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Realization of a Curve Plotter for Photovoltaic Systems

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Dedication

I lovingly dedicate this work to my dear parents, whose unconditional love, endless sacrifices, and constant support have guided me throughout every stage of my life. Their encouragement, patience, and prayers have always been my greatest source of strength and inspiration. No words can truly express my gratitude for everything they have done for me. They believed in me during difficult times, motivated me to keep moving forward, and stood by my side in every challenge I faced. This achievement is not mine alone, but also theirs, for without their care, trust, and dedication, reaching this milestone would not have been possible. May Allah bless them, protect them, and reward them with happiness and health for all they have given me. I hope I can make you happy and proud someday.

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Abstract

This final-year project presents the design and development of an I–V curve tracer for photovoltaic systems. The device is used to analyse and display the electrical characteristics of solar panels by plotting their I–V curves, measuring key parameters such as the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}), and calculating the output power and fill factor. The system includes a coloured display and data storage functionality for measurement monitoring. After simulating and validating the electronic circuits, a prototype was implemented and tested both in the FABLAB and with a real photovoltaic panel to verify its proper operation and performance.

Keywords: photovoltaic system, I-V curve plotter, solar panel characterization.

Résumé

Ce projet de fin d'études porte sur la conception et la réalisation d'un traceur de courbe I–V pour les systèmes photovoltaïques. Le dispositif permet d'analyser et d'afficher les caractéristiques électriques des panneaux solaires en traçant leurs courbes courant–tension (I–V), en mesurant des paramètres importants tels que le courant de court-circuit (I_{sc}) et la tension en circuit ouvert (V_{oc}), ainsi qu'en calculant la puissance de sortie et le facteur de forme. Le système intègre un écran couleur ainsi qu'une fonctionnalité de stockage des données pour le suivi des mesures. Après la simulation et la validation des circuits électroniques, un prototype a été réalisé puis testé au FABLAB ainsi qu'avec un panneau photovoltaïque réel afin de vérifier son bon fonctionnement et ses performances.

Mots-clés : Photovoltaïque, Traceur de courbe I–V, Caractérisation des panneaux solaires.

ملخص

يتمحور مشروع التخرج هذا حول تصميم وإنجاز جهاز لتتبع منحنى التيار–الجهد (I–V) الخاص بالأنظمة الكهروضوئية. يتيح هذا الجهاز تحليل وعرض الخصائص الكهربائية للألواح الشمسية من خلال رسم منحنيات التيار–الجهد (I–V)، وقياس بعض المعلمات المهمة مثل تيار القصر (I_{sc}) وجهد الدارة المفتوحة (V_{oc})، بالإضافة إلى حساب القدرة الخارجة ومعامل الامتلاء. يتضمن النظام شاشة ملونة ووظيفة لتخزين البيانات من أجل متابعة القياسات. بعد محاكاة الدوائر الإلكترونية والتحقق من صحتها، تم إنجاز نموذج أولي للجهاز واختباره داخل FABLAB ثم باستخدام لوحة شمسية حقيقية، وذلك للتأكد من حسن عمله وأدائه.

الكلمات المفتاحية: ألواح شمسية، خصائص الألواح الشمسية، منحنى I–V.

List of abbreviations

P-N junction: Positive-Negative Junction

EHP: Electron-hole Pair

PV: Photovoltaic

PERC: Passivated Emitter and Rear Cell

UV: Ultraviolet

n-type: Negative type

p-type: Positive type

E_g: Gap Energy

E_v: Valence Band Energy

E_c: Conduction Band Energy

p-region: Positive region

n-region: Negative region

SDM: Single-Diode Model

MPP: Maximum Power Point

MPPT: Maximum Power Point Tracker

FAQ: Foire Aux Questions

B2B: Business to business

I_{sc}: Short Circuit Current

V_{oc}: Open Circuit Voltage

STC: Standard Test Conditions

P: Power

V: Voltage

I: Current

V_{mp}: Voltage at Maximum Power

I_{mp}: Current at Maximum Power

P_{max}: Maximum Power

P&O: Perturb & Observation

OPC: Operating Conditions

GPV: Photovoltaic Generator

ADC: Analog-to-digital Converter

DC: Direct Current

PWM: Pulse Width Modulation

IGBT: Insulated Gate Bipolar Transistor

BJT: Bipolar Junction Transistor

SMPS: Switched-mode Power Supply

IP-: Negative Input

IP+: Positive Input

PCB: Printed circuit board

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General Introduction

Over the past few decades, the global energy landscape has undergone a profound transformation. Faced with the growing threats of climate change, fossil fuel depletion, and rising energy costs, nations and industries alike have increasingly turned to renewable energy sources as a sustainable alternative. Among these, solar energy stands out as one of the most promising and widely adopted solutions, offering a virtually inexhaustible supply of clean power harvested directly from sunlight at no fuel cost.

This global shift has been further accelerated by favorable government policies, financial incentives, and a sharp decline in the cost of photovoltaic (PV) technology over the last two decades. As a result, a growing number of companies, institutions, and individuals are investing in installing photovoltaic systems, both for economic benefit and as part of a broader commitment to environmental responsibility. From an environmental standpoint, solar energy produces no greenhouse gas emissions during operation, requires no water for electricity generation, and significantly reduces dependence on carbon-intensive energy sources, making it a cornerstone of the global effort to limit global warming and protect ecosystems from the harmful effects of pollution and resource extraction.

A photovoltaic panel is a carefully engineered assembly composed of multiple solar cells, typically made of silicon, arranged in a grid and protected by tempered glass on the front surface and an encapsulant material that binds the layers together, ensuring both mechanical stability and electrical insulation. Despite their apparent robustness, solar panels are continuously exposed to harsh outdoor conditions, including ultraviolet radiation, thermal cycling, humidity, and mechanical stress, which inevitably lead to various types of defects and degradation over time.

These failures can be broadly classified into two categories. The first includes defects that are visually detectable upon direct inspection, such as broken or shattered glass, delamination of the encapsulant, discoloration, and corrosion of connectors or junction boxes. The second, and arguably more critical, category encompasses defects that are invisible to the eye, such as microcracks within the solar cells, potential-induced degradation (PID), and hot spots, localized areas of abnormally high temperature caused by partial shading, cell mismatch, or internal resistance anomalies. These hidden defects require specialized diagnostic tools and techniques for their detection, including thermographic imaging, electroluminescence analysis, and precise electrical measurements of key parameters such as current (I) and voltage (V) under controlled conditions.

Failure to detect and address these defects promptly, whether visible or not, inevitably manifests as a progressive deterioration in panel performance. The actual power output of the panel gradually deviates from the rated specifications indicated on its nameplate, leading to reduced energy yield, financial losses, and in some cases, safety hazards. This underscores the critical importance of regular diagnostic procedures throughout the operational lifetime of a photovoltaic installation, in order to ensure optimal performance, extend service life, and maximize the return on investment.

The presented work focuses on the design and implementation of a dedicated measurement device capable of acquiring the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of a photovoltaic panel, computing key performance indicators such as the maximum output power and the fill factor, and plotting the current-voltage (I-V) and power-voltage (P-V) characteristics. The system is further equipped with a color display and a data storage application, providing an intuitive and practical interface for the user.

In order to achieve these objectives, the work was organized into four chapters. In the first chapter, we laid the theoretical foundations necessary for understanding the subject by reviewing the general principles of photovoltaic systems, from the fundamental definitions and the physical composition of a solar panel to the electrical characteristics of the photovoltaic cell. In the second chapter, we addressed the different existing methods used for I-V curve tracing, examining the operating principle and the specific characteristics of each approach. Building on the conclusions drawn from this comparison, the third chapter was devoted to the selection of the electronic load method as the most appropriate solution, followed by a simulation phase carried out using Proteus 8, with the aim of validating the correct functioning of the chosen components and circuits before moving to physical realization. Finally, the fourth chapter focused on the practical implementation of the project, covering the assembly of the circuits on breadboards, the design and fabrication of the printed circuit boards (PCBs), and the encapsulation of the final device, with tests conducted at each stage to ensure that every circuit performs its intended function correctly. The work concludes with an economic study, assessing the viability and potential interest of this project within the growing photovoltaic and renewable energy market.

CHAPTER 1: General Principles About Photovoltaic Modules

1-1 Introduction

It is essential to understand how solar modules convert light into electricity and how their electrical behaviour can be described mathematically. This chapter explores the fundamental principles behind this conversion, from the internal structure of a solar cell to the key electrical parameters that define its performance. A widely adopted mathematical model is introduced to represent the current-voltage relationship, along with the basic algorithm used to ensure that the module consistently operates at its maximum power point under varying environmental conditions. Together, these concepts establish the theoretical groundwork for the rest of this work.

1-2 Definition Of a Photovoltaic System

The photovoltaic effect was first discovered by Edmond Becquerel, a French scientist, in 1839 [1]. Sunlight is composed of photons, or packets of energy. These photons contain various amounts of energy corresponding to the different wavelengths of light. [2]. When photons strike a solar cell, which is a semiconductor P-N junction device. Depending on the technology used, it can be reflected or absorbed, or it can pass through the cell. The absorption of a photon in a solar cell results in the generation of an electron-hole pair (EHP). When an electron passes from an EHP to another across the P-N junction, it will generate a voltage across the junction, which can drive the current in an external circuit [3]. Therefore, power can be extracted from the solar cell. Figure 1.1 illustrates a solar energy schematic.



Figure 1.1: Schematic of Solar Electricity [4]

1-3 Components of a Photovoltaic Module

Connecting individual solar cells is the first step in building a PV module. This step's goal is to arrange the cells in series and parallel configurations in order to produce the necessary voltage and current for a particular application.

Usually, electro-conductive adhesives or copper ribbons are used to connect the front and rear contacts of the cells [4]. The cell pattern is the term used to describe the resulting interconnected structure. The module is enclosed in multiple protective layers to provide mechanical stability and environmental resistance after the cells are joined.

Transparent polymer materials are often placed around the cell layout during the encapsulation process, with a glass layer on the front and a polymer backsheet on the back. These layers preserve electrical insulation and let light into the solar cells while shielding them from moisture, dust, and mechanical strain. Therefore, a typical photovoltaic module is made up of a number of essential parts that cooperate to safeguard the cells and guarantee dependable operation. Figure 1.2 shows the composition of a PV module.

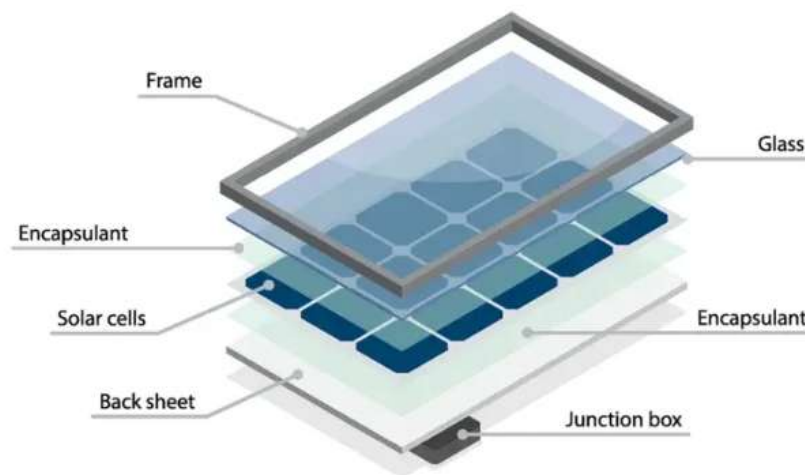


Figure 1.2: Components of a Photovoltaic Module [5]

1-3-1 Glass

A photovoltaic module's front surface is typically composed of tempered glass. This layer works as the first line of defense, allowing sunlight to reach the solar cells while protecting them from external elements like dust, moisture, and mechanical impacts.

1-3-2 Metal Frame

Usually composed of aluminium, encloses the majority of PV modules. Because aluminium is robust, lightweight, corrosion-resistant, and long-lasting enough to endure extended outside exposure, it is commonly employed [5]. The frame not only offers structural support but also makes mounting easier and permits airflow beneath the panels, which can enhance overall performance and thermal management.

1-3-3 Encapsulant

The translucent protective layer known as the encapsulant is positioned between the backsheet and the glass around the solar cells. Its function is to maintain the integrity of the module's many layers while shielding the cells from environmental deterioration, mechanical stress, and moisture. To ensure that sunlight reaches the photovoltaic cells, encapsulant materials must also provide excellent optical transparency and electrical insulation.

1-3-4 Solar cell

The main components of a solar panel are solar cells, sometimes referred to as PV cells. They are usually constructed from semiconductor materials, most frequently silicon, which uses the photovoltaic effect to directly turn sunlight into electricity. An electric current is produced when photons in the semiconductor material are excited by sunlight. Solar cells are made using a variety of technologies. Monocrystalline and polycrystalline silicon cells are the most prevalent varieties.

While polycrystalline cells are made from several silicon crystals and are typically more affordable, monocrystalline cells are made from a single silicon crystal and typically offer superior efficiency [5].

Other technologies include thin-film solar cells, which employ extremely thin layers of photovoltaic material and are lighter and more flexible than crystalline silicon cells, and passivated emitter and rear cell (PERC) structures, which increase efficiency by reflecting unabsorbed light into the cell [5].

1-3-5 Backsheet

The solar module's rear protective layer is formed by the backsheet. It is usually composed of sturdy polymer components that give the module structural strength and electrical insulation.

Additionally, the backsheet shields the interior parts from moisture, UV light, and other environmental elements that could eventually deteriorate the solar cells' effectiveness.

1-3-6 Junction Box

On the rear of the photovoltaic module is a tiny, waterproof housing called the junction box. Its purpose is to contain the solar panel's electrical connections and shield them from the elements. Bypass diodes, which are crucial to preserving module performance, are also present in the junction box. By allowing the electrical current to avoid damaged or shaded cells, these diodes lower power losses and stop the module from overheating [5].

1-4 Photovoltaic Cell

The solar cell is a p-n junction device. The negatively charged electrons provided by donor impurity atoms are referred to as n-type, whereas the positively charged holes produced by acceptor impurity atoms are referred to as p-type. The photovoltaic effect is the foundation of solar cells' operation. Three key processes comprise the PV effect.

1-4-1 Absorption

In a p-n junction electronic semiconductor, photons are absorbed to produce charge carriers (electron-hole pairs).

The absorption of a photon with energy ($E = h\nu$) higher than the gap energy (E_g) of the doped semiconductor material means that its energy is used to excite an electron from the valence band (E_v) to the conduction band (E_c), leaving a void (hole) at the valence level. The excess photon energy ($h\nu - h\nu_0$) gives the electron or hole more kinetic energy. The lowest energy or work function of the semiconductor needed to produce an electron-hole pair is denoted by " $h\nu_0$ " [6]. In a semiconductor, the extra energy is released as heat.

1-4-2 Separation of The Light-generated charge carriers

In an external solar circuit, the holes can flow away from the junction through the p-region, and electrons can flow out across the n-region and pass through the circuit before they recombine with the holes [6].

1-4-3 Electric Circuit

Ultimately, an electric circuit can be powered by the split electrons. It is necessary to design the n-type to be narrower than the p-type. As a result, the electrons can quickly flow across the

circuit and produce current before they recombine with the holes. Additionally, to improve light transmission into the semiconductor material and reduce surface reflection, an anti-reflective coating is applied over the n-layer [5]. Figure 1.3 defines the PV effect

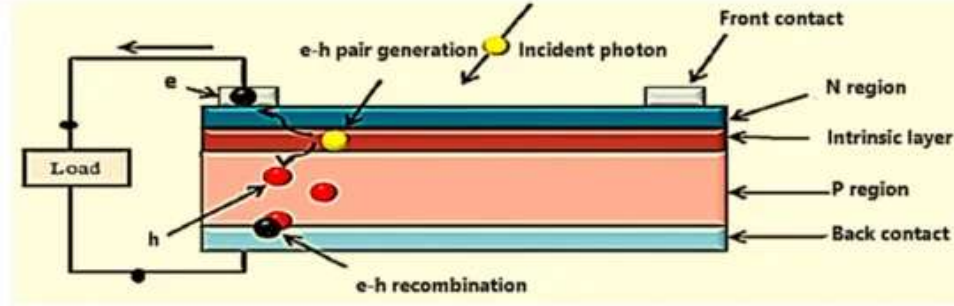


Figure 1.3: Photovoltaic effect [6]

1-4-4 Mathematical Model

It is possible to represent the photovoltaic cell with a mathematical model to make its electrical behaviour easier to understand.

The single-diode model (SDM) is commonly used and offers a favourable balance between accuracy and computational simplicity [7]. Figure 1.4 represents the electric model of the single-diode.

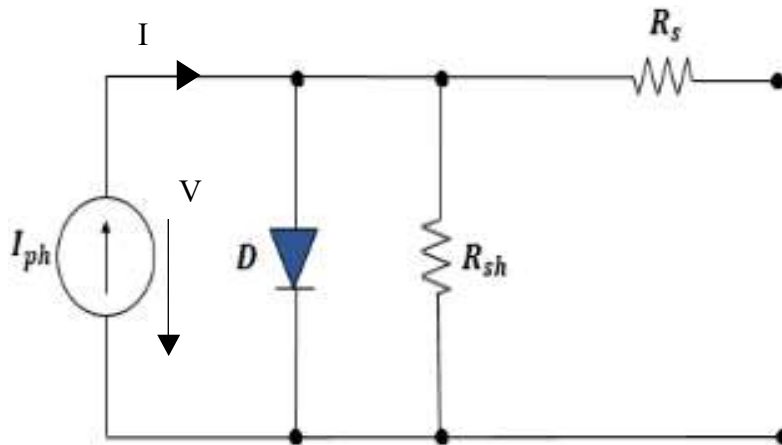


Figure 1.4: single-diode model [7]

Based on Kirchhoff's current law, the relationship between the output current I and the output voltage V is given by the following implicit equation:

$$I = I_{ph} - I_0 \cdot \left[\exp \left(\frac{V + R_s I}{n V_t} \right) - 1 \right] - \frac{V + R_s I}{R_{sh}} \quad (1.1)$$

Where:

$$V_t = \frac{K.T}{q} \quad (1.2)$$

With:

I_{ph}: photocurrent,

I₀: diode saturation current,

q: charge of an electron,

n: factor of ideality of the diode,

R_s: series resistances,

R_{sh}: shunt resistances,

T: temperature in Kelvin,

K: constant of Boltzmann.

