and plots such as the current–voltage ($I-V$) and power–voltage ($P-V$) curves. Such plots provide useful information regarding how the panel will operate under different environmental conditions, particularly solar irradiance and temperature variations [4].

The PV characteristics are as follows [4]:

- **Open Circuit Voltage (V_{oc}):** It is the highest voltage that a photovoltaic panel can produce when its output terminals are not shorted, no current is provided. It is a measure of the capability of the panel when it is in no-load condition.
- **Short-Circuit Current (I_{sc}):** This is the current produced when the panel terminals are directly short-circuited with one another, resulting in zero voltage output. is greatly influenced by the intensity of solar irradiance, and it increases as there is increased sunlight. It has less sensitivity to temperature compared to voltage.
- **Maximum Power Point (P_{mpp}):** It is the operating point on the $I-V$ curve for which voltage and current multiplied together become maximum, yielding the maximum possible power output from the panel. The voltages and currents at this point are specific to changes in irradiation and temperature. For maximum power extraction on a continuous basis, PV devices employ MPPT techniques which are dynamic and capable of changing working conditions.

4.1. Effect of Irradiance

The **Figure 1.4** indicate the effect of solar irradiance on the electrical response of a PV panel.

- **Current Voltage Performance:** As there is an increase in irradiance from **300 W/m²** to **1000 W/m²**, there is a significant increase in short-circuit current (I_{sc}). This is because there are more photons to generate charge carriers. The open-circuit voltage (V_{oc}) rises slightly.
- **Power Voltage Characteristics:** As irradiance, the power output by the panel goes up significantly. At **1000 W/m²**, it produces a lot of power as opposed to **600** or **300 W/m²**, which makes sure that irradiance is a master factor in power generation. The

graph further shows that the maximum power point (MPP) shifts towards higher values as the sun's radiation intensity increases.

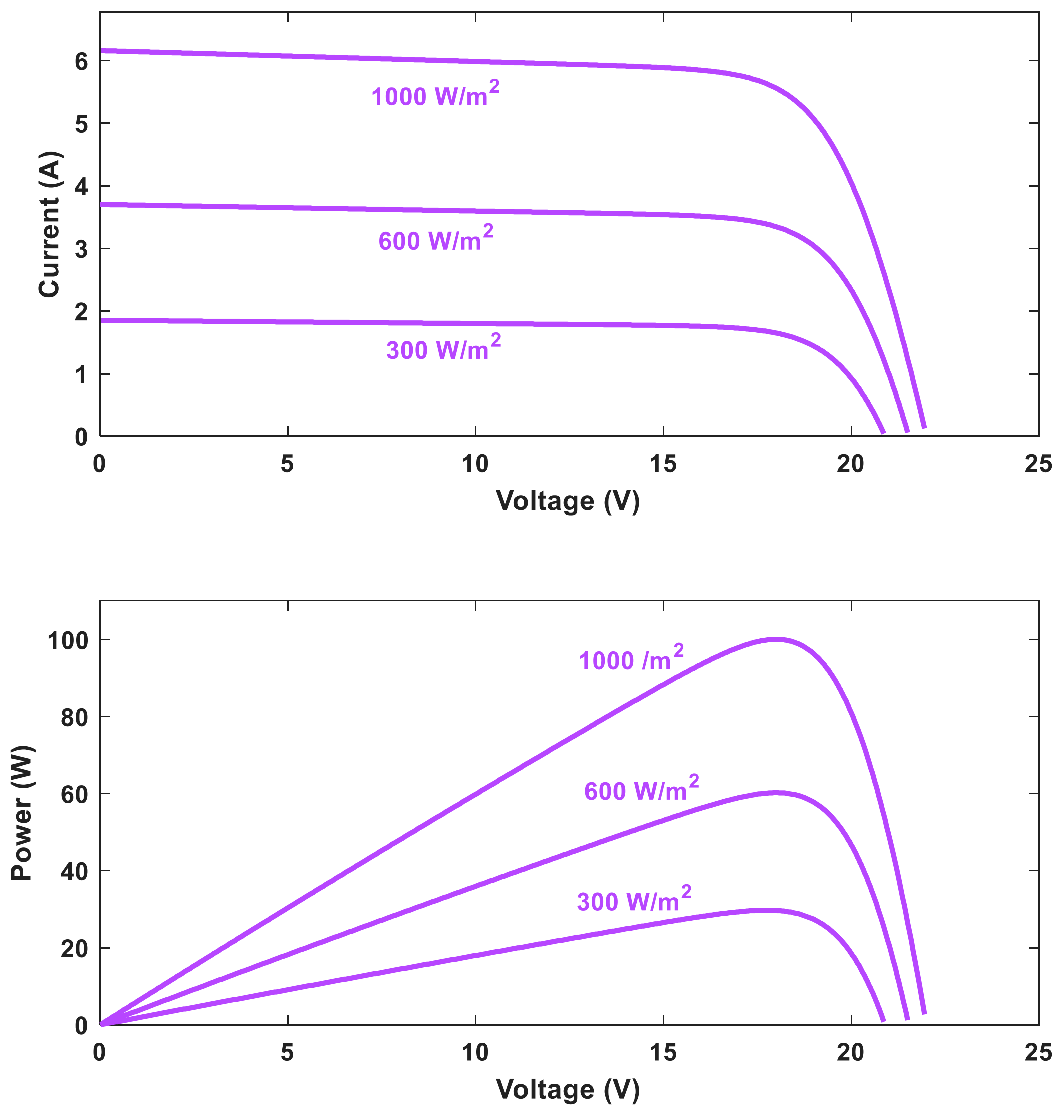

Figure 1.3. Effect of Irradiance.

4.2. Effect of Temperature

The correct plots show how the panel behavior varies with different temperature conditions.

- **Current Voltage Behavior:** With increasing temperature from **10 °C** to **45 °C**, the open-circuit voltage (V_{oc}) reduces considerably, while the short-circuit current (I_{sc}) rises by a very small amount. The reduction in V_{oc} is due to higher recombination and reduced bandgap energy in the semiconductor.
- **Power Voltage Behavior:** Maximum power output falls off with rising temperature. As the current rises slightly, the voltage loss is dominant and results in a net loss of power.

Parameters	Description	Value
Maximum Power	P_{mpp}	100 $[W]$
Maximum Voltage	V_{mpp}	18 $[V]$
Maximum Current	I_{mpp}	5.56 $[A]$
Open-Circuit Voltage	V_{oc}	22 $[V]$
Short-Circuit Current	I_{sc}	6.16 $[A]$

Table 1.1. PV module parameters

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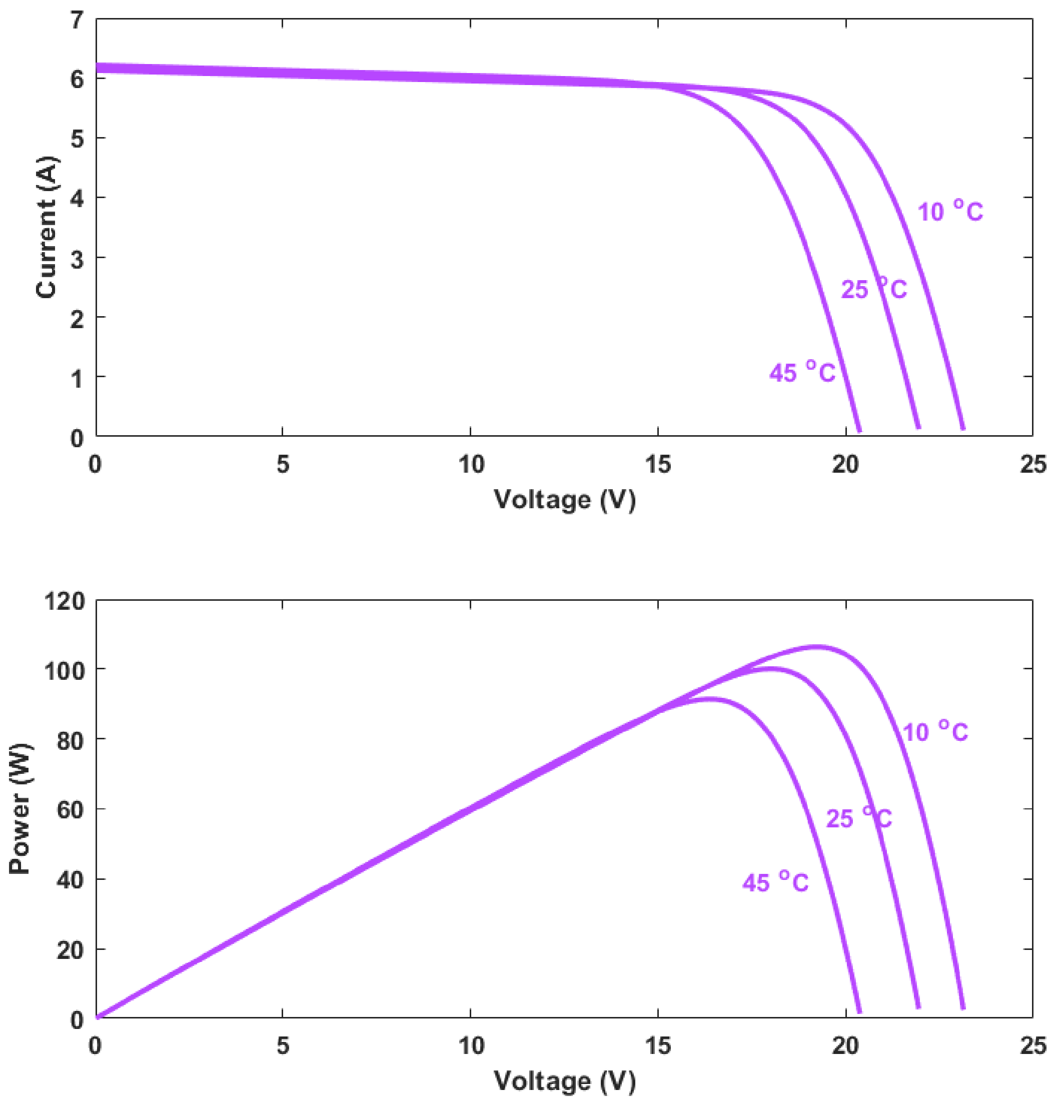

Figure 1.4. Effect of Temperature.

1. Association of Photovoltaic Panels in Series and in Parallel

When PV panels are connected in parallel, as in Figure 1.5, the total output current is comprised of the sum of each panel's current, but the voltage remains constant. This configuration is often used in applications requiring higher levels of current, e.g., low-voltage battery charging systems [5].

However, series connection of PV panels is one of the conventional practices in solar power utilization when there is a requirement of an increased output voltage. In this case, the positive end of a panel is joined with the negative end of the subsequent panel similar to series connected batteries [5].

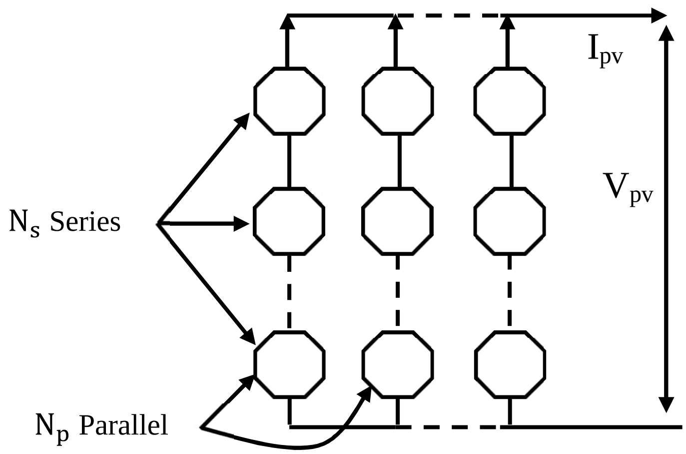

Figure 1.5. Association of PV Panels.

2. Protection for Series-Connected Photovoltaic Panel

PV panels wired in series must also receive adequate protection in order to enjoy longevity without being damaged. Possibly the most common problem lies with partial shading, which causes shaded panels to become reverse-bias mode. It leads to local overheating described as "hot spots" for lack of jargon very often causing damage that is long term to the panel. Aiding against risk is the fitting of bypass diodes between panels or sets of cells. These diodes become conductive when a panel's voltage becomes negative, enabling the bypassing of the malfunctioning unit by the current. This technique suppresses undue heating and supports reasonable power output, even with non-uniform light conditions [6].

3. Protection for Parallel-Connected Photovoltaic Panel

In parallel arrays, the occurrence of reverse current is more likely. When a panel is in shade or fails, other panels in the current of the array's array can reverse and move back into the failing panel, leading to overheating or damage. To prevent this, blocking diodes are incorporated into each branch, as illustrated in **Figure 1.6**. The diodes permit the current from the panel to flow to the load but not in the opposite direction. Additional protection devices such as fuses or circuit breakers are incorporated in some instances to safeguard against short-circuits or overcurrent. Together, these protective devices guarantee safe and effective operation despite the failure of individual panels [6].

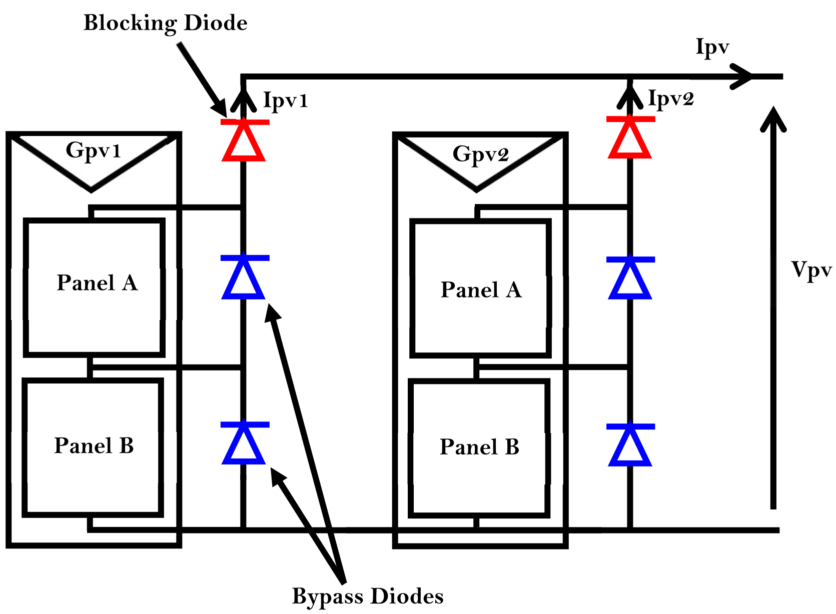

Figure 1.6. Protection of PV Panels.

4. Conclusion

Photovoltaic panels are uniform modules that can be placed in a variety of configurations series or parallel to fulfill particular energy demands. Their junction, though, must consider the individual electrical behavior of each module and adjust for problems such as shading or compatibility of performance. Effective electrical modeling and adequate protection by diodes and protective devices are crucial in optimizing performance and ensuring long-term reliability. By these principles, engineers can design PV systems that generate clean, efficient, and reliable solar power.

Chapter

2 Practical Implementation of SEPIC Converter

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1. Introduction

Power electronics is an essential field of electrical engineering dealing with the static conversion of electrical power from one form to another, intended to meet specific user requirements. The field has evolved very quickly due to improvements in semiconductor technology, which have enabled the development of high-efficiency and compact power conversion systems. Static converters are employed by power electronic systems to transform electrical energy sources into other loads, performing grid-to-load or load-to-grid conversions. The four different kinds of these conversions are each with a distinct specific converter **[7]**:

- **Rectifiers**: AC to DC.
- **Inverters**: DC to AC.
- **Dimmers**: Control the power supplied to a load.
- **Choppers**: DC to DC.

2. DC-DC Converters

The DC-DC chopper is a particular type of static converter that converts an alternating voltage (DC) into another direct voltage with extremely high energy efficiency. DC-DC choppers have wide applications in power supplies, energy storage and electric vehicles because they can maximize energy consumption and improve the system's efficiency. The most common DC-DC converters are of several types **[8]**:

- **Buck Converter:** Converts the input voltage to a lower output voltage.
- **Boost Converter:** Converts the input voltage to a higher output voltage.
- **Buck-Boost Converter:** Steps up or steps down the input voltage, but inverts the output voltage polarity.

3. SEPIC Converter Topology

The SEPIC converter **Figure 2.1.** is a highly rated DC/DC power converter type, admired for its efficiency and flexibility. With its simple topology, the SEPIC converter is capable of producing an output voltage greater, less, or the same as its input voltage, but of the same polarity. This adaptability is particularly useful for **PV Systems**, which have flexible voltage conversion in order to harvest maximum energy **[9]**.