1-5 Electrical Characteristics of Solar Panels

PV modules' electrical properties are crucial indicators of their quality and performance. These features include the module's functioning points as well as a few specific metrics, such as maximum power point (MPP), open-circuit voltage (V_{oc}), and short-circuit current (I_{sc}). When designing a PV system, these parameters must be understood.

1-5-1 Standard Test Conditions

It is the industry standard that is used to grade and compare all PV modules. STC is a predetermined set of laboratory test conditions that roughly correspond to the conditions under which solar panels, or PV modules, could be employed.

While other standards provide more accurate real-world approximations, STC is the most often used standard. Since it serves as the foundation for values, the same criterion is also applied while assessing possible installation sites [8]. Three components make up STC: Irradiance, Air Mass, and cell temperature.

1-5-2 Open Circuit Voltage

Open Circuit Voltage (V_{oc}) is the highest voltage that a solar panel can produce under standard test conditions, which include a cell temperature of 25°C, a light intensity of 1000W/m², and an atmospheric density of 1.5. Open-circuit voltage can be measured by connecting a multimeter across the panel's positive and negative terminals.

When solar panels are connected in series, their individual open-circuit voltages sum together. This combined V_{oc} is critical for determining the maximum number of panels that can be safely connected to an inverter or charge controller.

1-5-3 Short Circuit Current

A solar panel's short-circuit current (I_{sc}) is the highest current it can produce when its positive and negative terminals are connected directly, forming a channel with no resistance. The output voltage falls to zero in this situation. In order to measure I_{sc} , an ammeter is connected in series between the terminals of the panel, therefore creating a short circuit. Proper precautions should be taken, even though this test is normally safe for the panel if conducted momentarily in ambient sunshine.

It is used to size protective devices and current-carrying components, such as fuses, circuit breakers, cables, and charge controllers.

1-5-4 Understanding I-V and P-V Curves

A graphical depiction that shows every potential operational position of a solar panel or string, from open circuit to short circuit, is called an I-V (Current-Voltage) curve. It is made by applying a varied load to the PV circuit using a curve tracer, which records hundreds of paired current and voltage (I, V) measurements in a matter of seconds while sweeping from an open to a short circuit. This data is used to create the P-V (Power-Voltage) curve, which displays the power output ($P = V \times I$) at each matching voltage [9]. When combined, they create a comprehensive performance fingerprint that is significantly more insightful than individual metrics like V_{oc} or I_{sc} . The graph below shows how they come together to provide a complete performance fingerprint. Figure 1.5 shows the two electrical characteristics of the PV.

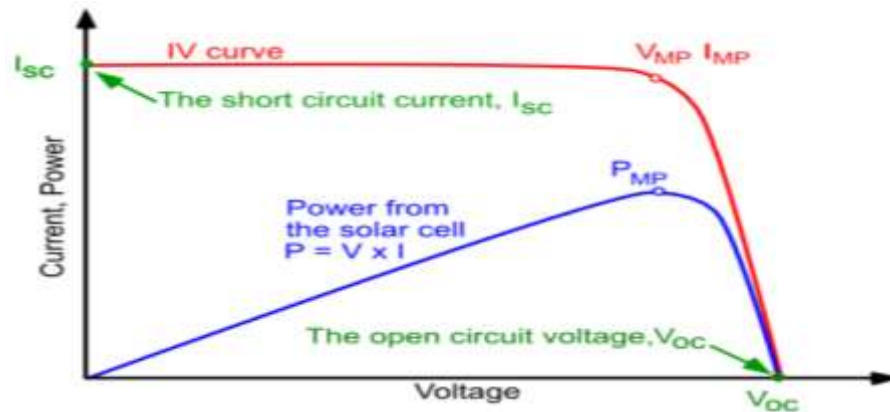


Figure 1.5: (I-V) and (P-V) characteristics curves for a Photovoltaic panel [10]

1-5-5 The Maximum Power Point (MPP) and Basic Tracking Algorithm

a) The Maximum Power Point

The precise working point on a solar panel's I-V and P-V curves where the product of Current (I) and Voltage (V) is maximized, producing the maximum Power (P_{max}) output, is known as the MPP. It is the highest point on the P-V curve. The appropriate position (at voltage V_{mp} and current I_{mp}) on the "knee" of the I-V Curve is where the area of the power rectangle is greatest, as illustrated in Figure 1.5. The MPP is continually changing because to variations in cell temperature and irradiance, or the amount of sunshine.

The majority of the time, a fixed operating voltage would miss this pic, losing a lot of energy. The only function of an MPPT (Maximum Power Point Tracking) charge controller or inverter is to locate and lock onto this moving point automatically and continuously in order to collect the maximum power that can be extracted from the panels [9].

b) The P&O Algorithm

Perturb and Observe (P&O), often known as the "Hill-Climbing" approach, is the most widely used fundamental algorithm. It operates by making little adjustments to the operating voltage on a regular basis and tracking the impact on power production.

Measure: To determine instant power ($P = V \times I$), the controller samples the voltage (V) and current (I) of the panel.

Perturb: The working voltage is then raised (this is the "perturb").

Observe and Compare: Power is measured once more. The new power and the previous power are then compared by the controller [9].

The perturbation shifted the operating point in the direction of the MPP if the power increased ($P_{\text{new}} > P_{\text{old}}$). The voltage will be perturbed in the same direction (increased once more) by the controller. If Power dropped ($P_{\text{new}} < P_{\text{old}}$), the perturbation caused the operating point to migrate past the pic and away from the MPP. The voltage will be disturbed in the opposite direction by the controller, which will lower it the following time [11].

The flowchart illustrates the P&O MPPT algorithm's decision-making process.

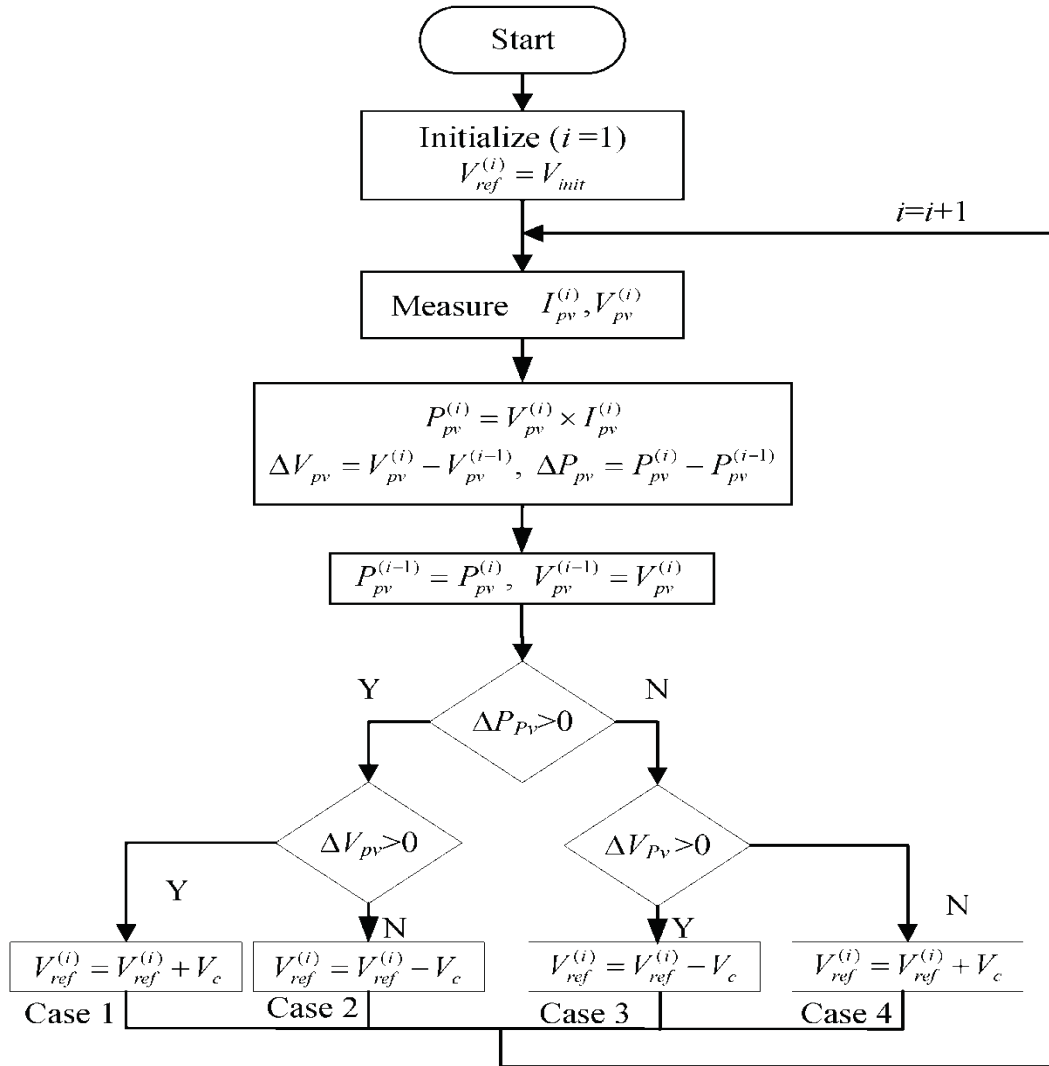


Figure 1.6: The Perturb and Observe (P&O) MPPT algorithm [12]

1-6 Conclusion

The concepts covered in this chapter form the essential knowledge required to understand how photovoltaic modules operate and how their electrical behaviour can be mathematically described. The single-diode model provides a practical framework for simulating current-voltage characteristics, while the I-V and P-V curves offer a complete visualization of module performance under various conditions. Understanding the maximum power point and the logic behind tracking algorithms is crucial for optimizing energy extraction in real-world applications.

CHAPTER 2: Principle of Curve Plotting

2-1 Introduction

This chapter examines the fundamental principles of I–V and P–V curve plotting, which serve as essential tools for characterizing the electrical performance and diagnosing flaws in photovoltaic modules. It details the operating principles of the I-V curve tracer, an apparatus that uses a data acquisition system and a power conditioning unit to capture critical parameters like V_{oc} and I_{sc} . The core of the chapter focuses on various curve tracing methods, including the variable resistance method, the capacitive load method, and techniques using power electronics such as the bipolar power amplifier-based method and the four-quadrant power amplifier-based method. Additionally, it explores the chopper-based method using buck, boost, and buck-boost converters, as well as the high-speed electronic load-based method utilizing MOSFET technology.

2-2 The Importance of I-V and P-V Curves

The I-V and P-V curves are crucial tools for describing PV cells or modules because they capture the device's electrical characteristics under specific operating conditions. The electrical behaviour and performance of the PV device can be assessed by analysing these curves. In practice, producing these curves typically requires measuring the corresponding current and voltage by applying a range of loads to the module's terminals.

Researchers can evaluate the module's projected performance under various levels of solar irradiation and load circumstances using the generated response curves, which offer important information about the electrical status of the module. However, a thorough diagnosis of module deterioration may not always be possible with this approach alone [13].

The resulting I-V or P-V curve represents the cumulative effect of many flaws since PV modules can experience multiple types of faults at the same time under normal operating conditions. Because of this, various diagnostic methods are frequently used in addition to I-V and P-V curve analysis to produce a more accurate evaluation of module health [14].

2-3 Operating Principle of the IV Curve Tracer

A data gathering system and a power conditioning unit are typically the two primary parts of an I-V curve tracer. The PV module's voltage and current are measured by the data acquisition system, which then transforms the readings into digital data for analysis. In the meantime, the PV generator is forced to operate at various DC operating points by the power

conditioning unit, enabling the entire current-voltage characteristic of the module to be determined [15].

By measuring these parameters, the I-V curve tracer provides crucial details about the PV system's electrical performance, including the MPP, V_{oc} , and I_{sc} .

When integrated with temperature and irradiance sensors, the system enables the determination of the primary electrical characteristics of a photovoltaic module or string under real operating conditions (OPC), reflecting the actual environmental conditions at the time of measurement. These parameters are subsequently corrected and translated to standard test conditions (STC) to ensure standardized evaluation and reliable comparison [16].

The gadget translates the measured current, voltage, and power values recorded under OPC into their equivalent values at STC so that they can be compared with manufacturer specifications. The experimentally measured electrical characteristics are adjusted using the temperature and irradiance measurements taken during testing.

2-4 Curve Tracing Methods

To ascertain the current-voltage (I-V) properties of a solar module, several curve tracing techniques have been devised. These methods differ in terms of how they function, how fast they measure, how accurate they are, and whether or not they are suitable for laboratory or field settings. Each technique records the corresponding voltage and current values while altering the electrical operating point of the photovoltaic device using a different mechanism.

2-4-1 Variable Resistance Method

The simplest approach for the characterization of photovoltaic (PV) modules is the use of a variable resistive load, whose resistance is adjusted from zero to a high value in order to sweep all operating points from short-circuit to open-circuit conditions.

However, due to the limited availability of high-power resistors, this method is restricted to low-power photovoltaic generators (GPVs). In addition, the manual adjustment of the load resistance makes the process slow and allows variations in solar irradiance and temperature to affect the measurements [17].

During the measurement process, environmental conditions may change. The voltage and current are measured at each step using a pair of digital multimeters, while a set of resistors is used as the load under test. These resistors are selected to ensure an adequate distribution of measurement points along the I–V curve.

Furthermore, two analog-to-digital converter (ADC) channels from a computer-based acquisition board are used to record each (I, V) pair. This approach eliminates the need for manual load adjustment and significantly reduces the acquisition time [17]. Figure 2.1 illustrates the variable resistance method.

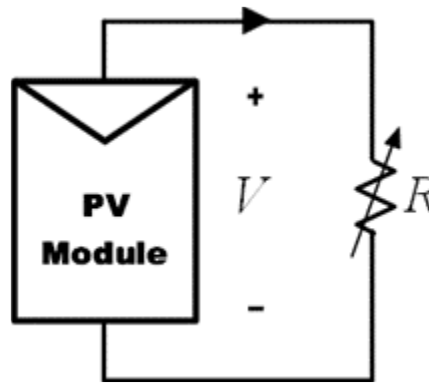


Figure 2.1: Variable Resistance Curve Tracing Method [17].

2-4-2 Capacitive Load Method:

A method based on charging a capacitor through the module, allowing the voltage and current to vary naturally as the capacitor charges. In this approach, the PV module charges a capacitor. At the beginning of the measurement, the capacitor is short-circuited. When switch S2 is opened, and S1 is closed, the capacitor begins to charge. As the capacitor accumulates charge, the current from the PV module decreases while the voltage increases.

Once the capacitor is fully charged, the module current drops to zero, reaching the open-circuit condition. To obtain a reliable I–V curve using the capacitive load method, the three switches (S1, S2, and S3) must be operated in the correct sequence, and the capacitor must be discharged before starting a new measurement [18]. Figure 2.2 defines the capacitive load method.

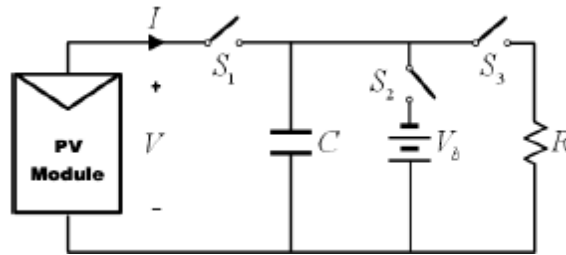


Figure 2.2: Capacitive Load Curve Tracing Method [18]

2-4-3 Bipolar Power Amplifier-Based Method:

A method that uses a bipolar power amplifier to apply a controlled voltage or current sweep to the device under test, enabling simultaneous measurement of voltage and current to trace its I-V characteristics.

This method uses a simple circuit that allows the current and voltage in the module to be reversed. As a result, it becomes possible to measure the module's dark I-V curves. The circuit design is based on a conventional Class B power amplifier. It uses two BJT transistors as loads to handle the forward and reverse currents, respectively. The bipolar transistors must operate in all three regions: cutoff, active, and saturation. As a result, most of the power delivered by the module is dissipated by these devices, which limits the method to medium-power applications [19]. Figure 2.3 shows the bipolar power amplifier method.

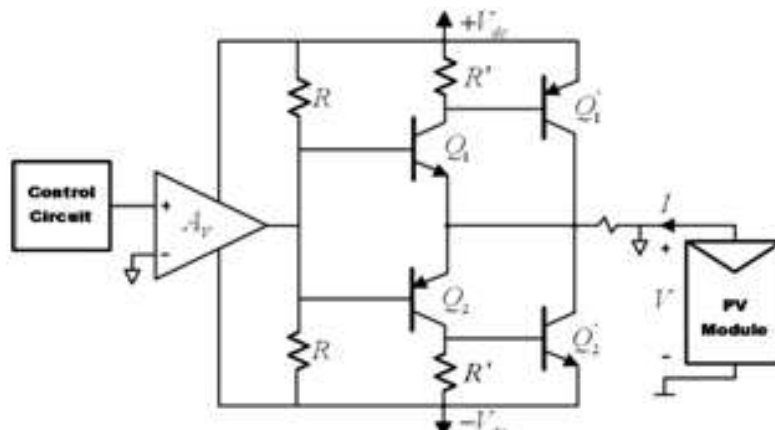


Figure 2.3: Bipolar Power Amplifier-Based Curve Tracing Method [19]

2-4-4 Four-Quadrant Power Amplifier-Based Method:

A method that uses a four-quadrant power amplifier capable of supplying and absorbing both positive and negative voltage and current, allowing the device under test to be operated in all regions of its I-V characteristics for a complete and accurate curve plot.

For a photovoltaic module, the primary goal is to obtain the I–V curve in the first quadrant. However, analysing points in the second and fourth quadrants can provide valuable diagnostic insight, helping to identify issues such as mismatches in the module, for example, when one or more cells are partially shaded in a series connection [19].