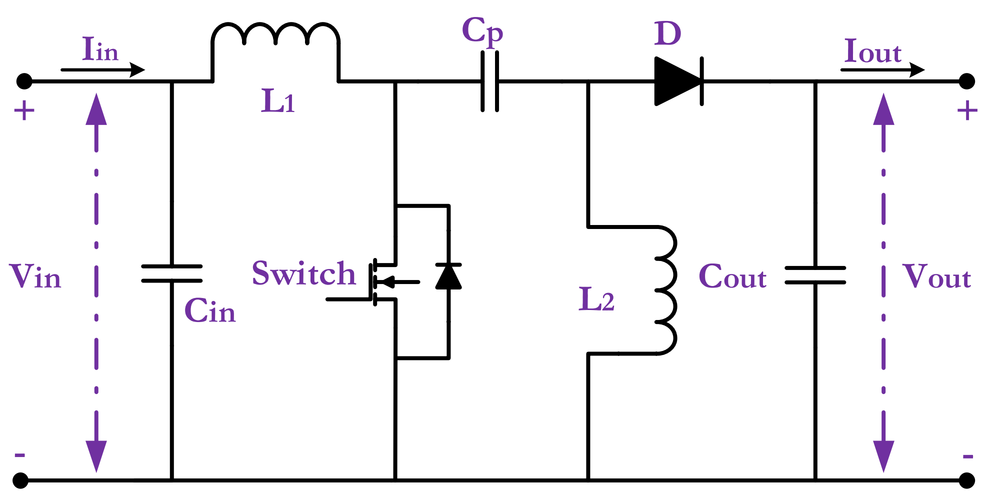

Figure 2.1. SEPIC Converter Circuit.

The input and output voltage relation is given by **Equation 1**.

$$V_{out} = V_{in}\frac{D}{1-D} \quad (1)$$

Where D is the duty-cycle.

When power losses are not considered, then **Equation (2)**.

$$P_{in} = P_{out} \quad (2)$$

$$V_{in}I_{in} = V_{out}\, I_{out} \quad (3)$$

By putting **Equation (1)** into **Equation (3)**, we get **Equation (4)**.

$$I_{out} = I_{in}\frac{1-D}{D} \quad (4)$$

4. Operating Principles of the SEPIC Converter

The SEPIC (Single-Ended Primary Inductor Converter) operates on the principle of controlling the transfer of energy among inductors and a coupling capacitor to maintain the output voltage. The converter consists of two inductors, a coupling capacitor, a switch (MOSFET), a diode, and an output capacitor **[10]**.

The operation of the SEPIC converter can be divided into two distinct states:

4.1. Switch ON (MOSFET Conducting)

- The input voltage is utilized inductor L1 to accumulate energy in its magnetic field.
- The capacitor C1 is charged so that its voltage will be approximately equal to the input voltage.
- The second inductor L2 is excited from capacitor C1 in order to transfer the energy to the load at output.
- The diode (D1) is reverse-biased so that during this phase current does not flow to the output.

The path of current is as depicted in **Figure 2.2**.

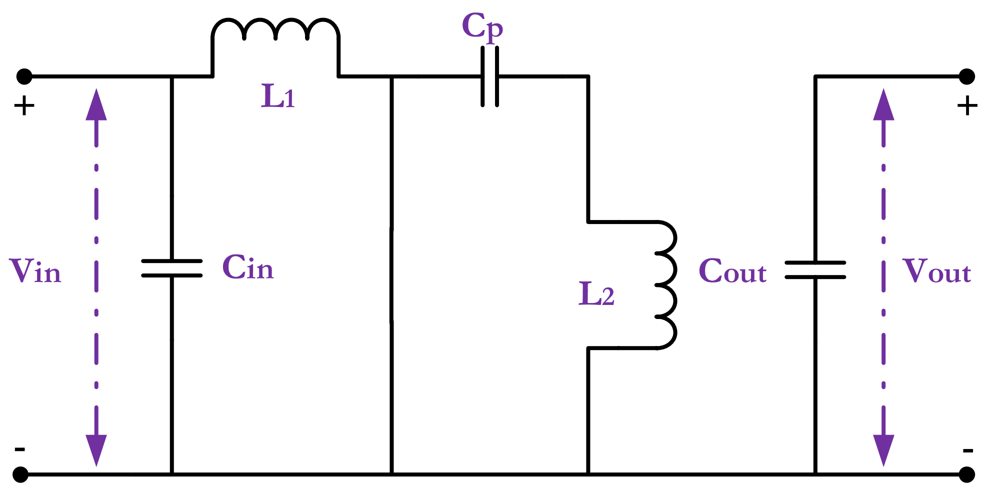

Figure 2.2. The path of current of The SEPIC Converter (Switch is on).

4.2. Switch OFF (MOSFET Not Conducting)

- By continuously switching between these two states, the SEPIC converter maintains a regulated output voltage.
- Inductor L1 releases its stored energy to capacitor C1 and inductor L2, continuing to supply the output.
- Inductor L2 continues to supply current to the load via diode D1, now turning forward-biased.
- Capacitor C2 filters the voltage, supplying a stable DC output.
- By continuously switching between these two modes, the SEPIC converter delivers a regulated output voltage.

The path of current is as depicted in **Figure 2.3**.

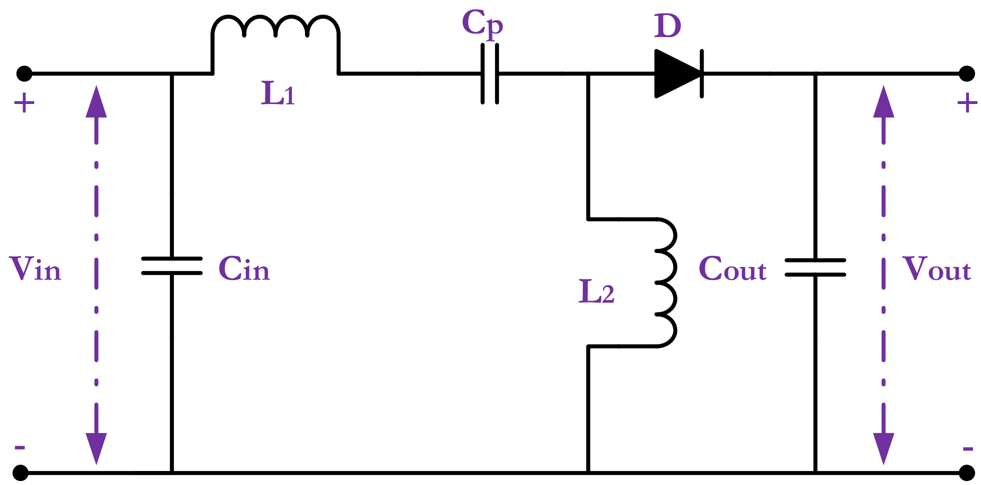

Figure 2.3. The path of current of the SEPIC Converter (Switch is off).

5. Operation Modes of the SEPIC Converter

5.1. Continuous Conduction Mode (CCM)

- The current through both inductors (L1 and L2) **never falls to zero** during the switching period.
- Delivers a steady output voltage with a **minimized ripple**.
- It is the preferred method for high-power applications.

5.2. Discontinuous Conduction Mode (DCM)

- The current through one or both inductors **drops to zero** before the next switching cycle begins.
- Happens at **light load conditions** or when the switching frequency is low.
- Has a **simpler control strategy** but suffers from increased ripple and reduced efficiency.
- Suitable for **low-power applications**.
- The inductor current **decreases to zero** prior to the beginning of the succeeding switching cycle.

- Happens at **low switching frequency**.
- Recommended for **low-power applications**.

6. Mathematical Modeling of SEPIC Converter

Mathematical modeling is necessary to examine the voltage conversion ratio, capacitor voltages, and inductor currents **[11]**.

- **Duty Cycle Calculation**

$$D = \frac{V_{out} + V_D}{V_{pv} + V_{out} + V_D} \quad (5)$$

Its maximum is:

$$D_{max} = \frac{V_{out} + V_D}{V_{pv(min)} + V_{out} + V_D} \quad (6)$$

- **Inductor Calculation**

The inductance values are defined mainly by the accepted ripple current. As a general rule, the maximum allowable ripple is 40% of the maximum Input current. The ripple current is defined by the following equation **[12]**:

$$\Delta I_l = I_{in} \times 40\% = V_{out} \times \frac{V_{out}}{V_{in(min)}} \times 40\% \quad (7)$$

$L_1 et\ L_2$ are defined as:

$$L_1 + L_2 = \frac{V_{in(min)}}{\Delta I_l \times f_{sw}} \times D_{max} \quad (8)$$

- **Coupling Capacitor Calculation**

The capacitor C_p must be calculated from the desired voltage ripple defined by the following expression **[13]**:

The capacitor C_p can be calculated from the given voltage ripple represented by the following equation **[13]**:

$$\Delta V_C = \frac{I_{out} + D_{max}}{C_p \times f_{sw}} \quad (9)$$

- **Filtering Capacitor Calculation**

C_{in} et C_{out} are given by:

$$C_{in} = C_{out} \geq \frac{I_{out} \times D_{max}}{V_{ripple} \times f_{sw}} \quad (10)$$

Parameters	Variable	Value
Input Capacitor	C_{in}	470 μF
Output Capacitor	C_{out}	470 μF
Inductor L1	L_1	300 μH
Inductor L2	L_2	300 μH
Coupling capacitor	C_P	470 μF
Switching frequency	f_{SW}	25 kHz

Table 2.1. SEPIC Converter Components.

7. Simulation Analysis of SEPIC Converter Under Load Variation

With a constant input of 15 V, the SEPIC converter maintains a stable output around 23.5 V throughout the 10 seconds **Figure 2.4.** operating in boost mode. The absence of voltage fluctuation confirms steady-state operation and good regulation under fixed load conditions.

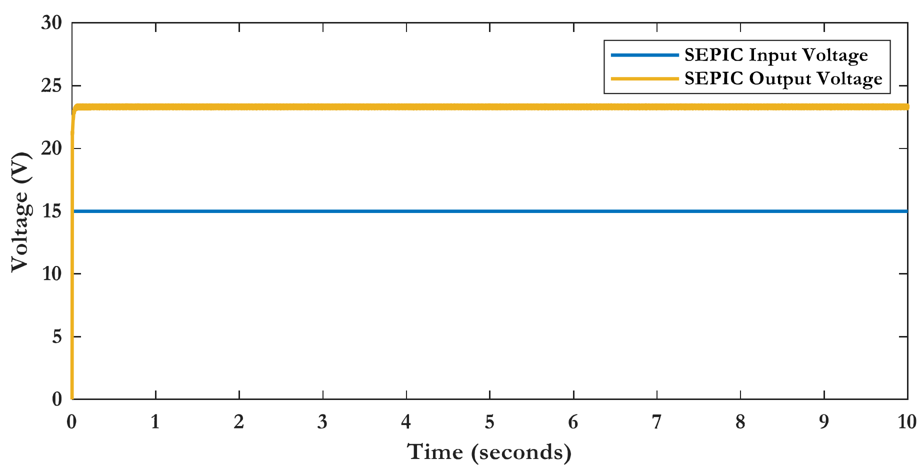

Figure 2.4. SEPIC Voltage Waveforms with a Fixed Load.

The plot **Figure 2.5.** demonstrates the input and output voltage waveforms of a SEPIC (Single-Ended Primary Inductor Converter) over 10 seconds, showing the converter's response to a step change in load around 5 seconds.

Input Voltage Behavior

The input voltage (**blue line**) is maintained at 15 V throughout the simulation.

Output Voltage Behavior

The output voltage (**yallow trace**) initially rises to about 23.5 V, indicating that the converter is in boost mode, stepping up the 15 V input to meet an increased load requirement.

A step change in load at t = 5 seconds results in a very sudden fall in output voltage from 23.5 V to ~12.5 V

After the transition, the SEPIC controls the output voltage to 12.5 V, now in buck operation, reducing the input voltage to meet the new load requirements.

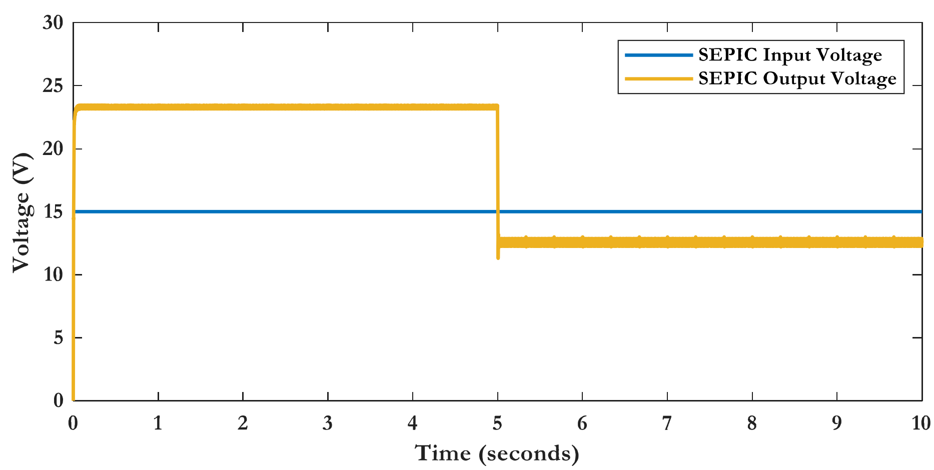

Figure 2.5. SEPIC Voltage Waveforms with a Variable Load.

8. Experimental Setup of the SEPIC Converter on a Breadboard

This section describes the experimental setup of a SEPIC converter on a breadboard:

- **List of Components**: Inductor (300 µH), capacitor (470 µF), fast diode, MOSFET, resistor, etc.

- **Breadboard Design and Wiring**: Assembly step-by-step procedure.

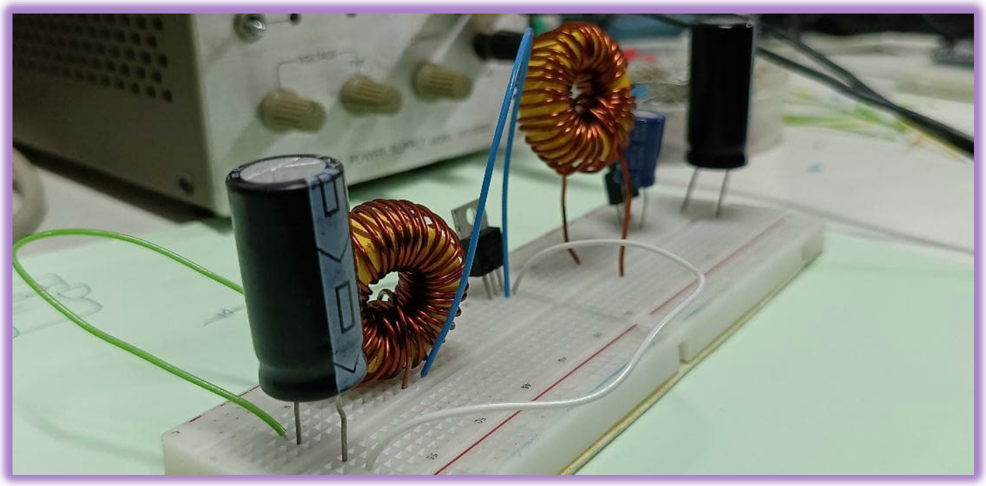

Figure 2.6. Breadboard, Wiring and Components.

- **Testing Equipment**:

  - **Multimeter** for voltage and current measurements.

Figure 2.7. Multimeter.

- **Oscilloscope** to analyze waveforms.

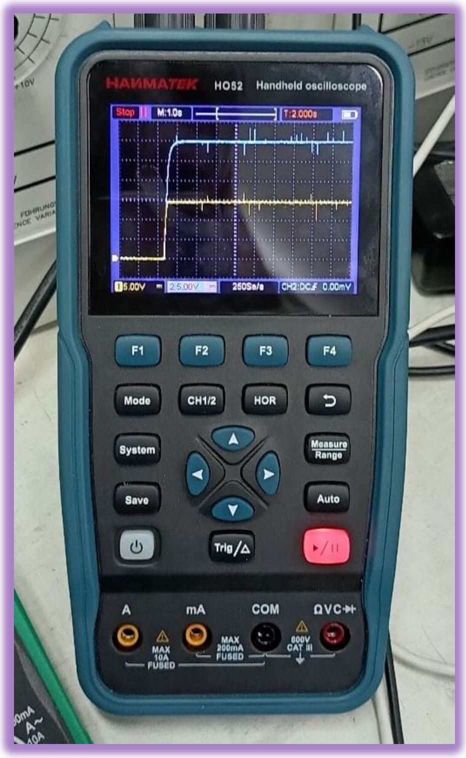

Figure 2.8. Oscilloscope.

- **Regulated Power Supply** the input voltage.

Figure 2.9. Power Supply.

9. Results and Discussion

Experimental validation of the SPIEC converter provided valuable information regarding its efficiency, performance, and stability in practice. Experimental test was made on a breadboard with components: inductor, capacitor, fast diode, MOSFET, and resistor. Test equipment utilized was a multimeter, oscilloscope, and regulated power source to test and examine the SEPIC converter's function.