A four-quadrant power supply; as shown in figure 2.4; can be viewed as a time-dependent voltage source whose output is controlled by a reference signal or programmed to sweep over a specified range of values.

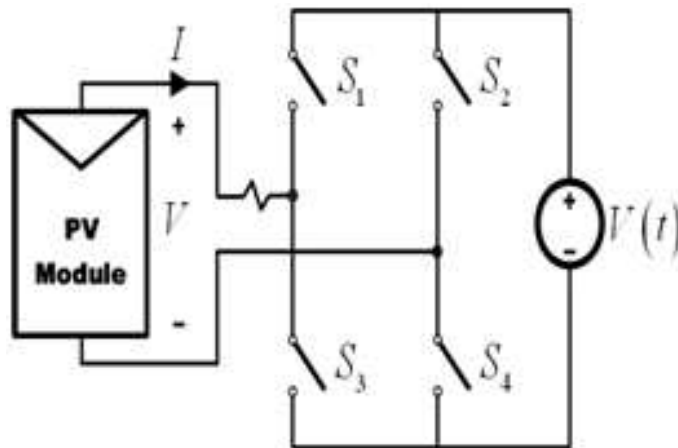


Figure 2.4: Four-Quadrant Power Amplifier–Based Curve Tracing Method [19]

2-4-5 Chopper-Based Method

Direct current (DC–DC) converters are commonly used in electrical systems to obtain an average output voltage that differs from the input voltage. This voltage conversion is achieved through pulse-width modulation (PWM), which is typically operated at a constant switching frequency. Figure 2.5 shows the chopper-based method.

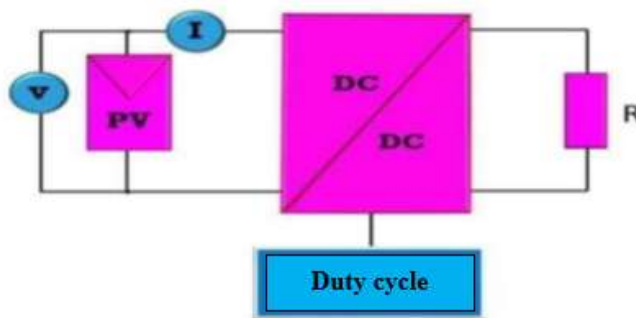


Figure 2.5: Chopper-Based Curve Tracing Method [20]

a) Buck Converter (Step-Down Converter):

A DC–DC converter that lowers the output voltage in relation to the input voltage is called a buck converter. When the load voltage is lower than the voltage associated with the maximum power point, it is especially appropriate. Figure 2.6 illustrates a step-down converter.

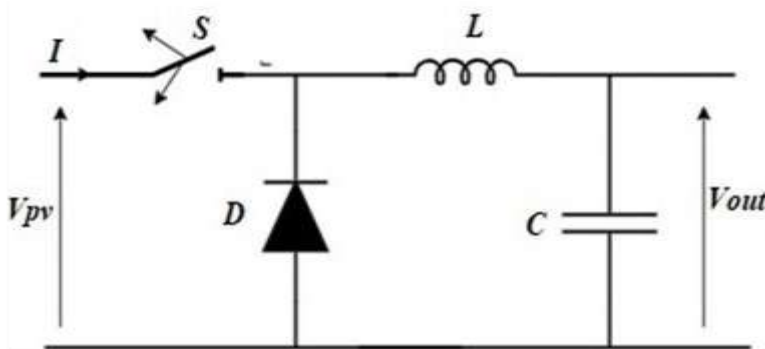


Figure 2.6: Step-Down Converter [20]

b) Boost Converter (Step-up Converter):

As its name implies, a boost converter produces an output voltage that is higher than the input voltage by raising the input voltage. Figure 2.7 illustrates a step-up converter.

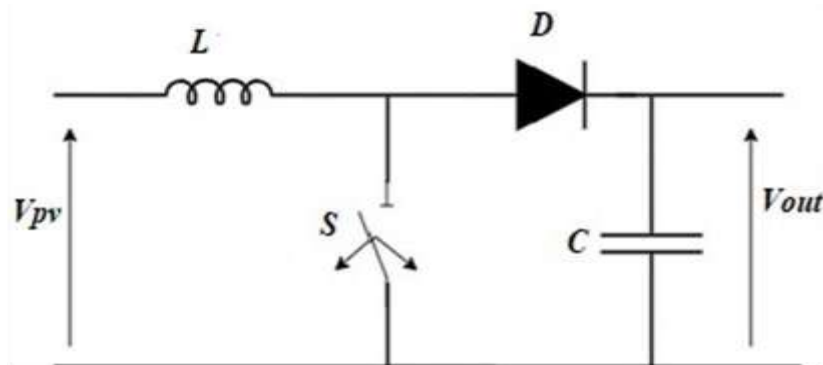


Figure 2.7: Step-Up Converter [20]

c) Buck-Boost Converter:

The buck-boost converter is a dual-function DC–DC converter, as shown in Figure 2.8, that can produce an output voltage either higher or lower than the input voltage by raising or lowering the input voltage. It may also produce positive or negative output voltages, which makes it appropriate for a variety of uses.

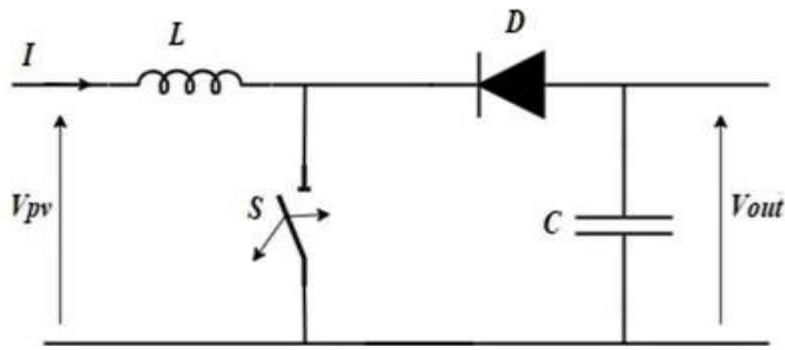


Figure 2.8: Buck-Boost Converter [20]

2-4-6 Electronic Load-Based Method:

A method that uses a programmable electronic load (transistors) to vary the current drawn from the device under test. By controlling the load, the corresponding voltage and current can be measured at each point, allowing the complete I–V characteristic of the module to be plotted accurately and efficiently.

In this method, which its circuit is presented in Figure 2.9, the voltage across the device is controlled by adjusting the gate-source voltage for MOSFETs and IGBTs, or the base current for BJTs. This makes it possible to quickly map out the I–V curve of a photovoltaic module. MOSFETs, which are the most common type of electronic load, simply control the current by changing the gate voltage [21].

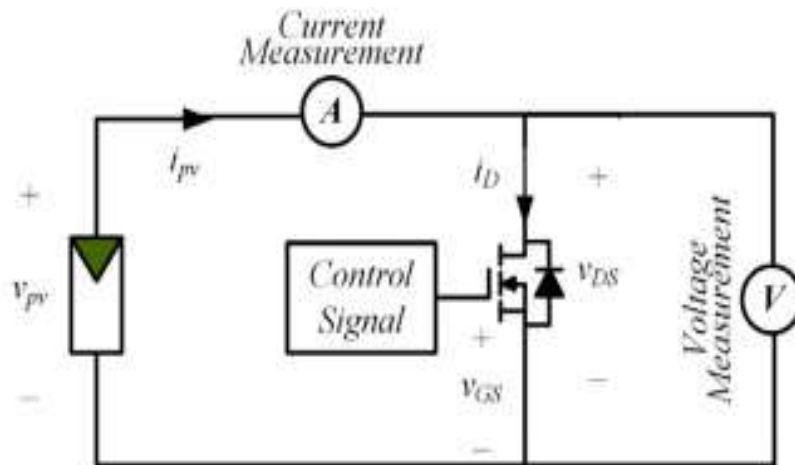


Figure 2.9: Electronic Load-Based Curve Tracing Method [21]

2-5 Conclusion

In summary, I–V and P–V curve plotting serves as an essential tool for characterizing the electrical performance and diagnosing flaws in photovoltaic modules. By using a curve tracer to sweep operating points, critical parameters like I_{sc} and V_{oc} are measured and subsequently translated to Standard Test Conditions (STC) for accurate comparison with manufacturer specifications. While methods range from simple variable resistors and capacitive loads to advanced power amplifiers and chopper-based DC–DC converters, each technique aims to efficiently capture the module's electrical status to provide a thorough evaluation of its overall health and efficiency.

CHAPTER 3: Study and Design of the Photovoltaic Plotter

3-1 Introduction

Before proceeding with the implementation of the Photovoltaic Plotter, it is essential to first choose a method of plotting from the ones presented in Chapter 2. This study utilizes a MOSFET-based electronic load driven by PWM signals, and then verifies the circuit simulation to ensure the system's design is correct and to avoid potential problems that could occur during implementation. The simulation will approve the circuits and ensure their functioning.

3-2 Layout of The Circuits

To simulate the function of the circuits, it is necessary to fix a PV model with specified characteristics to make the dimensioning possible and more realistic. For this study, the chosen characteristics are:

- $V_{oc} = 100 \text{ V}$
- $V_{mp} = 80 - 85 \text{ V}$
- $I_{sc} = 12 - 14 \text{ A}$
- $I_{mp} = 11.5 \text{ A}$
- $P = 700 - 1000 \text{ W}$

First, we have to create the new project with suitable properties so it will be possible to code in the source code inside Proteus to avoid the use of external applications.

For that, we create a new project, then create a firmware project, then select the suitable family, controller, and compiler. Like this, we will be able to use the code source of Proteus instead of the ARDUINO IDE for this part. In Figure 3.1, the interface of Proteus is shown for creating a firmware project.

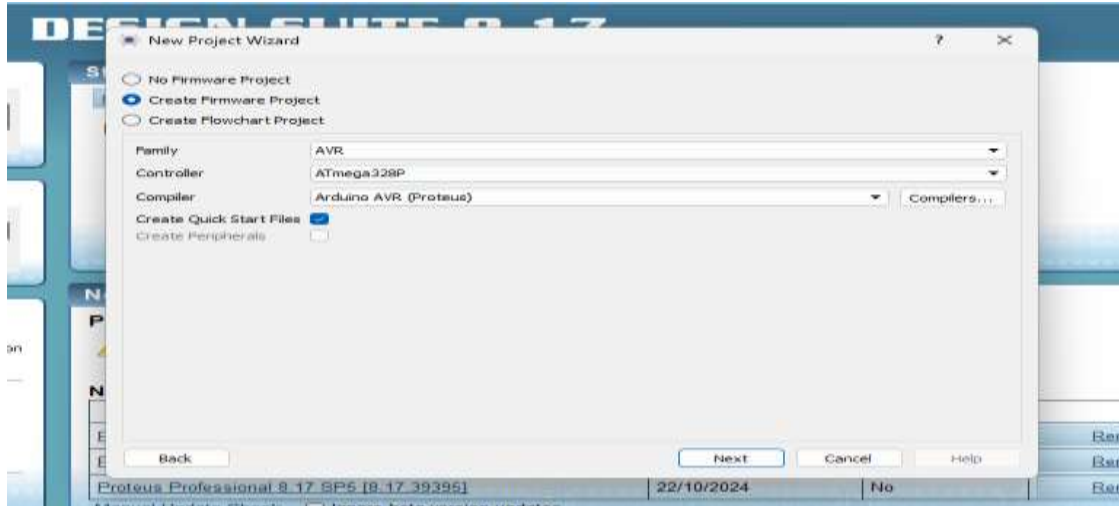


Figure 3.1: Creating a project with firmware

3-2-1 PV Input and Protection Circuit

This circuit has two functions: it ensures the protection of both the solar panel and the device, plus it represents the primary input interface of the whole device.

The core architecture consists of a fuse and a Schottky diode, besides two N-channel MOSFETs in back-to-back configuration on the low side, and a dedicated driver. For the rest of the components in this circuit, the remaining components were dimensioned based on the specific input and output requirements of the stage.

Starting with the fuse, it has to follow the following laws and standards so it can surely accomplish its function:

$$\text{Standard current: } I_{\text{fuse}} = 1.25 \cdot I_{\text{sc}} = 1.25 \times 14 = 17.5 \text{ A} \quad (3.1)$$

$$\text{Upper margin: } I_{\text{fuse}} = 1.4 \cdot I_{\text{sc}} = 1.4 \times 14 = 19.6 \text{ A} \quad (3.2)$$

$$\text{Limit: } I_{\text{fuse}} < 1.6 \cdot I_{\text{sc}} = 1.6 \times 14 = 22.4 \text{ A} \quad (3.3)$$

According to this calculation, the suitable fuse is the 20A fuse, and it must support up to 100V.

The protection diode must support 20A and a minimum of 100 V. For the simulation, we used 15LJQ100.

For the MOSFETs, we used IRFP260N 200V 50A as a power switch; with these, it is necessary to use a pull-down resistor to maintain the gate-source voltage at 0V when the driver is inactive prevent the MOSFET from opening itself. From the IRFP260N datasheet [23]:

- $V_{gs}=10V$ (when MOSFET ON)
- $Q_g = 170 \text{ nC}$ (capacitive gate)
- Input capacity: $C_{iss} = 5 \text{ nF}$

We want τ to be small enough to unload the gate quickly, but large enough not to unnecessarily load the driver.

If we took $R = 100 \text{ K}\Omega$:

$$\tau = R \cdot C \quad (3.4)$$

$$\tau = 100 \times 10^3 \times 5 \times 10^{-9} = 0.5 \times 10^{-3} \text{ s} = 0.5 \text{ ms}$$

In $5\tau = 2.5 \text{ ms}$. For our plotter, 2ms is enough.

$$I = \frac{v}{R} = \frac{10}{100 \times 10^3} = 0.1 \text{ mA} \quad (3.5)$$

Another point to take into consideration is the power dissipated by the resistor.

$$P = \frac{v^2}{R} = \frac{10^2}{100 \times 10^3} = 1 \text{ mW} \quad (3.6)$$

So, the resistor has to be of $100 \text{ K}\Omega / 0.25 \text{ W}$.

Plus, to these components, there is a resistor between the driver and the MOSFET's gate and Zener diodes as protection. Together forming the circuit presented in Figure3.2.

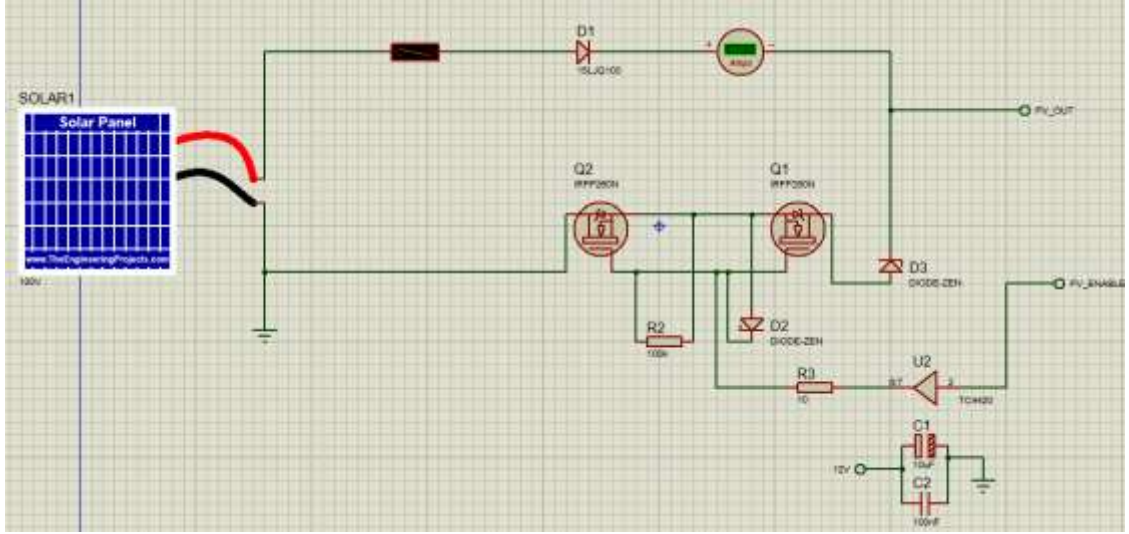


Figure 3.2: PV input and protection circuit

3-2-2 Power Supply Circuit

This circuit is crucial for powering the whole system. With this one, we will power the device and provide all the different necessary voltage stages for each component.

In the simulation, we used VSources for each voltage value and placed two capacitors near each one to filter and decouple the voltage. We also need a voltage inverter (in the simulation, we used the MC34063) and resistors, capacitors, and an inductor near it.

The voltage stages we got in the output of this circuit are: +15V, -15V, 12V, 5V, 3.3V. With these, we ensure the powering of all the components with the needed voltage. The 12V is the main value, from which we will get the rest of the power values.

For the dimensioning of C_8 , representing the capacitors near the 5V output:

$$V_{in} = 12 \text{ V} ; f = 150 \text{ KHz (typical frequency)} ; I = 2 \text{ A} ; D = 0.5$$

$$C_{in} \geq \frac{I_{out} \cdot D(1-D)}{f \cdot \Delta V} \quad (3.7)$$

We set $\Delta V = 0.5 \text{ V}$:

$$C_{in} \geq \frac{2 \times 0.5 \times (1-0.5)}{150000 \times 0.5} = 6.66 \mu F$$

$$C_{practical} = 25 \cdot C = 25 \times 6.66 = 166.5 \mu F \quad (3.8)$$

$$C_{\text{practical}} = 220 \mu\text{F} ; V_c \geq 2 \cdot V_{\text{out}} = 2 \times 12 = 24 \text{ V}$$

So, according to this calculation, the appropriate capacitor is one of 220 μF and can support 24 V, plus 100 ηF for decoupling.