Figure 2.10. The experimental setup.

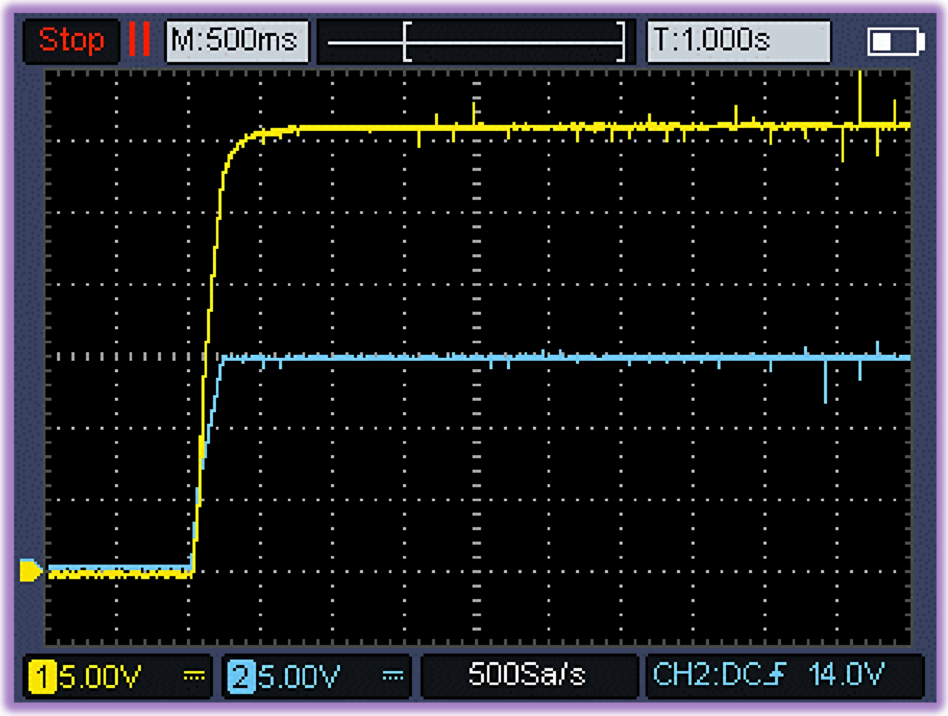

Figure 2.11. The Input voltage (**Blue**) and the Output voltage (**Yellow**) of the SEPIC Converter.

The SEPIC converter was successful in stepping up the input voltage. The input voltage of **15V** was stepped up to **31V**, indicating the ability of the converter to produce a higher output voltage.

The output voltage was also measured with a multimeter and validated by an oscilloscope, which presented the input voltage (**blue line**) and output voltage (**yellow line**) voltage waveforms (**Figure 2.11**). The output voltage waveform had very little ripple, indicating good filtering of the output capacitor.

10. Conclusion

This chapter has given a detailed overview of SEPIC converters, their operation, design aspects, and operation in real life. The mathematical modeling and test configuration demonstrate the SEPIC converter's effective voltage regulation.

Chapter

3 Analysis of a Perturb and Observe Based MPPT System

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1. Introduction

PV power plants are needed to adapt continuously to environmental alterations especially to irradiance and temperature in order to provide a maximum energy output. MPPT strategies play a vital role here, having the PV array operate at or near its MPP. Although many studies have accounted for MPPT behaviors under varying irradiance and temperature conditions, the effect of variable electrical load conditions is significant but mostly not investigated thoroughly **[14]**. The performance of a Perturb and Observe (P&O) type MPPT controller under dynamic load conditions is discussed in this chapter.

The P&O algorithm is chosen due to its simplicity of implementation and frequent use in embedded MPPT controllers. In this case, it is paired with a SEPIC topology that delivers step-down and step-up voltage control. Simulation and hardware experimentation are employed in this research to investigate the tracking performance, stability, and bounds of the system as the load impedance changes dynamically **[15]**.

This chapter begins with a theoretical description of the P&O algorithm. The dynamic performance of the MPPT system is subsequently analyzed using simulation models during instantaneous loading changes. Experimental confirmation shown of the operation of P&O under variable load.

2. MPPT Fundamentals and P&O Algorithm

2.1. MPPT Basics

The power output of a PV panel is non-linearly related to solar irradiance and temperature. For any given environmental condition, there exists an operating point known as the MPP at which the product of voltage and current is maximum. To operate at this point guarantees that the PV system delivers its maximum available power to the load **[16]**.

But due to ongoing alterations in the environmental conditions such as cloud movement, time of day, and room temperature the MPP continues to alter. For harvesting maximum power under such changing conditions MPPT algorithms are needed. MPPT algorithms are needed for continuously altering the operating point of the PV panel by altering a control variable typically the duty cycle of a DC-DC converter to trace the MPP in real-time **[16]**.

This section addresses the P&O algorithm, which is one of the simplest and most implemented MPPT techniques in real systems, notably low-cost systems and embedded ones.

2.2. P&O Algorithm

The P&O algorithm is based on a simple feedback mechanism. It perturbs duty cycle of the converter slightly and observes the resultant alteration in the output power. Based on whether the power increases or decreases, the algorithm decides the direction of the upcoming disturbance **[17]**.

The steps in general are:

1. Measure the voltage and current of the PV array to calculate the output power $\boldsymbol{P = V \times I}$.
2. Compare the current power $\boldsymbol{P(k)}$ with the previous power $\boldsymbol{P(k-1)}$.
3. If the power is greater following the last perturbation:
    - Continue perturbing in the same direction.
4. If the power is decreased:
    - Reverse the direction of perturbation.
5. Do this continuously repeatedly.

The converter duty cycle is updated accordingly, thereby fixing the PV voltage in the direction of the MPP **[17]**.

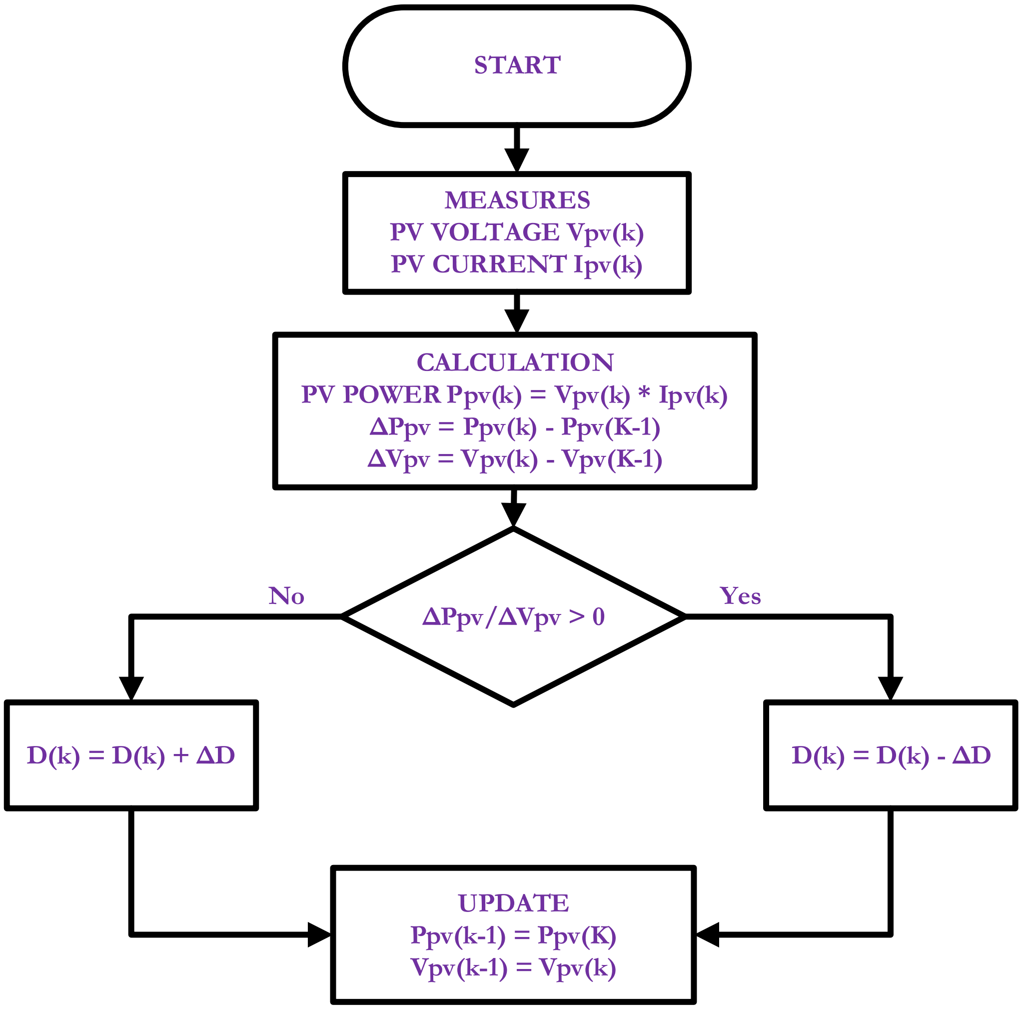

Figure 3.1. Flowchart of the P&O algorithm.