Using the same logic for the capacitor of the 3.3V source:

$$C_{\text{in}} \geq \frac{I_{\text{out}} \cdot D(1-D)}{f \cdot \Delta V} \quad (3.9)$$

We set $\Delta V = 0.3 \text{ V}$:

$$C_{\text{in}} \geq \frac{2 \times 0.5 \times (1-0.5)}{150000 \times 0.3} = 11.11 \mu\text{F}$$

Practical SMPS rule: (switched mode power supply)

$$C_{\text{in}} \cdot 15 = 11.11 \times 15 = 166.66 \mu\text{F} \quad (3.10)$$

$$V_{\text{cap}} = 2 \cdot V_{\text{in}} = 2 \times 12 = 24 \text{ V}$$

Again, according to this calculation, we need a 120 μF which supports 24V with a 100 ηF , for filtering and decoupling.

Now to get +15V:

We set $\Delta V = 0.5 \text{ V}$; $I = 1.5 \text{ A}$

$$C_{\text{in}} \geq \frac{I_{\text{out}} \cdot D(1-D)}{f \cdot \Delta V}$$

$$C_{\text{in}} \geq \frac{1.5 \times 0.5 \times (1-0.5)}{150000 \times 0.5} = 5 \mu\text{F}$$

$$C_{\text{in}} \cdot 15 = 5 \times 15 = 75 \mu\text{F}$$

$$V_{\text{cap}} = 2 \cdot V_{\text{in}} = 2 \times 12 = 24 \text{ V}$$

So, we need a 100 μF beside a 100 ηF near the +15 V source.

For the last voltage stage, which is -15V, we need an inverter to transform the +15 V to -15V. This inverter needs a protection diode, 1K Ω , 11K Ω , 0.33 Ω resistors, and 100 μF , 1000pF capacitors with a 100uH inductor and the +15V source. All the power supply circuit is presented in Figure 3.3.

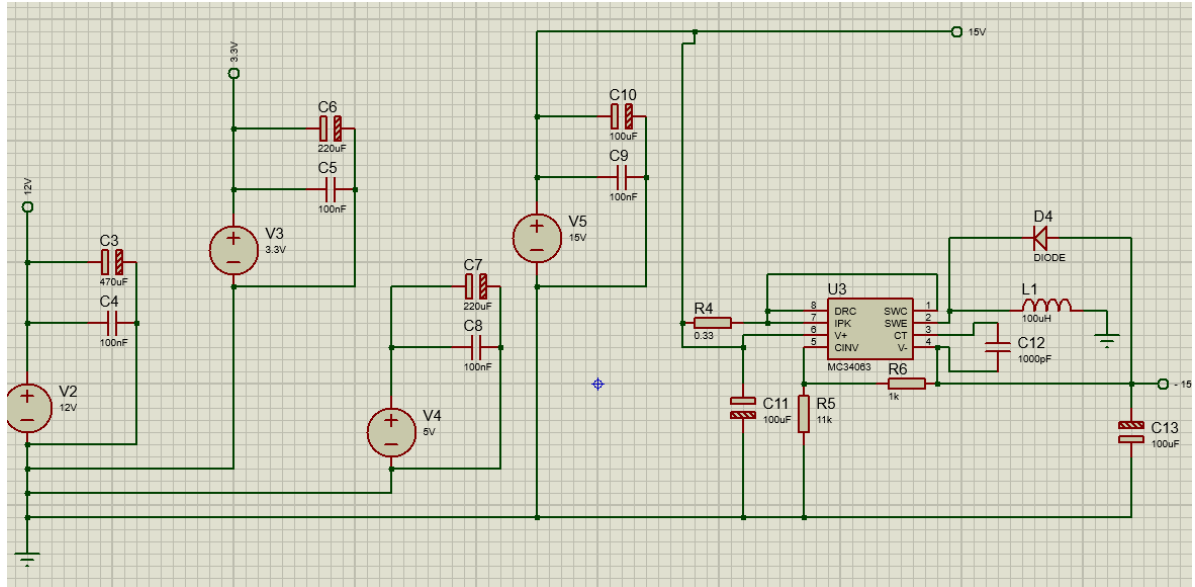


Figure 3.3: Power Supply Circuit

3-2-3 Control Circuit

This circuit is the brain of the device; it controls all the other circuits through a microcontroller. In this case, we used ATMEGA328p, which will execute the code and give instructions to all the components. The reason behind choosing the ATMEGA328p is that the ESP32 was not available in Proteus and even after downloading its library, Proteus still did not simulate it correctly and we could not launch the simulation.

The ATMEGA328p here is responsible for the switching of the power between ON and OFF throughout a signal that arrives from a button via an optocoupler to isolate the MOSFETs of the input and protection circuit. It is also responsible for varying the PWM signal from 0 to 255 to make it possible to take the measurements at different points to plot the curve. It is connected to a display screen (LCD LM016L), so we can see the I_{sc} , V_{oc} , and P_{max} at the end of the measurement. It is also connected to the ADS1115 board to read the measurements made by the sensors. For the crystal that is connected with the ATMEGA328P we must set its frequency to 16 MHz to make it accurate with for this microcontroller. The connections are shown in Figure 3.4 below.

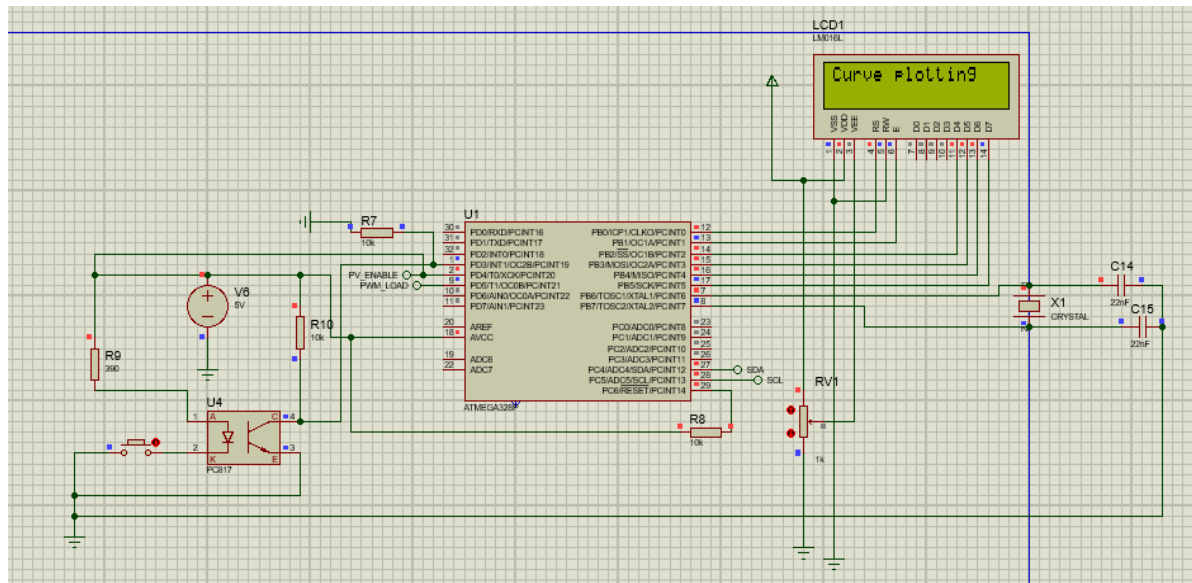


Figure 3.4: Control Circuit

In the code source, we write the following program, which will vary the PWM, enable the device, and display the result on the LCD screen.

```
main.ino
1 #include <Wire.h>
2 #include <Adafruit_ADS1X15.h>
3 #include <LiquidCrystal.h>
4 Adafruit_ADS1115 ads;
5 LiquidCrystal lcd(8, 9, 10, 11, 12, 13);
6 const int pwmPin = 3;
7 // --- CONFIGURATION ---
8 const float ratioTension = 31.0; // Based on R11=300k, R12=10k
9 const float sensibilitACS = 0.100; // 100mV/A for the 20A model
10 const float VCC_SYSTEM = 5.0; // voltage (5.0V)
11 float Voc = 0, Isc = 0, Pmax = 0;
12 void setup() {
13   lcd.begin(16, 2);
14   pinMode(pwmPin, OUTPUT);
15   analogWrite(pwmPin, 0);
16   if (!ads.begin()) {
17     lcd.print("Error in ADS1115");
18     while (1); }
19   ads.setGain(GAIN_TWOTHIRDS);
20   lcd.print("Curve plotter");
21   delay(100);
22 void loop() {
23   lcd.clear();
24   lcd.print("Voc measurement");
25   // 1. Voc measurement
26   analogWrite(pwmPin, 0);
27   delay(1000);
28   Voc = getVoltage();
29   // 2. Curve plotting
30   Pmax = 0;
31   float currentMax = 0;
32   lcd.clear();
33   lcd.print("Curve plotting");
34   for (int i = 0; i <= 255; i++) {
35     analogWrite(pwmPin, i);
36     delay(60);
```

```

37     float Vpv = getVoltage();
38     float Ipv = getCurrent();
39     float Ppv = Vpv * Ipv;
40     if (Ppv > Pmax) Pmax = Ppv;
41     if (Ipv > currentMax) currentMax = Ipv;}
42     Isc = currentMax;
43     analogWrite(pwmPin, 0);
44     // 3. final display
45     displayResults();
46     float tensionSeuil = Voc;
47     while (abs(getVoltage() - tensionSeuil) < 0.5) {
48         delay(1500); }
49     float getVoltage() {
50         // Read A0
51         int16_t adc0 = ads.readADC_SingleEnded(0);
52         float tensionEntreeADC = ads.computeVolts(adc0);
53         return tensionEntreeADC * ratioTension;}
54     float getCurrent() {
55         // Read A1
56         int16_t adc1 = ads.readADC_SingleEnded(1);
57         float vOutACS = ads.computeVolts(adc1);
58         float offset = VCC_SYSTEM / 2.0;
59         float current = (vOutACS - offset) / sensibiliteACS;
60         return (current > 0.1) ? current : 0.0; }
61     void displayResults() {
62         lcd.clear();
63         lcd.setCursor(0, 0);
64         lcd.print("V:"); lcd.print(Voc, 1); lcd.print("V ");
65         lcd.print("I:"); lcd.print(Isc, 2); lcd.print("A");
66         lcd.setCursor(0, 1);
67         lcd.print("Pmax: "); lcd.print(Pmax, 1); lcd.print("W");}

```

Figure 3.5: Curve Plotter Code

We have the input voltage of the microcontroller, 5V, and we will use its Bluetooth feature later in the implementation phase with the ESP32. Because of that, the calculation must be based on the real components to be used, so we must consider this to define the current consumption. In normal operation, the ESP32 needs 200 – 300 mA, plus pic radio frequency: 500 mA. In total, we must size for a current of 0.5 A, with a voltage drop during Bluetooth pics of 0.2 V and a typical duration of a radio frequency burst of 100 μ s.

3-2-4 Measurement Circuit

In this circuit, we will take the measurements of the voltage and current coming from the solar panel. Using a current sensor ACS712ELCTR-20A-T, but for the voltage sensor, none of them were available in Proteus, so we used a voltage divider with two resistors of 10 K Ω and 300K Ω .

For the current sensor, we need a filtering capacitor of 100nF and a Vcc of 5 V. In the input (IP+) we will connect the output of the first circuit, while the pin (IP-) will be connected to the load circuit later, and the first resistor of the voltage divider.

Both outputs of the ACS712ELCTR-20A-T and the voltage divider will be directly connected to the ADS1115 board, which serves as a high-precision interface that converts analog signals from sensors into digital data with 16-bit resolution for superior accuracy. It also features a programmable gain amplifier to detect very small voltage changes and uses the I2C protocol to expand the number of available analog inputs on a microcontroller.

This will send the final values and results to the ATMEGA328P via SDA and SCL pins as digital values to display them. This board operates on a supply voltage anywhere between 2V and 5.5V on the V_{cc} pin, but in reality there is a strict rule: The analog input voltage must never exceed $V_{CC} + 0.3V$, so in this simulation, and because the ATMEGA328P and the ACS712 typically operate at 5V, since it outputs a signal that can reach 5V, powering the ADS1115 with only 3.3V would exceed its safety limits and potentially destroy the chip. Furthermore, a 3.3V supply would clip any sensor readings above that level, preventing the ADC from accurately measuring the full range of the data the measurement circuit is illustrated in Figure 3.6.

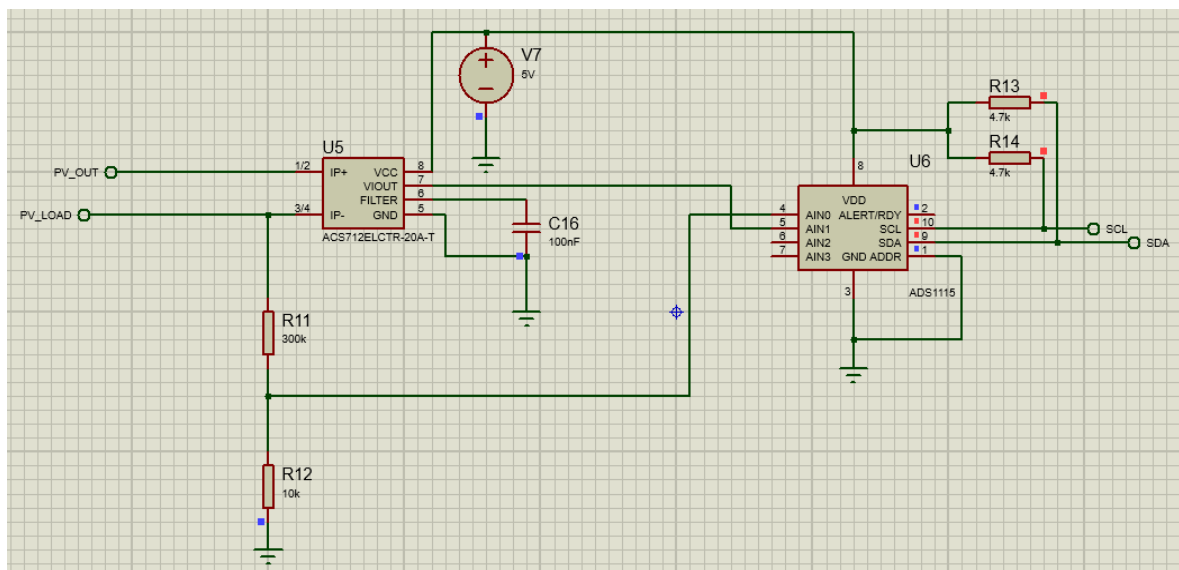


Figure 3.6: Measurement Circuit

3-2-5 Electronic Load Circuit

For this last circuit, it represents the load for the device; it's here where the variation of the PWM will be applied to plot the curves, mimicking a wide range of resistive conditions from open circuit to short circuit. By utilizing MOSFETs (IRFP260N) in parallel connections, driven by a PWM signal plus a series resistor of 7Ω . As the PWM duty cycle increases, the MOSFET allows more current to flow, forcing the panel to operate at different points along its

characteristic curve. This allows the system to sweep the entire output range rapidly and safely, capturing the relationship between voltage and current to identify the MPP. This circuit is also composed of a MOSFET driver and an optocoupler for isolation.

The input of this circuit is the PV_LOAD, which is coming from the (IP-) of the current sensor, and it will be connected to the drain of the MOSFETs in parallel, which will be controlled by their driver through the gates.

To define the number of MOSFETs to use, we must take into consideration the power that must be dissipated:

$$P_{diss, max} = \frac{V_{oc} \cdot I_{sc}}{4} = \frac{100 \times 14}{4} = 350 \text{ W} \quad (3.11)$$

From the IRFP260N datasheet: $P_{adm} \approx 300\text{W/MOSFET}$ [23]. But this is only in a controlled environment where the components are kept at 25°C. so for the implementation, we consider 60W/MOSFET

$$N \geq \frac{P_{diss, max}}{P_{adm}} = \frac{350}{60} = 5.83 \quad (3.12)$$

So, we will need six MOSFETs of 50A, 200V. Each one needs a gate resistor:

$$I_{g, pic} = \frac{V_{DD}}{R_g} \quad (3.13)$$

$$R_g = \frac{V_{DD}}{I_{g, pic}}$$

With: $V_{DD} = 12 \text{ V}$ and $I_{g, peak} \approx 1 \text{ A}$

$$R_g = 12/1 = 12 \Omega$$

We need 6 resistors of 12 Ω for each MOSFET's gate. Besides this, the driver TC4420 needs a decoupling capacitor whose value is calculated as follows:

For: $I = 2 \text{ A}$; $\Delta t = 0.5 \mu s$; $\Delta V = 0.2 \text{ V}$

$$C = \frac{I \Delta t}{\Delta V} = \frac{2 \times 0.5}{0.2} = 5 \mu F \quad (3.14)$$

We will use a 10 μF with 100 ηF

The MOSFETs also need a bulk capacitor:

For: $I = 0.5 \text{ A}$; $\Delta t = 1 \text{ ms}$; $\Delta V = 0.5 \text{ V}$

$$C = \frac{I \cdot \Delta t}{\Delta V} = \frac{0.5 \times 0.001}{0.5} = 0.001 \text{ F} = 1000 \mu\text{F}$$

We can either use capacitor of $1000 \mu\text{F}$ or $470 \mu\text{F}$ one.

Finally for this circuit we need a LED resistor for the optocoupler PC817 which is calculated as:

For: $V_{\text{GPIO}} = 3.3 \text{ V}$; $V_f = 1.2 \text{ V}$; $I_f = 5 \text{ mA}$

$$R = \frac{V_{\text{GPIO}} - V_f}{I_f} = \frac{3.3 - 1.2}{0.005} = 420 \Omega \quad (3.15)$$

The closest value is 390Ω .

For the PWM frequency, we chose $f = 20 \text{ KHz}$, and we have:

$$T = \frac{1}{f} = 1/20000 = 100 \mu\text{s} \quad (3.16)$$

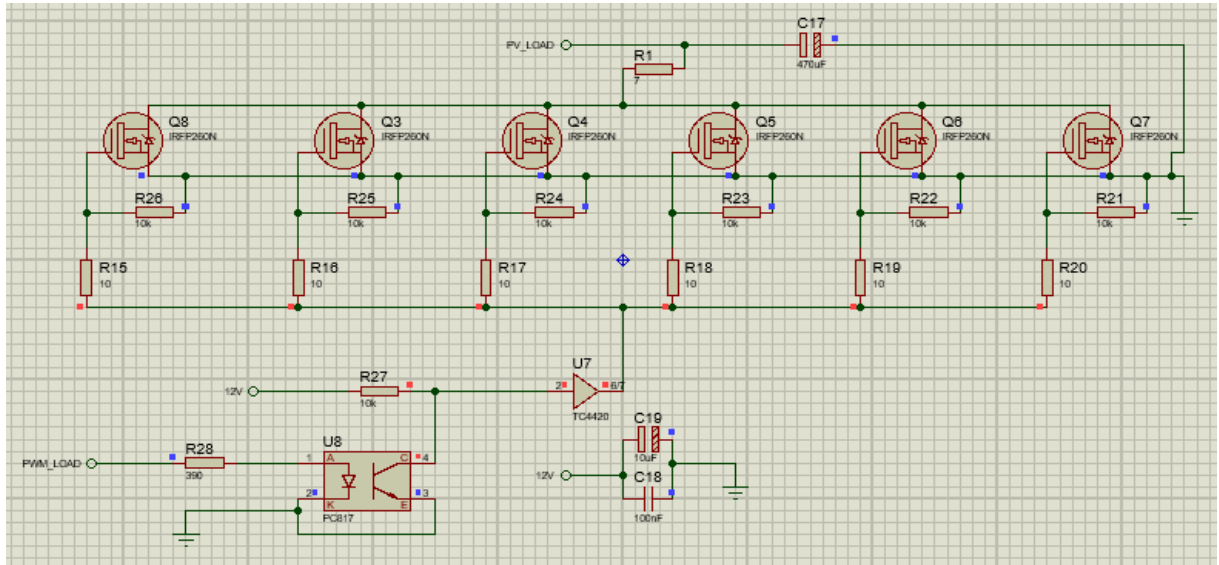


Figure 3.7: Load Circuit

3-3 Simulation Results

Before launching the simulation, we must modify some values in the parameters to make it possible to simulate all six MOSFETs in parallel. In the system, set animation options, then spice options in the tolerances, set the values to:

- ABSTOL: $1\text{e-}9$
- VNTOL: 0.0001

- CHGTOL: 1e-12
- RELTOL: 0.01
- PIVTOL: 1e-10
- PIVREL: 0.001
- GMIN: 1e-6
- TRANGMIN: 1e-9
- R Shunt: 1e9

Then in the transient:

- Number of steps: 200
- TTOL: 1e-7
- TMIN: 1e-10

Next, in MOSFET, check the use SPICE2 MOSFET limiting, then OK. After these modifications, the simulation will work well without any errors.

When we launch the simulation, if we place DC Ammeter and voltage probes after the diode and the fuse in the first circuit, we will see a current of 13.9 A and 99 V, as shows Figure 3.8, which are logical values, this is due to the presence of the series resistor in the electronic load circuit, without this resistor we will find a current value of 119 A, which represent a short circuit, this phenomenon is the result of the MOSFETs having an internal resistor of $0.044\ \Omega$ plus using six MOSFETs in parallel make it even smaller so we add the resistor to represent a resistive charge to solve the problem.

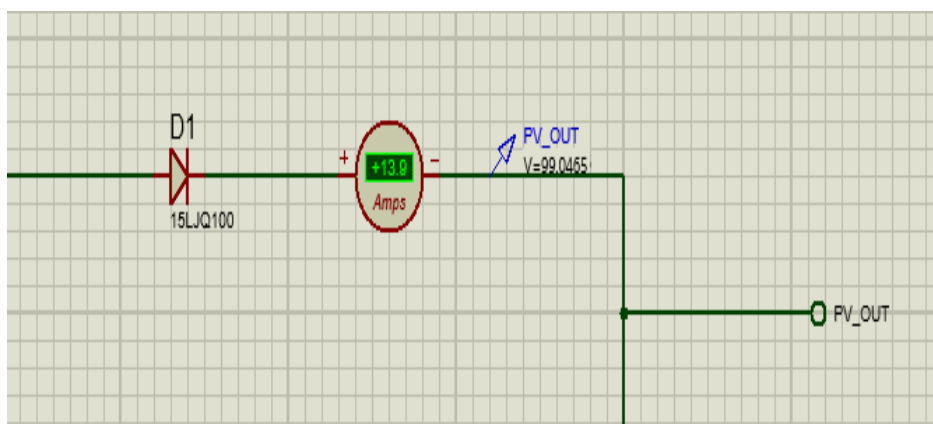


Figure 3.8: Current & voltage values

Plus, with this panel, we can't limit the output current to a specific value; we can only fix the voltage value, while the current depends on the load. The results of this simulation are illustrated in Figure 3.9 below.

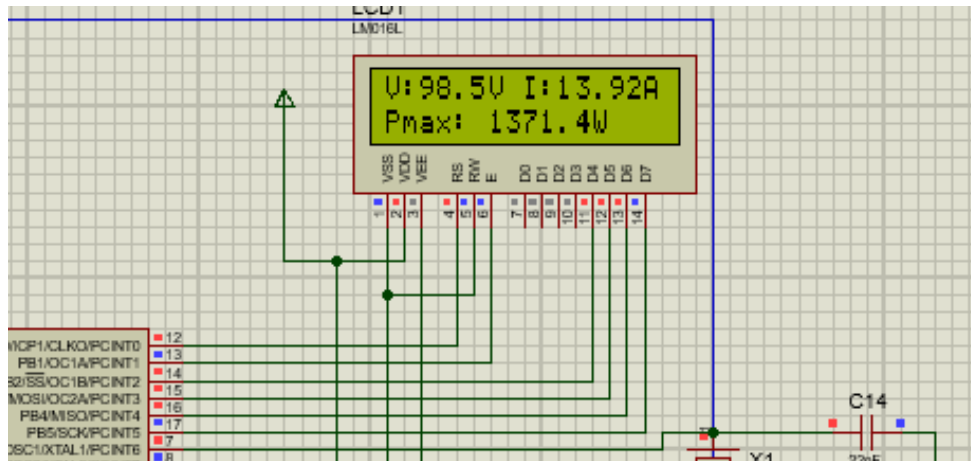


Figure 3.9: Results display

3-4 Conclusion

From these simulation results, we can confirm the functioning of these circuits and the general principle of the device, especially the use of the MOSFET-based method of curve plotting. Certain exact models were not available in the Proteus 8 libraries, which led to the selection of other alternatives as a solution. This verification ensured that the substituted models accurately reflected real-world behaviour, providing a reliable foundation for the physical assembly. Even with the limits of the libraries of Proteus, such as the missing components and the display of only the values without the curves, we could eliminate so many problems that occurred during the simulation to avoid them in the realization.

CHAPTER 4:

Implementation of the Photovoltaic Curve Plotter

4-1 Introduction

In this chapter, after verifying the general principle of the circuits, we will proceed to the implementation of the photovoltaic plotter in the breadboard, and then we will divide the circuit into an optimal repartition to make the printed circuit boards (PCBs). We will also replace some of the components used in the simulation with the ones we chose in the first place.

4-2 Experimental Setup and Breadboard Prototyping

This part represents an important stage in the project, as it forms the link between the simulation phase and the final implementation. The objective of this step was to verify the operation of the different circuits in practice and to make the necessary adjustments before moving to the final prototype.

For this purpose, the circuits were first assembled on breadboards. This choice made the testing process easier, since it allowed us to modify the connections, replace components when needed, and test each part of the circuit separately. The arrangement of the components on the breadboard was selected in a way that facilitates the verification of each circuit function and reduces possible wiring errors.

4-2-1 PV Input and Protection Circuit Implementation on Breadboard

During the practical implementation of the PV input and protection circuit, some components were changed compared to the simulation. However, the main function of the circuit remained the same, which is to protect both the measuring device and the solar panel under test.

The selected components were chosen according to their electrical ratings in order to withstand high voltage and current levels without being damaged during the tests. This allows the circuit to be used with solar panels having a power of up to 700 W. The main components used in this part are:

- fuse of 20A / 500V.
- Schottky diode: HBR20100.
- Transient Voltage Suppressor (TVS) diode: 1,5KE150A.
- MOSFET : IRFP260N.
- Zener diode of 12V.
- Resistors: 10 Ω and 100K Ω .

- MOSFET driver: TC4420.
- Capacitors: $10\mu\text{F}$ / 25V and 100nF

4-2-2 Power Supply Circuit Implementation on Breadboard

This circuit was used to supply the electronic parts of the device. Based on the datasheets of the different components, the required voltage levels were defined. As mentioned in Chapter 3, the main voltage needed in the circuit is **+12 V**, and the other voltage levels are obtained from it.

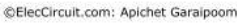
The +12 V was supplied by an adapter that converts the 220 V AC mains voltage into 12 V DC, with a maximum current of 3 A. After that, two LM2596 regulator modules were used. These modules take 12 V as input and provide 3.3 V and 5 V as outputs. These two voltages are used to power the ESP32, the TFT screen, the ADS1115 module, and the other integrated circuits according to their operating voltage.

For the +15 V stage, an XL6009 boost regulator module was used. The +12 V, +5 V, +3.3 V, and +15 V stages were implemented using ready-to-use regulator modules, which made the breadboard implementation easier and reduced the number of additional components.

For these three regulators, we added two capacitors in the input and output of each one, two capacitors for decoupling and filtering.

To obtain the -15 V voltage, we designed a specific converter circuit instead of using a ready-made module. This circuit takes 12 V DC as input and gives -15 V DC at the output. It is based on the MC34063 integrated circuit, which can be used as a buck, boost, or inverting regulator depending on the external components and the circuit connection.

In our case, the MC34063 was used as an inverting regulator. The circuit was based on the connection shown in Figure 4.1, with some changes in the values of the external components in order to obtain the required output voltage.



The duty ratio relation is given by:

$$\frac{t_{on}}{t_{off}} = \frac{|V_{out}| + V_f}{V_{in} - V_{sat}} = 1.41 \quad (4.2)$$

By considering:

$V_{in}=12V$,
 $|V_{out}|=15V$,
 $V_f=0.5V$,
 $V_{sat}=1V$.

$$I_{pk} = 2 \cdot I_{out} \cdot \left(\frac{t_{on}}{t_{off}} + 1 \right) \quad (4.3)$$

$$I_{pk} = 2 \times 0.1 \times (1.41 + 1) = 0.482 \text{ A}$$

Therefore, the theoretical value of R_{sc} is:

$$R_{sc} = \frac{0.3}{I_{pk}} = \frac{0.3}{0.482} = 0.62 \Omega$$

4-2-3 Control and Measurement Circuit Implementation on Breadboard

In the simulation, the system was divided into five separate circuits. However, during the breadboard implementation, it was possible to reduce this number and simplify the practical setup. The measurement and control parts were therefore grouped on the same breadboard.

This circuit is responsible for measuring the voltage and current delivered by the solar panel. The measured signals are first obtained through the sensors, then sent to the analog-to-digital converter module. After that, the digital data is transmitted to the ESP32, which processes the values and displays them on the TFT screen.

The sensors used in this part are the LV25-P voltage sensor and the LA25-NP current sensor. The LV25-P can be used for voltage measurements up to 500 V, with a primary nominal current of 10 mA. Therefore, an input resistor is required to limit the current passing through the sensor. The LA25-NP sensor was used for current measurement, with a measuring range up to 25 A.

Before using these sensors in the final circuit, a calibration step was carried out using the laboratory power supply. This step was necessary to compare the sensor output with known input values and to improve the accuracy of the measured voltage and current.

4-2-4 Electronic Load Circuit Implementation on Breadboard

For the last circuit, six IRFP260N MOSFETs were first used in parallel. However, during the simulation, this arrangement caused a very high current, similar to a short-circuit condition. This problem was solved in Proteus by adding a $7\ \Omega$ resistor in series with the load.

Since the components in Proteus are considered ideal, their real power limitations are not fully represented. For this reason, it was not possible to use ordinary resistors in the practical implementation. After checking the available components, power resistors of 25 W, 50 W, and 100 W were found, but a $7\ \Omega$ resistor with the required power rating was not available.

Therefore, the selected solar panel was changed and replaced with another one whose characteristics were compatible with the available power resistors. The chosen solar panel has the following characteristics:

$$V_{oc} = 21.6\text{ V}$$

$$I_{sc} = 5.14\text{ A}$$

$$P = 80\text{ W}$$

Based on these values, the required resistance was approximately $4\ \Omega / 100\text{ W}$. In the practical circuit, this resistance was obtained by connecting four $1\ \Omega / 50\text{ W}$ resistors in series, but in reality, the four resistors we have their total resistance of $4.5\ \Omega$, which caused drops in the measured current so we kept only three resistors with a total value of $3.8\ \Omega$. This resistive load was then used with the six MOSFETs. With this load, it is possible to test a panel of a power up to 200 W, with the condition of recalculating the resistor values.

To improve the safety of the circuit, an LM358N integrated circuit was added as a current protection stage. This component compares two voltages: the shunt voltage V_{shunt} , which represents the current flowing in the circuit, and the reference voltage V_{ref} , which is set using a voltage divider.

As long as V_{shunt} remains lower than V_{ref} , the circuit operates normally. When V_{shunt} becomes higher than V_{ref} , this means that the current has exceeded the allowed limit. In this case, the LM358N reduces or stops the MOSFET conduction in order to protect both the device and the solar panel. In other words, the LM358N acts as a current supervision stage.

However, this circuit could not be implemented on a breadboard because of the high power dissipated by the resistors. For this reason, it required a more suitable practical setup with proper wiring, heat dissipation, and secure connections.

4-3 The Printed Circuit Boards

From the beginning of this project, one of the main objectives was to reach the PCB realization stage for the designed circuits. As mentioned previously, the simulation phase was carried out using Proteus 8. However, some components used in the practical circuit, such as the sensors, were not available in the Proteus libraries.

For this reason, the PCB design was completed only for three circuits: the PV input and protection circuit, the -15 V power supply circuit, and the load circuit.

To create a PCB in Proteus, the option “Create a PCB layout from the selected template” must be selected when starting a new project. This option allows the schematic design to be linked directly to the PCB layout environment, where the components can be placed and routed.

To create a PCB for any circuit, it is first necessary to verify that each component has an assigned footprint. After completing the schematic capture, the design is transferred to the PCB layout environment, where the list of used components appears.

The components are then placed on the board according to the required arrangement. After that, the track mode is selected, and the auto-routing option can be used to connect the components according to the schematic capture. Once the routing is completed, Proteus also allows a 3D view of the PCB to be generated in order to check the final appearance of the circuit.

The final step in Proteus is to export the design as Gerber files. These files are then used by the CNC machine to manufacture the printed circuit board.

4-3-1 PV Input PCB

Most of the components of this circuit were available in Proteus, except for the HBR20100CT and 1,5KE150A diodes, so we created the PCB layout and replaced these two with just holes with the same distance between the pins.

This circuit is a single-sided PCB as shown in Figure4.2, which means there are copper connections only on one side of the board; we chose the bottom surface.

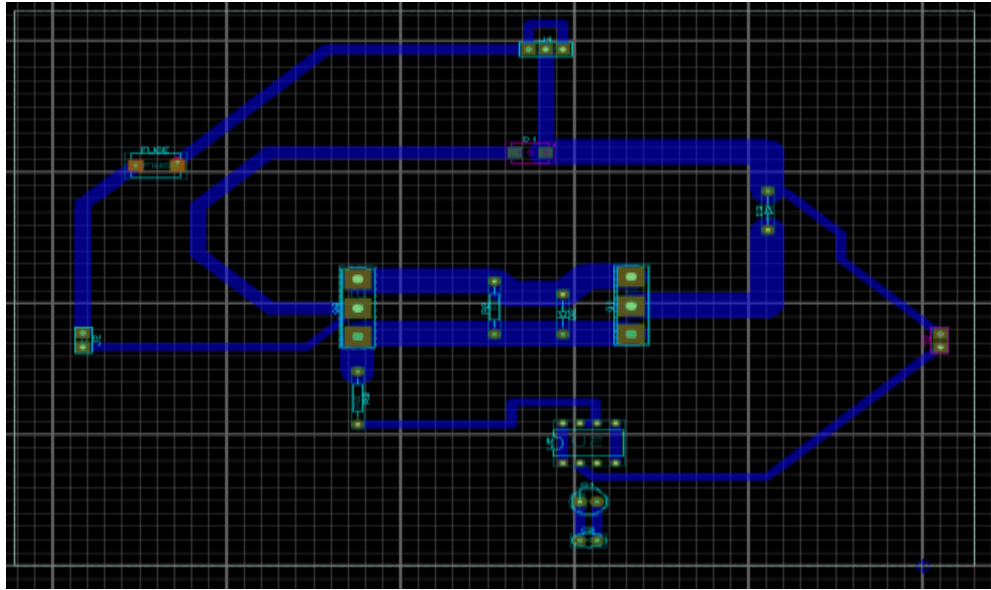


Figure 4.2: Input circuit PCB layout

4-3-2 Power Supply Circuit PCB

For the power supply circuit, the three positive voltage regulators were already available as ready-to-use modules with their own PCB packaging. Therefore, only the -15 V converter circuit needed to be designed as a separate PCB.

The objective was to design this PCB as a single-sided circuit in order to simplify the manufacturing process. For this reason, the routing was done on the bottom copper layer. The PCB was designed in Proteus, and then the required Gerber files were exported before moving to the manufacturing step.

The circuit was manufactured using the LPKF S104 machine available. Since the circuit was relatively small, it was suitable for this type of machine. However, it was only possible to perform the board routing and drill the component holes. The machine still required additional parts or another processing line to complete all the manufacturing steps.

As a result, the PCB was partially manufactured, but it still needed additional finishing steps before being considered a complete and ready-to-use printed circuit board.