2.3. Advantages of P&O

P&O method has several benefits that render it highly suitable for low-power and embedded MPPT applications [18]:

- Relative simplicity: The method is easy to understand and implement, especially on small microcontrollers like Arduino.
- Complicatedness of computation: In comparison with advanced methods like fuzzy logic or neural networks, P&O entails no computationally intensive calculations, reducing processing overhead.

- Real-time operation: It may be implemented with minimal delay, enabling fast response to dynamic situations.
- Compatibility: It is applicable to a wide range of DC-DC converter topologies (e.g., Buck, Boost, SEPIC, Zeta).

2.4. Trade-off Between Step Size and Response

The size of the perturbation step has a crucial impact on performance:

Small step size:

- Increased accuracy and reduced ripple.
- Reduced rate of tracking when conditions change rapidly.

Large step size:

- Faster response.
- More oscillations and possible instability.

Thus, a fixed-step P&O algorithm can neither achieve high accuracy nor good dynamic response simultaneously.

3. Dynamic Simulation Analysis

This section contrasts the dynamic performance of the P&O-based MPPT system with a SEPIC converter. Focus is on the system response to different perturbation step sizes as well as variable load conditions. Simulation results illustrate implications to tracking efficiency, ripple, and stability.

The objective of this simulation is to evaluate the performance of the P&O MPPT algorithm for a PV system using a SEPIC converter. The main objective is to evaluate the response of the P&O method during load variation cases.

To this end, the simulation was conducted under two load levels to observe how the algorithm would respond to sudden changes in load demand and how it would re-track the MPP when disturbed.

3.1. Steady-State and Transient Response

The operation of the P&O algorithm was tested using different perturbation step sizes. The system response was measured under steady irradiation and load conditions to assess tracking behavior near the MPP.

Figure 3.2. illustrates the system response for employing a **large step size** in perturbation.

- For **large step size**, the MPPT algorithm provides **fast responses** to operating condition variations and reaches the MPP rapidly in fewer cycles.
- But this creates **severe fluctuations** in PV output.
- Even though convergence is faster, the system never stabilizes at a precise MPP point, resulting in constant power loss in the form of ripple.

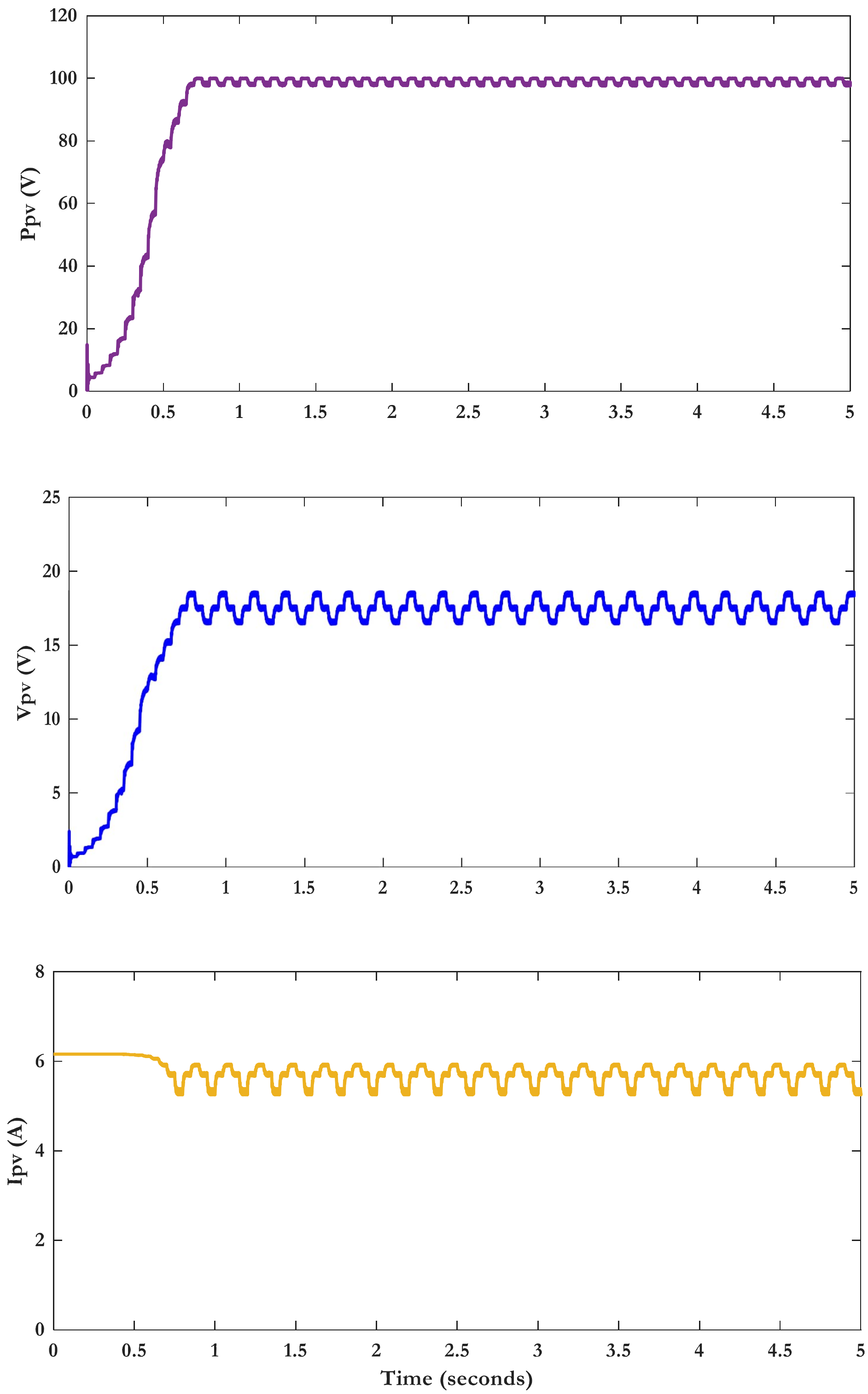

Figure 3.2. PV Waveforms with Large Step-Size.

Figure 3.3. represents the PV system response for **small step size**.

- The system possesses much smaller ripple and higher steady-state accuracy.

- However, the tracking speed is slow and response to change in operating conditions is low.
- This demonstrates the traditional trade-off in classical P&O: fast convergence vs. small ripple.

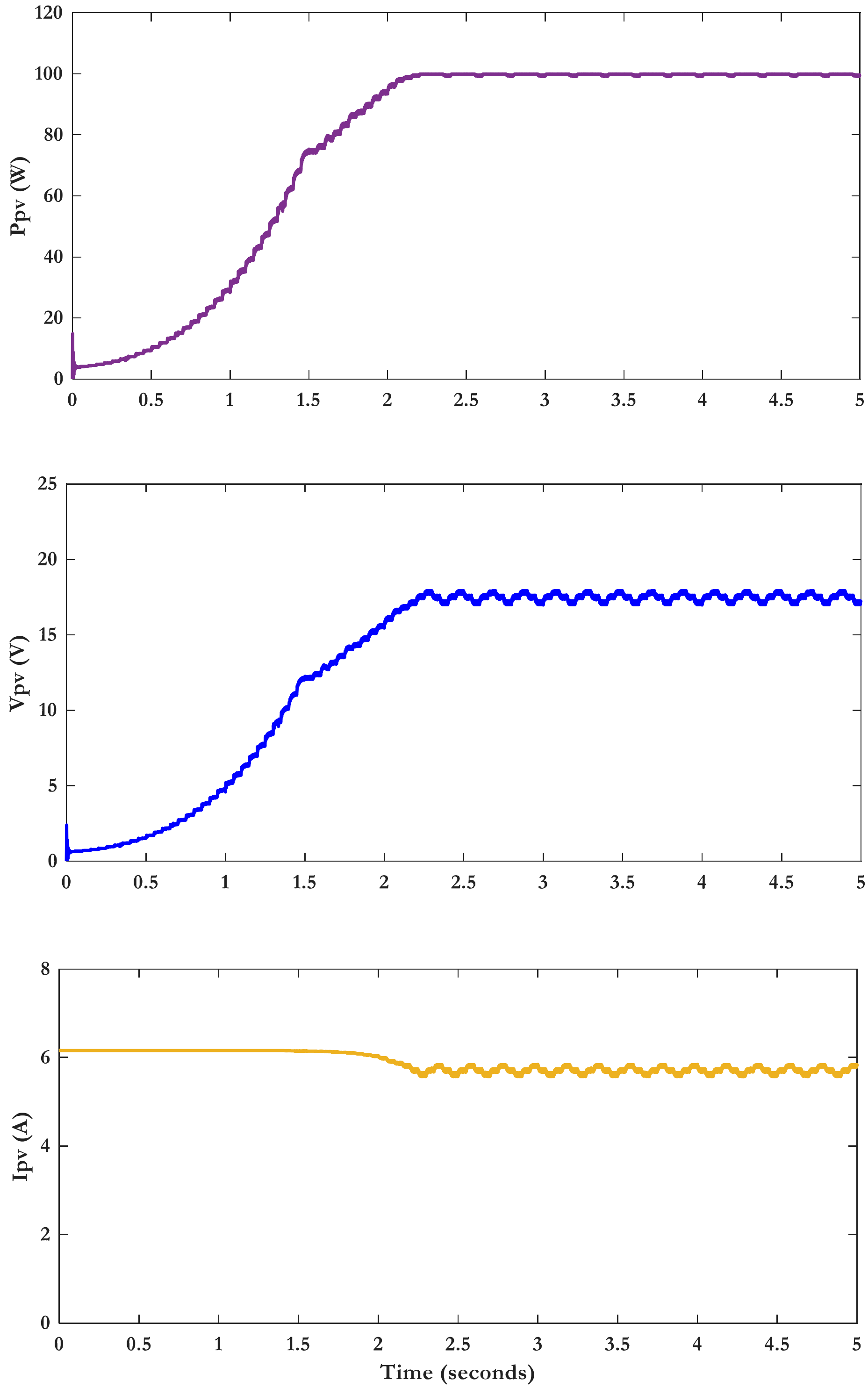

Figure 3.3. PV Waveforms with Small Step-Size.

Comparing Figures 3.1 and 3.2:

- **Large step size Figure 3.1.** leads to large voltage ripple and power ripple of around 4%.
- **Small step size Figure 3.2.** erases voltage ripple and slows down power oscillations to less than 2%.
- Response time is reduced with large steps but **high perturbation appears**.
- Perturbation is reduced with small steps but **slow response**.
- These results point to the careful selection of the size of the perturbation step taking into consideration the application sensitivity to ripple and its dynamic response requirements.
- **Figure 3.3** illustrates the system's behavior under dynamic load conditions.

3.2. Capability of the P&O Algorithm Under Variable Load

With a sudden change in the load, the current and output voltage of the PV immediately change. This may confuse the P&O algorithm so that it may misinterpret the change as a result of its own perturbation. Hence, it can temporarily shift towards the negative direction.

But as **Figure 3.4** illustrates, the algorithm can nevertheless come back to the MPP after a few cycles. The convergence is slower and ripple is greater in transients compared to before, but the system remains stable and functioning.

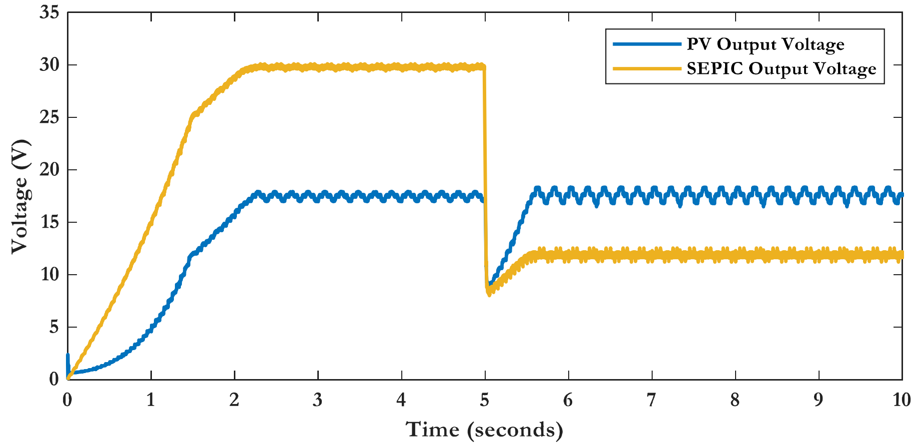

Figure 3.4. PV Waveforms with Variable Load.

3.3. Combined Behavior: MPPT with SEPIC Under Variable Load

The combination of P&O algorithm and SEPIC converter presents a stable solution:

- The SEPIC provides voltage flexibility in varying load conditions.
- The P&O algorithm controls the duty cycle and re-tracks the MPP under disturbances.

Short-term tracking errors result from dynamic load variations but the system stabilizes quickly, exhibiting excellent MPP tracking for realistic conditions.

4. Analysis of Experimental Results

The objective of this experimental validation **Figure 3.5.** is to evaluate the performance of the P&O MPPT algorithm with two different perturbation step sizes small and large within a PV panel **Figure 3.6.** and the SEPIC converter. The goal is to examine the influence of step size on tracking response and system performance.

The purpose of this experimental research is to:

- Assess the effects of step size (small vs. large) on precision in tracking and rate of convergence.
- Analyze output parameters such as ripple, settling time, and stability for all configurations.
- Identify the trade-offs between fast tracking (large step size) and steady-state accuracy (small step size) in a real setup.

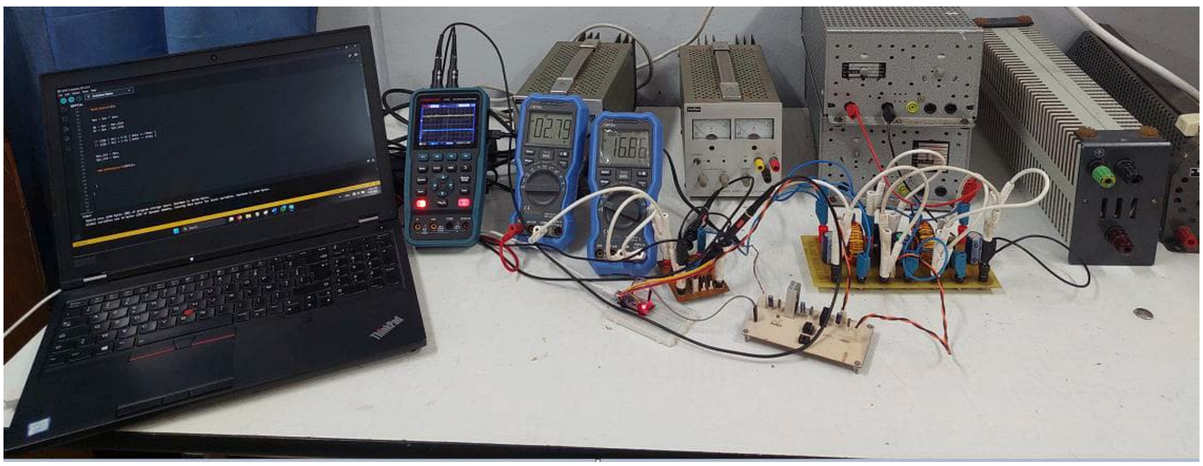

Figure 3.5. Experimental PV system.

Figure 3.6. PV Panel used in the Experiment.

4.1. Analysis of Step Size Impact on MPPT Performance

Figure 3.7. shows the PV system waveforms for the case of applying a large perturbation step size, while **Figure 3.8.** provides the performance with a small step size under the same operating conditions.

From the **Figure 3.7.** it is clear that the **larger step size** causes the system to **converge to the MPP faster**, as evidenced from the steep initial voltage and current rises. The waveforms, however, also suffer from **large oscillations** under steady state, as is evident on the current signal **yellow trace** and the voltage signal **bleu trace**. These are strictly a consequence of low resolution in perturbations, causing the system to overshoot and undershoot the actual MPP continuously.

On the other hand, **Figure 3.8.** shows that with a **small step size**, the system **converges to the MPP more slowly** but with the current **yellow trace** and voltage **bleu trace** signals subsequently smoother.

This demonstrates the expected trade-off: **small step sizes** improve accuracy and reduce ripple but with the cost of slower convergence in dynamic transitions.

These results demonstrate that:

Large step size achieves **faster MPP tracking** but with **greater ripple and potential power loss**.