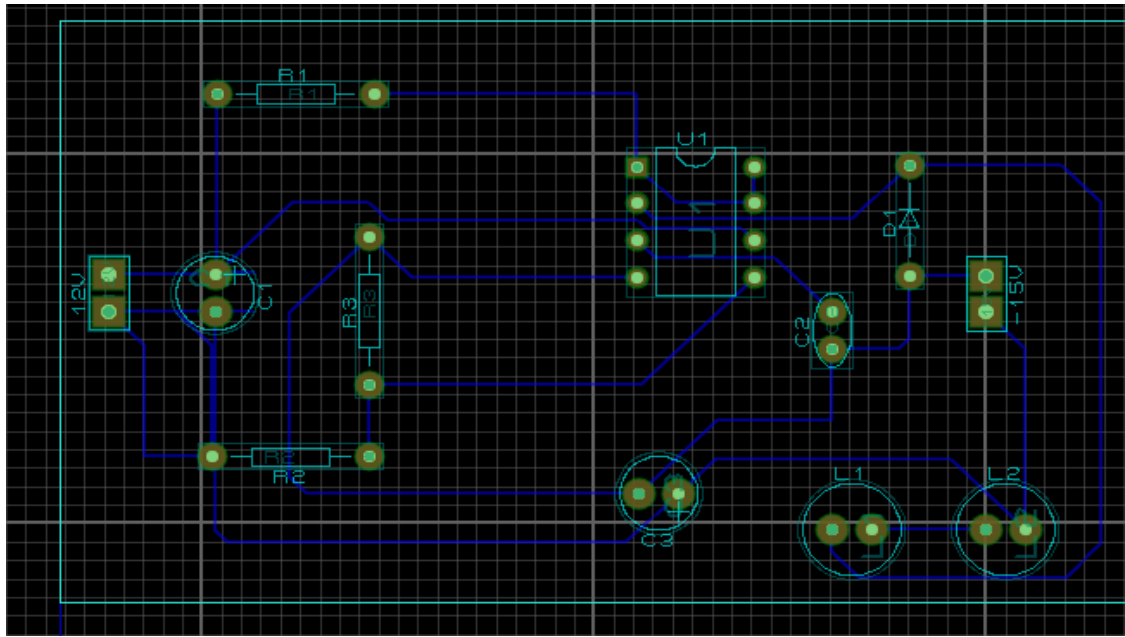


Figure 4.3: Power supply (-15V) circuit

4-3-3 Load Circuit PCB

For this last circuit, the PCB was designed only using Proteus. The circuit is divided into two main voltage stages. The first one is the control stage, which does not require a high current. For this part, a T20 track width was sufficient.

The second one is the power stage, where a higher current is expected to flow. For this reason, a much wider track, such as T200, was used. This choice helps the power tracks support the required current and allows the power components to operate correctly without excessive heating or voltage drop.

In this circuit, it was a little bit harder to adjust the components to have a single-sided circuit, because it has so many components, and each one is connected to more than one. So it ends up as a double-sided circuit with both bottom and top copper connections, and for that, it would require more time to be printed.

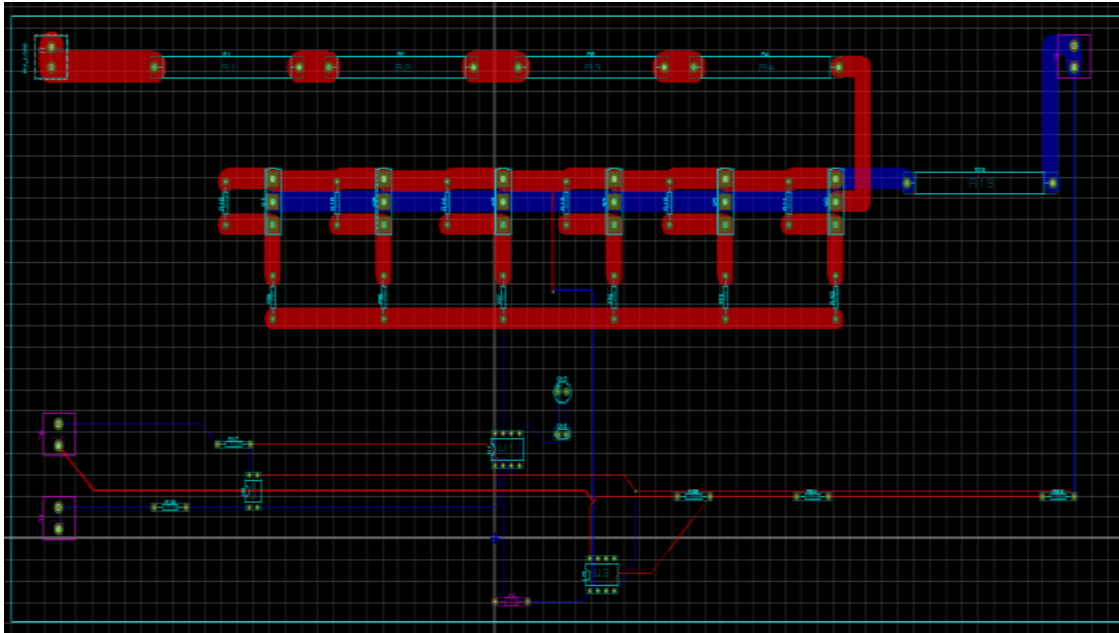


Figure 4.4: Load circuit PCB

4-4 Final Prototype

As mentioned previously, the initial objective was to manufacture PCBs for all the circuits of the prototype. However, due to the lack of certain materials and the limited manufacturing resources available, this objective could not be fully achieved.

Instead of keeping the circuits assembled only on breadboards, a more reliable solution was adopted by soldering the components onto perforated boards. This approach improved the mechanical stability of the prototype and made it more suitable for repeated use. Initially, four perforated boards were used, with one board dedicated to each circuit. These boards were then interconnected and installed inside an insulating enclosure.

During this final assembly stage, several possible simplifications were identified in order to reduce the size of the device and improve its internal organization. The first modification concerned the PV input and protection circuit. This circuit was removed after it caused a short-circuit problem when it was placed with the other circuits inside the enclosure. This simplification was possible because other components in the prototype already provided a certain level of protection. As a result, the circuit directly connected to the solar panel became the control and measurement circuit.

Another simplification was made in the power supply stage. Instead of using several regulators, the number of regulators was reduced to only one 5 V regulator, which was used to supply the ESP32. We replaced the ATMEGA328p from the simulation with the ESP32 for the purpose of transferring the data via Bluetooth. This regulator was then soldered onto the same board as the control and measurement circuit, which reduced wiring and made the prototype more compact.

For the electronic load circuit, six MOSFETs were initially considered. However, during the tests, one of them was found to be damaged. This caused the MOSFET to heat up immediately when the circuit was closed, because the current bypassed the three power resistors and the other resistive elements and flowed mainly through this damaged MOSFET. To solve this problem, the damaged component was removed, and only five MOSFETs were kept in the final load circuit.

Another improvement was made by eliminating the cooling fans. At first, the fans were considered necessary to cool the power components. However, after modifying the program written in the Arduino IDE, it became possible to reduce the thermal stress on the circuit. The program was designed to cut off the load after completing the measurement cycle, which limited unnecessary power dissipation and prevented excessive heating. After these simplifications, the final prototype was reduced to two perforated boards instead of several separate boards.

Regarding the sensors, which require a symmetrical supply voltage of +15 V and -15 V, the first solution was to use a regulator to obtain +15 V from the 12 V supply and an inverter circuit to generate -15 V from the same source. However, the inverter circuit was not stable enough to be used inside a closed enclosure. It sometimes caused short-circuit problems and occasionally stopped operating correctly. For this reason, it was considered to replace this solution with a Traco Power converter, using a 12 V input and providing a symmetrical ± 15 V output. Since the suitable Traco Power module was not available at the time of the realization of this work, the sensors were temporarily supplied using a laboratory power supply.

One of the main challenges during this stage was to optimize the placement of the components in order to simplify the soldering process and facilitate the interconnection between the two circuits. Particular attention was also given to the grounding system. All ground connections had to be correctly linked together to ensure proper operation of the prototype and to avoid measurement errors or circuit malfunctions.

To simplify testing and maintenance, banana sockets were added to each board. This solution made it possible to connect and disconnect the circuits easily and to test each board independently before integrating it into the complete prototype.



Figure 4.5: final prototype

4-5 The Functioning Concept of The Prototype

The input of the solar panel is connected to the first circuit, where the voltage and current are measured using the LV25-P and LA25-NP sensors. The LV25-P voltage sensor is connected in parallel between PV+ and PV-, while the LA25-NP current sensor is connected in series with the load. After passing through the current sensor, the current flows through the electronic load, which is composed of the series power resistors and the parallel MOSFETs, before returning to the PV- of the solar panel.

The electronic load is controlled progressively using a stabilized PWM signal generated by the ESP32. By varying the duty cycle of this PWM signal, the conduction of the MOSFETs can be controlled gradually. At 0% duty cycle, the load is almost disconnected, which corresponds to the open-circuit condition. In this case, the open-circuit voltage V_{oc} can be measured, and the current is equal to 0 A. At 100% duty cycle, the MOSFETs are fully conducting, which brings the circuit close to the short-circuit condition, but without ignoring the series resistors. This

allows the short-circuit current I_{sc} to be measured, while the voltage becomes very low but not zero.

This progressive variation of the load makes it possible to change the operating point of the solar panel and collect the required measurement points for plotting the I-V and P-V curves.

Concerning the ESP32 code, the first tests did not give a curve close to the expected characteristic shape. For this reason, an interpolation method was used to obtain a smoother and more representative curve. After each PWM variation cycle, the program returns to the initial point, where the load is disconnected. This step helps to reduce power consumption in the load and prevents excessive heating of the power components.

4-6 Prototype Testing

After soldering all the circuits on the perforated boards, we moved to the final step, which is testing our prototype. We did three tests at three different times during the day. We conducted the tests on 11/06/2026. The first test was at 11:04, where the irradiance was 800 W/m^2 , which was measured using an external sensor, and we found the results presented in the figure below (Figure 4.5).

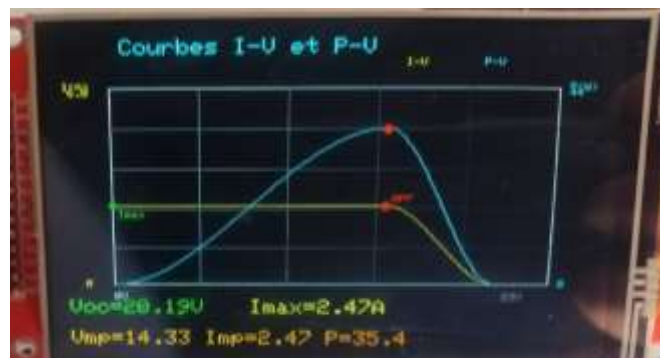


Figure 4.6: First test result

The second test was made at 12:14, where the irradiance was 950 W/m^2 . We also changed the display to make it possible for the user to choose whether to display the measurements only or the curves only. We obtained the results presented in the figures below.



Figure 4.7: Measurements of the second test

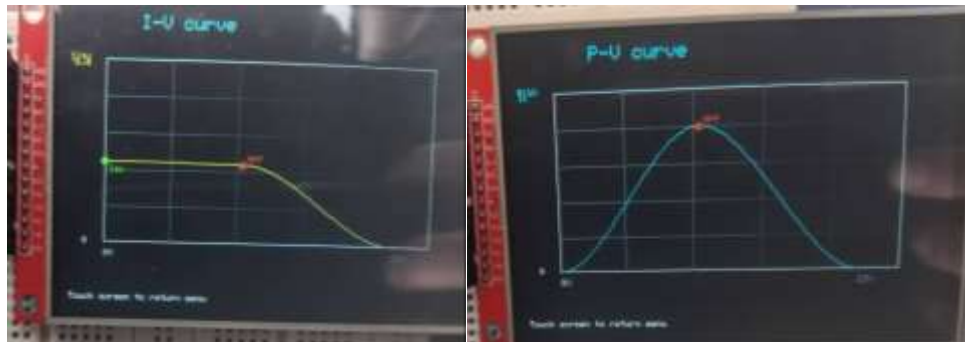


Figure 4.8: I-V & P-V curves of the second test

For the last test, it was done at 14:08, where the irradiance was 1050 W/m^2 . it is the highest measure we could take during this day; the results are in the next figure.



Figure 4.9: Measurement of the third test

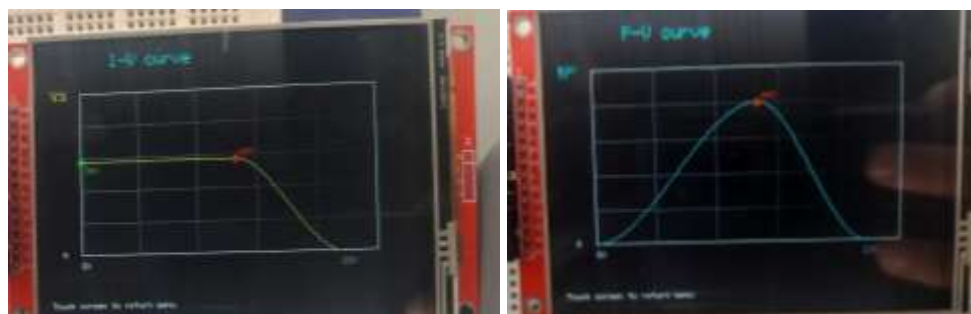


Figure 4.10: I-V & P-V curves of the third test

4-7 Result Interpretation

The obtained results are consistent with the test conditions. The measurements were carried out on a sunny day, and the solar irradiance increased progressively with time. As a result, the measured voltage and current also showed an increasing tendency, which is consistent with the normal behaviour of a photovoltaic panel.

Regarding the accuracy of the device, the displayed values were compared with the measurements obtained using an external voltmeter and ammeter. The difference between the two measurements was approximately 0.1 V for the voltage and 0.1 A for the current, which shows an acceptable precision for the developed prototype.

4-8 Future Improvement of The Prototype

Our prototype can still be improved in the future to make it closer to a finished product or a real professional curve plotter. We can:

- Add a battery to make it more independent.
- Use the tracopower to make it more independent
- Manufacture the PCB circuits to make the device smaller.
- Create our own enclosure.
- Use a bigger screen for the display.

4-9. Conclusion

In this chapter, the practical implementation of the photovoltaic I-V and P-V curve tracer was presented. After the simulation phase, the different circuits were first tested on breadboards in order to verify their operation and make the necessary adjustments.

The PCB design was then carried out using Proteus for the circuits that could be implemented. However, due to some practical limitations, the final prototype was assembled on perforated boards and placed inside an insulating enclosure. Finally, the prototype was tested under real outdoor conditions, and the obtained results confirmed the correct operation of the device and its ability to measure and display the main electrical parameters of the photovoltaic panel.

General Conclusion

This final-year project focused on the design and realization of a photovoltaic I-V curve plotter intended for the characterization and diagnosis of solar panels. The main objective was to develop a device capable of measuring the open-circuit voltage V_{oc} , the short-circuit current I_{sc} , the output power, and the fill factor, while displaying the corresponding I-V and P-V curves.

The work began with a theoretical study of photovoltaic systems, including the operating principle of solar cells, the structure of photovoltaic modules, and their main electrical characteristics. The importance of I-V and P-V curves was highlighted, since they provide a complete representation of the electrical behavior of a photovoltaic panel and make it possible to evaluate its performance more accurately than simple isolated measurements.

Several curve tracing methods were then studied and compared. The electronic load-based method was selected because it offers a good balance between simplicity, controllability, and practical implementation. Based on this choice, the system was divided into different functional parts: the PV input and protection circuit, the power supply circuit, the control and measurement circuit, and the electronic load circuit. The ESP32 was used for control and data processing, while voltage and current sensors were used for measurement acquisition.

The practical realization was carried out progressively, starting with breadboard tests, followed by circuit optimization and final assembly on perforated boards due to the limited availability of PCB manufacturing resources. During this stage, several simplifications were made to reduce the size of the prototype and improve its reliability, including the reduction of the number of boards, the simplification of the power supply stage, and the optimization of the electronic load.

The prototype was tested using a real photovoltaic panel under outdoor conditions. The obtained results confirmed the correct operation of the system, as the measured voltage, current, and power followed the expected behavior of a photovoltaic panel. The comparison with external measuring instruments showed small differences, about 0.1 V for voltage and 0.1 A for current, which is acceptable for a first prototype.

In addition to the technical aspect, the project was also studied from an economic and entrepreneurial point of view. The Business Model Canvas and financial study showed that the device could be useful for photovoltaic installation companies, maintenance companies, engineering offices, universities, and research centers. It can represent a local and accessible solution for photovoltaic diagnosis, especially compared with imported measurement equipment.

Although the prototype is functional, several improvements are still possible. These include manufacturing compact PCBs, improving the enclosure, adding an autonomous power supply, integrating irradiance and temperature sensors, improving the graphical interface, and adding wireless communication or a mobile application for data storage.

In conclusion, this project made it possible to design, implement, and test a functional photovoltaic curve plotter using accessible electronic components. It represents a solid basis for future development and could be improved into a portable, reliable, and cost-effective diagnostic tool for photovoltaic system characterization and maintenance.

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Annexes

1- Modèle économique BMC de mon projet

1-1 Proposition de valeur

Nous proposons un dispositif capable de tracer les caractéristiques électriques des panneaux solaires, permettant d'assurer un diagnostic fiable des paramètres électriques et de prévoir la dégradation ainsi que la durée de vie des installations photovoltaïques. Notre traceur se distingue par son format compact, son écran couleur tactile, ainsi que par une application permettant le stockage et le suivi à long terme des mesures. Ce projet répond aux besoins des techniciens de terrain qui ne disposent pas actuellement d'un outil simple, portable et fiable pour évaluer l'état d'une installation photovoltaïque.

1-2 Segment client

Notre proposition de valeur cible sept segments de clientèle distincts : les entreprises spécialisées dans l'installation de panneaux solaires, les entreprises de maintenance des systèmes photovoltaïques, les bureaux d'études spécialisés dans les projets photovoltaïques, les distributeurs d'appareils de mesure électrique, les entreprises exploitant des installations photovoltaïques, les centres de recherche en énergies renouvelables et les facultés des sciences techniques. Nos clients les plus stratégiques seront les entreprises de maintenance photovoltaïque et les bureaux d'études, car ils présentent des besoins récurrents et disposent de budgets structurés pour l'acquisition d'équipements.

1-3 Relation client

Nous établirons des relations avec nos clients basées sur un accompagnement personnalisé et une proximité continue. Nous assurerons la maintenance des dispositifs vendus et mettrons à disposition un espace client en ligne permettant aux clients de passer des commandes et de suivre les interventions de service après-vente. Nous proposerons également une foire aux questions (FAQ) afin de répondre aux demandes courantes, et nous collecterons activement les retours des clients dans le but d'améliorer continuellement nos produits et nos services.

1-4 Canaux de distribution

Nous atteindrons nos clients principalement à travers notre site web, qui permettra également de passer des commandes en ligne. Nous participerons à des salons scientifiques et à des concours afin de renforcer notre visibilité auprès des professionnels et des institutions du secteur. Nous prévoyons également de développer notre présence sur LinkedIn pour assurer une

prospection B2B directe et établir des partenariats avec des distributeurs d'appareils de mesure électrique afin d'élargir notre portée commerciale.

1-5 Activités clés

Nos activités principales comprendront la fabrication de traceurs I-V en versions standard et personnalisées, la maintenance des dispositifs vendus, ainsi que le développement de l'application de stockage des mesures. Nous mènerons également des activités continues de recherche et développement afin d'améliorer nos produits et d'intégrer de nouvelles fonctionnalités. La gestion de la chaîne d'approvisionnement avec nos fournisseurs de composants constituera une activité quotidienne essentielle pour assurer le bon fonctionnement de notre production.

1-6 Ressources clés

Nos ressources humaines seront composées d'un gérant, d'ingénieurs en électrotechnique et en informatique, ainsi que d'un agent de sécurité. En matière d'équipements, nous aurons besoin d'une machine CNC, de multimètres, d'une alimentation de laboratoire, d'une fer à souder et d'une pompe à dessouder. Notre expertise technique dans la conception et la fabrication de traceurs I-V restera notre actif propriétaire le plus précieux.

1-7 Partenaires clés

Nos principaux fournisseurs de composants électroniques seront BinaryTech et PowerLab. Nous collaborerons également avec un fabricant de boîtiers, une entreprise d'emballage et de conditionnement, ainsi qu'un prestataire logistique chargé de la livraison de nos produits finis. Notre comptable assurera la gestion financière et administrative de l'entreprise. Nous bénéficierons aussi du soutien institutionnel de la NESDA et du CDER, ce qui renforcera notre visibilité et notre crédibilité dans le secteur des énergies renouvelables.

1-8 Structure des coûts

Nos charges fixes comprendront la location des locaux, les salaires du personnel, ainsi que le budget marketing. Nos charges variables comprendront les factures d'électricité, d'eau et de gaz, les composants électroniques, les boîtiers, l'emballage et le conditionnement, ainsi que les frais de livraison des composants et des produits finis.

1-9 Flux des revenus

Nos revenus proviendront de trois sources principales : la vente unitaire de traceurs I-V en versions standard et personnalisées, la vente de traceurs accompagnés de l'application de stockage des mesures, ainsi que les contrats de maintenance des dispositifs vendus. Les services de maintenance et l'application représenteront des sources de revenus récurrents que nous souhaitons développer afin d'assurer un flux de trésorerie stable et prévisible à long terme.

2- Tableau de BMC

Partenaires clés	Activités clés	Proposition de valeur	Relation avec les clients	Clients
- Fournisseur de composants électroniques (BinaryTech, PowerLab). - Fabricant de boîtiers. - Entreprise d'emballage et de conditionnement. - Entreprise de livraison / prestataire logistique. - Comptable. - NESDA : organisme d'accompagnement et de soutien à l'entrepreneuriat. - CDER : partenaire institutionnel dans le domaine des énergies renouvelables	- Production de traceurs de courbes I-V (versions standards et personnalisées). - Maintenance des traceurs I-V. - Développement d'une application de stockage des données	- Un dispositif permettant de tracer les caractéristiques électriques des panneaux solaires. - Permettre un diagnostic fiable des paramètres électriques des panneaux solaires. - Permettre la prédiction de la dégradation et de la durée de vie des panneaux solaires. - Format compact avec un écran couleur tactile. - Intégration d'une application pour le stockage des mesures.	- Maintenance des dispositifs vendus. - Accompagnement personnalisé des clients. - Site web permettant de passer des commandes. - Collecte des retours et des réclamations des clients. - Espace client. - Foire aux questions (FAQ).	- Entreprises d'installation de panneaux solaires. - Entreprises de maintenance des systèmes photovoltaïques. - Bureaux d'études spécialisés dans les projets photovoltaïques. - Distributeurs d'appareils de mesure électrique - Entreprises disposant d'installations photovoltaïques. - Centres de recherche en énergies renouvelables. - Universités
Ressources clés Ressources humaines : 2 ingénieurs en électricité. 1 ingénieur en informatique. 1 agent de sécurité. Ressources matérielles : 1 CNC machine. 2 Multimètres. 2 sondes de multimètre. 1 alimentation de laboratoire. 1 station de soudage. 2 fils à souder. 2 Nettoyeurs de panne de fer à souder. 2 Pompe à dessouder.		Flux de revenus - Vente unitaire des traceurs. - Services de maintenance des traceurs I-V. - Vente des traceurs accompagnés de l'application		
Structure des coûts Location / Livraison des produits finis Marketing / Boîtiers Salaires / Emballage Électricité, eau et gaz / Composants électroniques Charges fixes = 2 428 000 DA Charges variables = 708 600 DA Coût total du projet = 7 506 840 DA				

Tableau 1: tableau BMC

Source : Élaboré par nous-mêmes

Tableau d'analyse SWOT

	Facteurs contribuant à la réalisation des objectifs	Facteurs entravant la réalisation des objectifs
Facteurs Internes	Force 1. Nous possédons l'expertise technique nécessaire pour fabriquer ce dispositif, puisque nous avons déjà conçu et réalisé un prototype fonctionnel. 2. Notre expertise dans la conception et la fabrication du dispositif nous permet d'assurer sa maintenance et sa réparation en interne, ce qui réduit la dépendance aux prestataires externes. 3. Le projet peut être facilement amélioré et personnalisé, car le dispositif est développé par notre propre équipe, ce qui nous permet de l'adapter aux différents besoins des clients et aux différents types d'installations photovoltaïques,	Faiblesse 1. Le dispositif peut nécessiter une validation technique ou une certification avant d'être exporté. 2. Bien qu'un prototype ait été développé, le passage du prototype à la production en série peut nécessiter une expérience industrielle supplémentaire. 3. En tant que nouveau produit, le dispositif peut avoir besoin de temps pour gagner la confiance des clients et être accepté sur le marché.
Facteurs Externes	Opportunités 1. Les politiques publiques algériennes encouragent de plus en plus l'utilisation des énergies renouvelables, en particulier l'énergie solaire photovoltaïque, ce qui crée un environnement favorable pour ce projet. 2. La limitation des importations et l'encouragement de la production locale représentent une opportunité pour les appareils de mesure fabriqués localement 3. L'Algérie a lancé un programme national de développement des énergies renouvelables visant à développer une capacité solaire photovoltaïque à grande échelle, ce qui augmentera le besoin en outils de test et de diagnostic des systèmes photovoltaïques.	Menaces 1. Certains clients peuvent préférer les dispositifs importés, car ils les considèrent comme plus fiables ou plus professionnels que les produits locaux. 2. Le développement rapide des technologies photovoltaïques et des équipements de mesure peut nécessiter une innovation continue afin de rester compétitif. 3. Une fois le dispositif introduit sur le marché, des concurrents peuvent essayer de copier le concept ou de proposer des alternatives similaires à faible coût.

Tableau 2: analyse SWOT

Source : Élaboré par nous-mêmes

D'après le tableau SWOT, le projet semble avoir une bonne position de départ, car il répond à un besoin réel dans le domaine photovoltaïque : le contrôle et le diagnostic des panneaux solaires. Le fait d'avoir déjà un prototype donne plus de crédibilité au projet. Cependant, pour réussir sur le marché, il faudra surtout améliorer la fiabilité du produit, obtenir la confiance des clients et proposer un prix compétitif par rapport aux produits importés. Donc, le projet est bien placé, mais il doit être bien développé et testé avant d'être commercialisé

3- Besoins du projet en ressources humaines

Nature des utilisateurs	Nbr	Compétences / qualifications
Gérant	1	Gestion de projet, coordination d'équipe, connaissances de base en systèmes photovoltaïques, gestion financière, communication, négociation et gestion des partenariats.
Ingénieur	2	Génie électrique, systèmes photovoltaïques, conception électronique, mesure et étalonnage, maintenance des dispositifs. Informaticien pour développement logiciel, gestion de bases de données et support de l'application
Agent de sécurité	1	Sécurité du lieu de travail, contrôle d'accès, surveillance des locaux, respect des règles de sécurité, nettoyage et entretien de l'hygiène, organisation des espaces de travail, et contribution au maintien d'un environnement de travail sûr et propre

Tableau 3: besoin en ressources humaines

Source : Élaboré par nous-mêmes

4- Estimation des coûts du projet

4-1 Estimation du montant total de l'investissement :

Désignation	Montant (DA)
1 CNC machine (3 500 000 DA)	3 565 740 DA
2 multimètres (4 850 DA/unité)	
2 Multimètre probe (600 DA/unité)	
1 Alimentation laboratoire (45000 DA/unité)	
1 fer a souder (3900 DA)	
2 fils à souder (1 200 DA/unité)	
2 Nettoyeur de panne de fer à souder (920 DA/unité)	
2 Pompe à dessouder (850 DA/unité)	
Installation électrique (250 000 DA)	250 000 DA

4 bureaux 6 chaises 3 armoires 3 Armoire de stockage	(20 000 DA/unité) (6 000 DA/unité) (14 500 DA/unité) (5 000 DA/unité)	174 500 DA
3 Ordinateurs	(80 000 DA/unité)	240 000 DA
1 Projecteur	(10 000 DA/unité)	10 000 DA
Wi-Fi TP-Link		20 000 DA
Installation des équipements		80 000 DA
Frais généraux liés à la création (additional electronic components, wires, screws, and spare parts, Printing reports)		30 000 DA
Fonds de roulement		592 000 DA
Montant total de l'investissement		4 962 240 DA

Tableau 4: Estimation du montant total de l'investissement

Source : Élaboré par nous-mêmes

Le tableau 4 représente le montant nécessaire pour l'acquisition de l'investissement lié au projet. La plus grande partie de l'investissement concerne les équipements de production, la machine CNC en particulier, car elle est essentielle pour la fabrication du traceur I-V. Les autres dépenses, comme le mobilier, les ordinateurs, l'installation électrique et le matériel de télécommunication, sont aussi nécessaires pour organiser le travail et assurer le fonctionnement de l'entreprise.

Le fonds de roulement représente l'argent prévu pour l'approvisionnement en composants électroniques nécessaires à la première production. Le montant total de l'investissement est donc logique, car il regroupe à la fois les équipements de départ, les installations et les matières premières nécessaires au démarrage de l'activité.

4-2 Estimation des approvisionnements en matières premières

Ce tableau représente le coût des composants nécessaires pour fabriquer les traceurs I-V pendant les trois premières années. Le montant augmente chaque année parce que la production augmente progressivement : 20 pièces la première année, 25 pièces la deuxième année et 30 pièces la troisième année.

Les achats de matières premières passent de 592 000 DA en première année à 746 000 DA en deuxième année, puis à 958 500 DA en troisième année. Cette évolution est normale, car

l'entreprise aura besoin de plus de composants électroniques pour produire un nombre plus élevé de traceurs. Le fonds de roulement de la première année correspond donc au coût des composants nécessaires au démarrage de la production.

Liste des matières premières		Année 1	Année 2	Année 3
Fusible 16 A	Quantité achetée	20	25	30
	Prix unité	700	700	730
	Coût d'achat de la matière première 1	14 000	17 500	21 900
Diode HBR 150CT	Quantité achetée	20	25	30
	Prix unité	100	100	120
	Coût d'achat de la matière première 2	2 000	2 500	3 600
Diode 1,5KE150A	Quantité achetée	20	25	30
	Prix unité	60	60	70
	Coût d'achat de la matière première 3	1 200	1 500	2 100
MOSFET IRFP260N	Quantité achetée	100	125	150
	Prix unité	350	350	370
	Coût d'achat de la matière première 4	35 000	43 750	55 500
Driver MOSFET TC4420	Quantité achetée	20	25	30
	Prix unité	550	550	570
	Coût d'achat de la matière première 5	11 000	13 750	17 100
Condensateur 10uF	Quantité achetée	20	25	30
	Prix unité	15	15	20
	Coût d'achat de la matière première 6	300	375	600
Capacité 100nF	Quantité achetée	200	250	300
	Prix unité	10	10	15
	Coût d'achat de la matière première 7	2 000	2 500	4 500
Resistance 10R	Quantité achetée	140	175	210
	Prix unité	10	10	15
	Coût d'achat de la matière première 8	1 400	1 750	3 150
Resistance 10KR	Quantité achetée	140	175	210
	Prix unité	15	15	20
	Coût d'achat de la matière première 9	2 100	2 625	4 200

Liste des matières premières		Année 1	Année 2	Année 3
Regulateur LM2596	Quantité achetée	20	25	30
	Prix unité	750	750	770
	Coût d'achat de la matière première 10	15 000	18 750	23 100
Condensateur 220uF/25V	Quantité achetée	40	50	60
	Prix unité	15	15	20
	Coût d'achat de la matière première 12	600	750	1 200
Condensateur 1000uF/16V	Quantité achetée	20	25	30
	Prix unité	25	25	30
	Coût d'achat de la matière première 16	500	625	900
Capteur de courant LA25-NP	Quantité achetée	20	25	30
	Prix unité	4500	4500	4700
	Coût d'achat de la matière première 17	90 000	112 500	141 000
Capteur de tension Lv25-P	Quantité achetée	20	25	30
	Prix unité	8 000	8 000	9 000
	Coût d'achat de la matière première 18	160 000	200 000	270 000
Resistance 100R	Quantité achetée	20	25	30
	Prix unité	15	15	20
	Coût d'achat de la matière première 20	300	375	600
Resistance 390R	Quantité achetée	60	75	90
	Prix unité	15	15	20
	Coût d'achat de la matière première 21	900	1 125	1 800
Resistance 1KR	Quantité achetée	20	25	30
	Prix unité	10	10	15
	Coût d'achat de la matière première 25	200	250	450
Diode 1N5819	Quantité achetée	20	25	30
	Prix unité	15	15	20
	Coût d'achat de la matière première 26	300	375	600
Ecran TFT 4"	Quantité achetée	20	25	30
	Prix unité	5900	5900	6000
	Coût d'achat de la matière première 27	118 000	147 500	180 000

Liste des matières premières		Année 1	Année 2	Année 3
ADS1115	Quantité achetée	20	25	30
	Prix unité	1400	1400	1500
	Coût d'achat de la matière première 28	28 000	35 000	45 000
ESP 32	Quantité achetée	20	25	30
	Prix unité	2200	2200	2300
	Coût d'achat de la matière première 29	44 000	55 000	69 000
Resistance 1R/50W	Quantité achetée	80	100	120
	Prix unité	480	480	500
	Coût d'achat de la matière première 31	38 400	48 000	60 000
PC817	Quantité achetée	20	25	30
	Prix unité	60	60	70
	Coût d'achat de la matière première 32	1 200	1 500	2 100
Fiche banane	Quantité achetée	140	175	210
	Prix unité	80	80	90
	Coût d'achat de la matière première 35	11 200	14 000	18 900
Dissipateur thermique	Quantité achetée	120	200	240
	Prix unité	120	120	130
	Coût d'achat de la matière première 36	14 400	24 000	31 200
Montant total des achats de matières premières		592 000 DA	746 000 DA	958 500 DA

Tableau 5: Estimation des approvisionnements en matières premières

Source : Élaboré par nous-mêmes

4-3 Estimation des coûts de la main-d'œuvre :

Le tableau qui va suivre les salaires annuels prévus pour le personnel du projet. Pour le début, l'équipe est limitée afin de réduire les charges, avec un gérant, deux ingénieurs et un agent de sécurité. Ensuite, le nombre de travailleurs augmente en deuxième et en troisième année, surtout pour accompagner l'augmentation de la production.

L'augmentation des salaires d'une année à l'autre est logique, car elle prend en compte l'évolution de l'activité

Intitulé du poste	Nombre de travailleurs			Montant du salaire/an		
	Année 1	Année 2	Année 3	Année1/employé	Année2/employé	Année3/employé
Le gérant	1	1	1	480 000 DA	528 000 DA	576 000 DA
Ingénieur	2	3	3	480 000 DA	528 000 DA	576 000 DA
Agent de sécurité	1	2	3	288 000 DA	300 000 DA	312 000 DA
Total de charge personnel (salaires)				1 728 000 DA	2 712 000 DA	3 240 000 DA

Tableau 6: Estimation des coûts de la main-d'œuvre

Source : Élaboré par nous-mêmes

4-4 Estimation des services externes du projet

Ce tableau représente les dépenses nécessaires au fonctionnement du projet en dehors des salaires et des matières premières. Les charges augmentent progressivement pendant les trois années, ce qui est logique car l'activité et la production augmentent aussi.