Small step size increases steady-state efficiency by **minimizing oscillations** but at the cost of **increased response time**.

For practical systems, step size choice has to be a **trade-off** between response time and stability depending on how sensitive the application is to ripple and tracking delay.

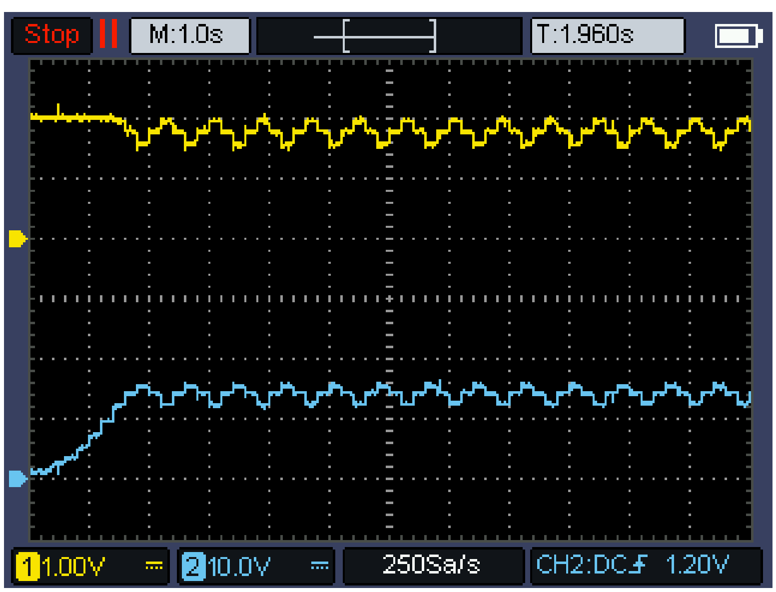

Figure 3.7. PV Waveforms with Large Step-Size.

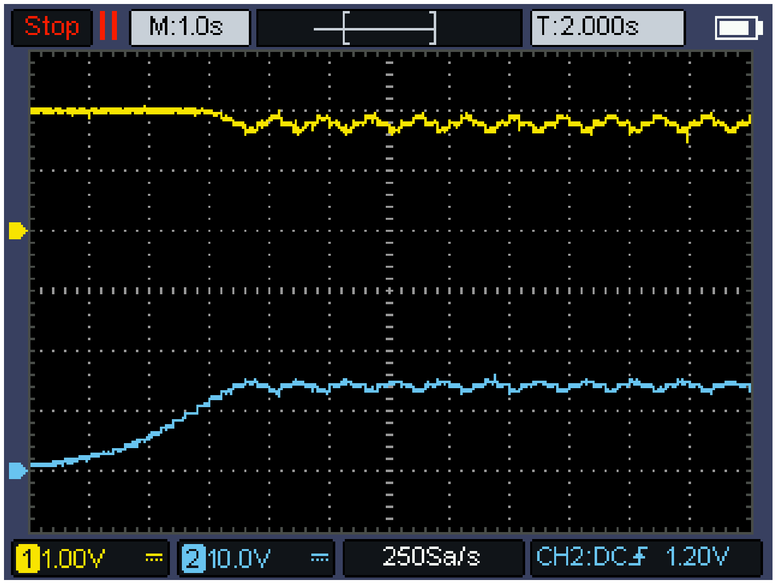

Figure 3.8. PV Waveforms Small Step-Size.

5. Conclusion

This chapter presented an in-depth analysis of the Perturb and Observe (P&O) MPPT algorithm for a photovoltaic system using a SEPIC converter, including step size and load change effects.

Through simulation and experimental verification, the following key points were noted:

A larger step size achieves faster convergence to the Maximum Power Point (MPP) but with bigger steady-state oscillations, leading to less power efficiency.

A smaller step size provides smoother operation with less ripple but slower track speed, particularly noticeable during fast load or irradiance changes.

The SEPIC converter, in being able to perform both buck and boost operation, easily allows MPPT under varying input and load conditions, voltage regulation being retained throughout.

Under variable load, the classical P&O algorithm is still active, but its convergence is slower because it is not able to differentiate between power changes due to its own perturbation and power changes due to load variation.

Overall, the study confirms that while the classical P&O method is simple and effective, its performance is both step-size sensitive and load dynamic sensitive. The findings provide a foundation for future improvements such as adaptive step-size methods or hybrid approaches to realize both precision and tracking speed under actual operating conditions.

Perspectives

This work demonstrated the effectiveness of the P&O algorithm with a SEPIC converter for MPPT under variable load conditions. For future work, the following improvements are suggested:

- Implement an **adaptive step-size** P&O to improve both speed and precision.
- **Compare with other MPPT techniques** such as Incremental Conductance or fuzzy logic.
- Study system behavior under **partial shading** to evaluate tracking robustness.
- Improve **hardware performance** using faster controllers or optimized converter design.

References

[1] M. G. Villalva, J. R. Gazoli, and E. R. Filho, “Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays,” IEEE Transactions on Power Electronics, vol. 24, no. 5, pp. 1198–1208, May 2009, doi: 10.1109/TPEL.2009.2013862.

[2] C. Vermesan and T. Østerbø, “Modeling and Simulation of Photovoltaic Cells,” in Proceedings of the International Conference on Renewable Energies and Power Quality (ICREPQ’11), Las Palmas de Gran Canaria, Spain, Apr. 2011.

[3] A. D. Rajapakse, D. Muthumuni, and A. P. Meliopoulos, “Simulation of photovoltaic systems using PSCAD/EMTDC,” in 2006 IEEE Power Engineering Society General Meeting, Montreal, QC, Canada, 2006, pp. 1–8, doi: 10.1109/PES.2006.1709156.

[4] J. A. Gow and C. D. Manning, “Development of a Photovoltaic Array Model for Use in Power-Electronics Simulation Studies,” IEEE Proceedings - Electric Power Applications, vol. 146, no. 2, pp. 193–200, Mar. 1999, doi: 10.1049/ip-epa:19990028.

[5] S. R. Bull, “Renewable Energy Today and Tomorrow,” Proceedings of the IEEE, vol. 89, no. 8, pp. 1216–1226, Aug. 2001, doi: 10.1109/5.940290.

[6] M. A. Green, “Solar Cells: Operating Principles, Technology, and System Applications,” Englewood Cliffs, NJ, USA: Prentice-Hall, 1982.

[7] Mohan, N., Undeland, T. M., & Robbins, W. P. (2003). *Power Electronics: Converters, Applications, and Design* (3rd ed.). Wiley.

[8] Erickson, R. W., & Maksimović, D. (2001). *Fundamentals of Power Electronics* (2nd ed.). Springer.

[9] Rashid, M. H. (2011). *Power Electronics: Circuits, Devices, and Applications* (4th ed.). Pearson.

[10] Kazimierczuk, M. K. (2015). *Pulse-Width Modulated DC-DC Power Converters* (2nd ed.). Wiley.

[11] Hart, D. W. (2011). *Power Electronics* (1st ed.). McGraw-Hill Education.

[12] Basso, C. P. (2014). *Switch-Mode Power Supplies: SPICE Simulations and Practical Designs* (2nd ed.). McGraw-Hill Education.

[13] Pressman, A. I., Billings, K., & Morey, T. (2009). *Switching Power Supply Design* (3rd ed.). McGraw-Hill Education.

[14] H. Patel and V. Agarwal, "MATLAB-Based Modeling to Study the Effects of Partial Shading on PV Array Characteristics," IEEE Transactions on Energy Conversion, vol. 23, no. 1, pp. 302–310, Mar. 2008, doi: 10.1109/TEC.2007.914308.

[15] S. Jain and V. Agarwal, "Comparison of the Performance of Maximum Power Point Tracking Schemes Applied to Single-Stage Grid-Connected Photovoltaic Systems," IET Electric Power Applications, vol. 1, no. 5, pp. 753–762, Sept. 2007, doi: 10.1049/iet-epa:20060361.

[16] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays," IEEE Transactions on Power Electronics, vol. 24, no. 5, pp. 1198–1208, May 2009, doi: 10.1109/TPEL.2009.2013862.

[17] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, "Optimization of Perturb and Observe Maximum Power Point Tracking Method," IEEE Transactions on Power Electronics, vol. 20, no. 4, pp. 963–973, Jul. 2005, doi: 10.1109/TPEL.2005.850975.

[18] T. Esram and P. L. Chapman, “Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques,” IEEE Transactions on Energy Conversion, vol. 22, no. 2, pp. 439–449, Jun. 2007, doi: 10.1109/TEC.2006.874230.