Désignation	Année 1	Année 2	Année 3
Frais d'électricité / de gaz / d'eau	46 600 DA	72 400 DA	88 000 DA
Coûts de maintenance et de réparation	10 000 DA	15 000 DA	20 000 DA
Frais de location	600 000 DA	650 000 DA	800 000 DA
Frais d'assurance du matériel et des équipements	50 000 DA	55 000 DA	60 000 DA
Frais de marketing (publicité et promotion)	100 000 DA	130 000 DA	150 000 DA
Boîtiers	40 000 DA	50 000 DA	60 000 DA
Emballage	12 000 DA	15 000 DA	18 000 DA
Livraison des produits finis	8 000 DA	10 000 DA	12 000 DA
Total	866 600 DA	997 400 DA	1 208 000 DA

Tableau 7: Estimation des services externes du projet

Source : Élaboré par nous-mêmes

4-5 Estimation des coûts d'amortissement des investissements

Désignation	Durée d'amortissement (en années)	Dotations aux amortissements (DA)
Machines et équipements de	5 ans	713 148
Matériel de bureau	5 ans	34 900
Matériel informatique	5 ans	48 000
Matériel audiovisuel	5 ans	2 000
Matériel de télécommunication	5 ans	4 000
Montant total	802 048 DA	

Tableau 8: Estimation des coûts d'amortissement des investissements

Source : Élaboré par nous-mêmes

5- Estimation des revenus du projet

5-1 Estimation du volume des ventes annuelles :

Désignation		Année 1	Année 2	Année 3
Produit : / service 1 Traceur I-V	Qté	20	25	30
	P.U	180 000	190 000	190 000
	Ventes du produit 1	3 600 000	4 750 000	5 700 000
Produit / service 2 Maintenance de traceur	Qté	5	10	10
	P.U	11 000	12 000	12 000
	Ventes du produit 2	55 000	120 000	120 000
Produit / service 3 Développement de l'application	Qté	7	15	20
	P.U	40 000	40 000	40 000
	Ventes du produit 3	280 000	600 000	800 000
Chiffre d'affaires total		3 935 000	5 470 000	6 620 000

Tableau 9 : Estimation du volume des ventes annuelles

Source : Élaboré par nous-mêmes

Le tableau 9 montre les revenus prévus pour les trois premières années. Le chiffre d'affaires augmente progressivement, car le nombre de traceurs vendus passe de 20 pièces en année 1 à 25 pièces en année 2, puis à 30 pièces en année 3.

Les revenus viennent principalement de la vente des traceurs I-V, qui représentent la source principale du chiffre d'affaires. Les services de maintenance et le développement de

l'application ajoutent aussi des revenus complémentaires. Le chiffre d'affaires passe de 3 935 000 DA en année 1 à 5 470 000 DA en année 2, puis à 6 620 000 DA en année 3, ce qui montre une évolution positive de l'activité.

5-2 Comptes de résultat annuel

Désignation	Année 1	Année 2	Année 3
Chiffre d'affaires ... (1)	3 935 000 DA	5 470 000 DA	6 620 000 DA
Achats consommés ... (2)	592 000 DA	746 000 DA	958 500 DA
Charges externes ... (3)	866 600 DA	997 400 DA	1 208 000 DA
Valeur ajoutée = (1) - (2) - (3)	2 476 400 DA	3 726 600 DA	4 453 500 DA
Salaires et charges sociales ... (5)	1 728 000 DA	2 712 000 DA	3 240 000 DA
Excédent brut d'exploitation = (4) - (5)	748 400 DA	1 014 600 DA	1 213 500 DA
Amortissements et provisions ... (7)	802 048 DA	802 048 DA	802 048 DA
Résultat d'exploitation = (6) - (7)	-53 648 DA	212 552 DA	411 452 DA
Impôts sur les sociétés / IFU ... (9)	0 DA	40 385 DA	78 176 DA
Résultat net = (8) - (9)	-53 648 DA	172 167 DA	333 276 DA
Évolution du chiffre d'affaires	-	+39,01 %	+21,02 %

Tableau 10: Comptes de résultat annuel

Source : Élaboré par nous-mêmes

Ce tableau présente l'évolution du résultat annuel du projet sur trois années. Durant la première année, le projet présente un déficit de **53 648 DA**, ce qui peut être normal pour une entreprise en phase de démarrage, car les charges de lancement et les investissements restent importants.

À partir de la deuxième année, l'entreprise commence à réaliser un bénéfice de **172 167 DA**. En troisième année, le résultat net s'améliore davantage pour atteindre **333 276 DA**. Cette évolution positive s'explique par l'augmentation progressive du chiffre d'affaires, la maîtrise des charges et le développement de l'activité.

6- Résultat de l'étude

Cette étude montre que le projet de fabrication d'un traceur I-V présente un potentiel intéressant, surtout dans le domaine du diagnostic et du suivi des installations photovoltaïques. L'étude réalisée a permis d'estimer les besoins du projet, notamment les ressources humaines, les équipements, les matières premières, les services externes et les revenus attendus.

Le résultat net montre que le projet pourrait être déficitaire au démarrage, ce qui peut être normal pour une nouvelle activité dans le secteur des énergies renouvelables. Cependant, à partir de la deuxième année, le résultat devient positif grâce à l'augmentation progressive des ventes et à une meilleure organisation de l'exploitation. Cette évolution montre que le projet peut devenir rentable à moyen terme.

Avec un bon positionnement sur le marché, **NexTrace IV-1** répond à un besoin réel lié au contrôle et au diagnostic des panneaux solaires, surtout avec le développement des énergies renouvelables en Algérie. Avec une bonne gestion, une amélioration continue du produit et une stratégie commerciale adaptée, ce projet peut évoluer progressivement et devenir une activité viable à moyen et à long terme.

Proteus 8 Professional

Proteus 8 is an electronic design and simulation software developed by Labcenter Electronics. It is used for drawing electronic schematics, simulating analog and digital circuits, and designing printed circuit boards (PCBs). The software also supports microcontroller simulation, including Arduino, PIC, and AVR families, allowing users to test embedded systems before hardware implementation. Due to its wide range of electronic components and easy-to-use interface, Proteus 8 is commonly used in electronics education, research, and engineering projects.

Proteus 8 was used in this work to design and simulate electronic circuits prior to practical implementation. The software made it possible to verify the operation of the different components, including the MOSFETs and their driver, the microcontroller, the ADC card, and more, while reducing implementation errors and development time.

This software has many features that help engineers in the study of electronic and electrical circuits and components, such as:

- Schematic capture and electronic circuit design.
- Simulation of analog and digital electronic circuits.
- Microcontroller simulation (Arduino, PIC, AVR, ARM, etc.).
- Printed Circuit Board (PCB) design and routing.
- 3D visualization of the designed PCB.
- Design Explorer tool for managing and organizing complex projects.
- Bill of Materials (BOM) generation for electronic components.
- Source code integration for embedded systems simulation.
- Multi-sheet schematic support for large circuit designs.
- Possibility of connecting different schematic sheets.
- Virtual instruments such as oscilloscopes, voltmeters, ammeters, and signal generators.
- Real-time debugging and testing of electronic systems.
- Large electronic component library.
- Detection of design errors before hardware implementation.
- Reduction of development time and prototyping cost.

- User-friendly graphical interface for circuit analysis and design.
- Support for educational, industrial, and research applications.

Arduino IDE

Arduino IDE is an open-source integrated development environment developed for programming microcontrollers and embedded systems. It provides a simple interface that allows users to write, compile, and upload code to different development boards such as Arduino and ESP32. The Arduino IDE supports the C and C++ programming languages and includes several libraries and tools for communication, debugging, and hardware control. Due to its wide hardware compatibility, it is widely used in embedded systems development, electronics projects, and educational applications.

This software is widely used because of its simplicity of use and features like:

- Open-source software used for programming microcontrollers and embedded systems.
- Compatible with several development boards such as Arduino, ESP32, ESP8266, and AVR-based boards.
- Simple and user-friendly interface suitable for beginners and advanced users.
- Integrated code editor with syntax highlighting and error detection.
- Possibility of writing, compiling, and uploading programs directly to the microcontroller.
- Support for C and C++ programming languages.
- Large collection of libraries for sensors, displays, communication modules, and peripherals.
- Serial Monitor and Serial Plotter tools for debugging and data visualization.
- Cross-platform compatibility (Windows, Linux, and macOS).
- Integration with ESP32 board packages for Wi-Fi and Bluetooth applications.
- Real-time code uploading and testing on the hardware.
- Community support with extensive online documentation and examples.
- Used in this project for developing and uploading the control and measurement code to the ESP32 microcontroller.

In this project, the Arduino IDE was used to develop and upload the control and measurement program to the ESP32 microcontroller. It allowed the implementation of sensor acquisition, display management, and control functions required for the electronic system. The software also facilitated testing, debugging, and real-time monitoring of the system through the serial communication tools integrated into the environment.

Practical Implementation Circuits

The components are soldered on perforated boards, each circuit on a different one, and then they are connected via cables, which are presented below with characteristics of the solar panel that was used for the tests.



Figure: Solar Panel Characteristics

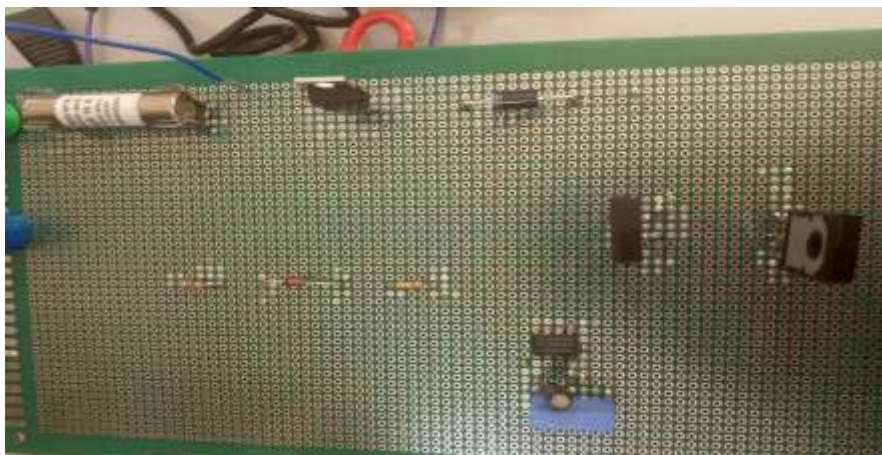


Figure: Input and Protection Circuit on Perforated board

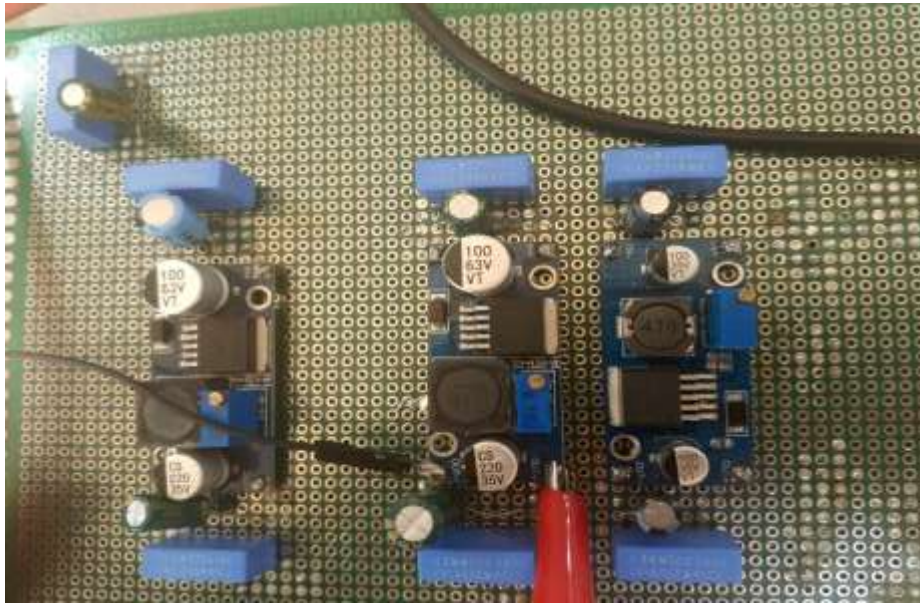


Figure : Power Supply Circuit on Perforated Board(+12V, 5V, 3.3V)

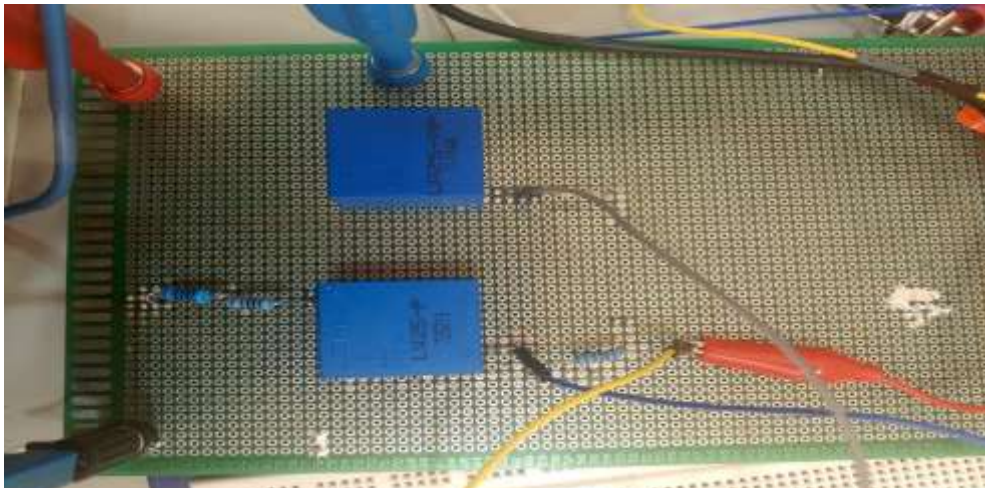


Figure : Measurements Circuit on Perforated Board

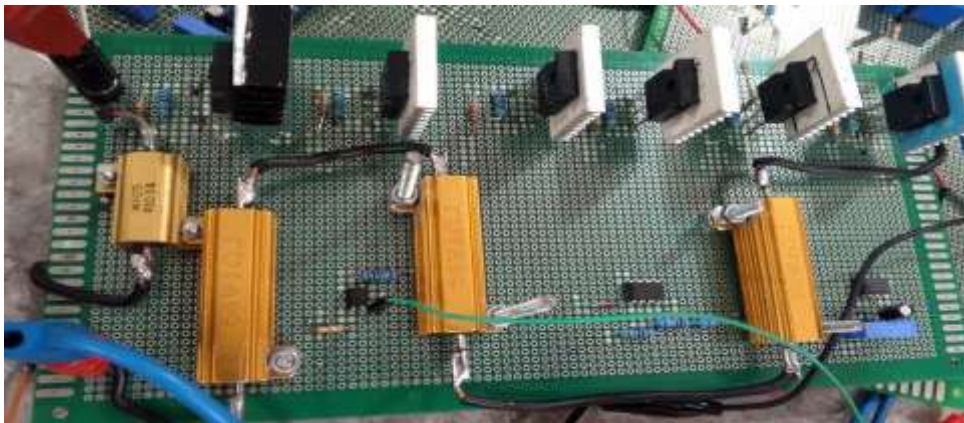


Figure : Load Circuit on Perforated Board

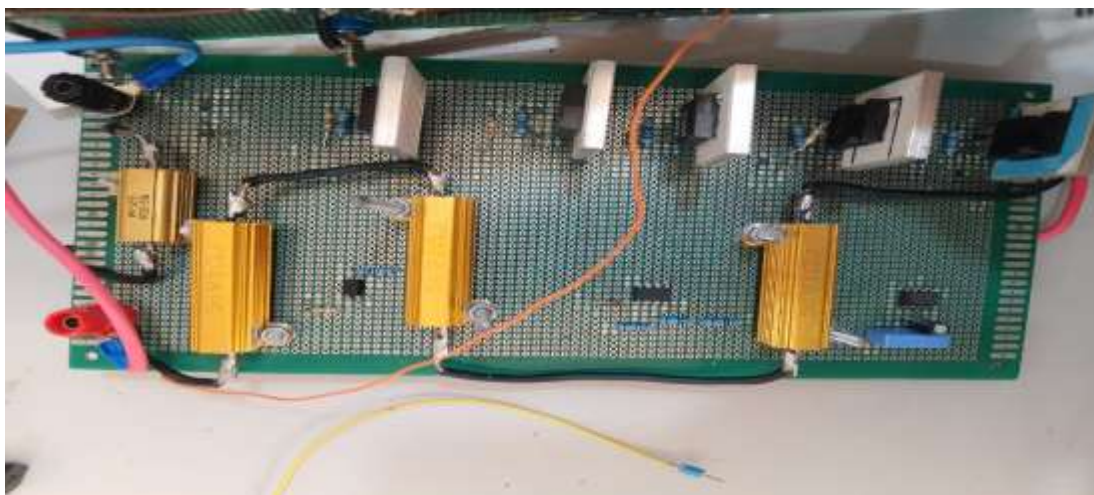


Figure : final load circuit

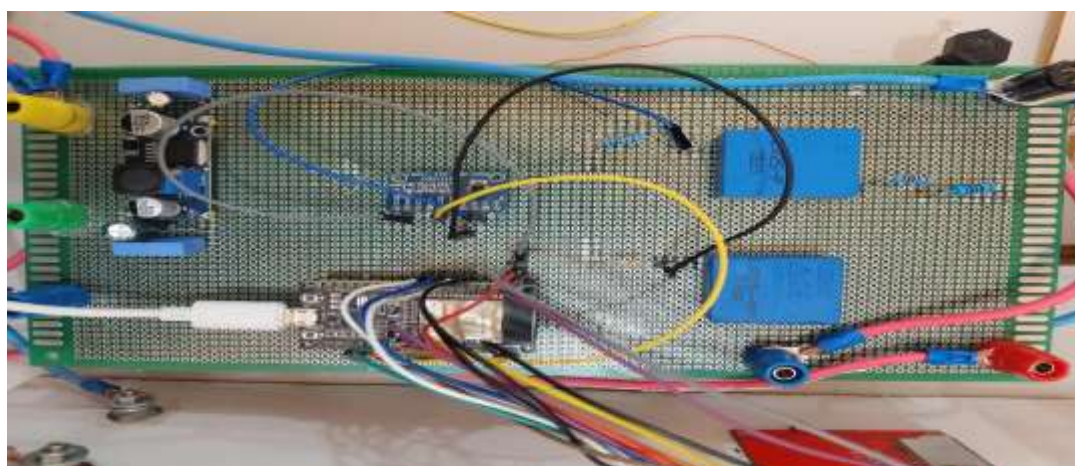


Figure : final control & measure circuit