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Thème

Design, Implementation, and Data storage for a Photovoltaic System

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Dedication

I dedicate this work with sincere gratitude to everyone who supported and encouraged me throughout my academic journey and helped me achieve this important milestone.

First, I would like to express my deepest thanks to my dear father, **Belkacem BELMILIANI**, whose sacrifices, strength, and constant encouragement have always motivated me to move forward and never give up. Your wisdom and support have been a guiding light in my life, and I will always be grateful for everything you have done for me.

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With all my respect, appreciation, and sincere gratitude

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Abstract:

The continuous growth in electrical energy demand and the environmental concerns associated with fossil fuel consumption have increased the interest in renewable energy sources. Among these sources, photovoltaic (PV) energy has emerged as an efficient and sustainable solution for clean electricity generation.

This final-year project focuses on the design and development of an intelligent photovoltaic curve tracing and monitoring system based on the ESP32 microcontroller. The proposed system enables real-time acquisition of electrical measurements from a photovoltaic panel, data processing, and wireless transmission through Bluetooth communication.

To enhance data management and analysis, a mobile application was developed using MIT App Inventor. The application allows real-time data reception, local storage, and visualization of measurements in both tabular and graphical forms through I–V (Current–Voltage) and P–V (Power–Voltage) characteristic curves. It also provides a simple and user-friendly interface for monitoring and analyzing photovoltaic system performance.

The obtained results demonstrate the effectiveness of the proposed solution for photovoltaic module characterization, monitoring, and data recording, while ensuring portability, ease of use, and real-time visualization of measurements.

Keywords: Mobile application, MIT App Inventor, Photovoltaic System, ESP32, I–V Curve, P–V Curve, Data Acquisition, Bluetooth Communication, Real-Time Monitoring, Renewable Energy.

Resumé:

Face à l’augmentation continue de la demande en énergie électrique et aux préoccupations environnementales liées à l’utilisation des combustibles fossiles, les énergies renouvelables occupent une place de plus en plus importante. Parmi elles, l’énergie photovoltaïque constitue une solution efficace et durable pour la production d’électricité propre.

Ce projet de fin d'études porte sur la conception et la réalisation d'un système intelligent de traçage et de surveillance des caractéristiques photovoltaïques basé sur le microcontrôleur ESP32. Le système développé permet l'acquisition en temps réel des données électriques d'un panneau photovoltaïque, leur traitement ainsi que leur transmission sans fil via la technologie Bluetooth.

Afin d'améliorer l'exploitation des mesures, une application mobile a été développée à l'aide de MIT App Inventor. Cette application assure la réception des données en temps réel, leur stockage local et leur visualisation sous forme de tableaux et de courbes caractéristiques I–V (courant–tension) et P–V (puissance–tension). Elle offre également une interface simple et intuitive facilitant l'analyse des performances du système photovoltaïque.

Les résultats obtenus démontrent l'efficacité de la solution proposée pour la surveillance, l'enregistrement et la caractérisation des modules photovoltaïques, tout en garantissant une meilleure portabilité, une utilisation simplifiée et une visualisation instantanée des données.

Mots-clés : Application mobile, MIT App Inventor, Système photovoltaïque, ESP32, courbes I–V et P–V, acquisition de données, Bluetooth, surveillance en temps réel, énergie renouvelable.

ملخص :

أدى التزايد المستمر في الطلب على الطاقة الكهربائية والمخاوف البيئية الناتجة عن استهلاك الوقود الأحفوري إلى زيادة الاهتمام بمصادر الطاقة المتجددة. وتُعد الطاقة الكهروضوئية (الشمسية) من بين أهم هذه المصادر، لما توفره من وسيلة فعالة ومستدامة لإنتاج الكهرباء النظيفة.

يتناول مشروع التخرج هذا تصميم وتطوير نظام ذكي لتتبع ومراقبة الخصائص الكهروضوئية بالاعتماد على المتحكم الدقيق ESP32 . يتيح النظام المقترح اقتناء القياسات الكهربائية للوح الشمسي في الزمن الحقيقي، ومعالجة البيانات وإرسالها لاسلكياً عبر تقنية البلوتوث.

ولتحسين استغلال البيانات وتحليلها، تم تطوير تطبيق للهاتف المحمول باستخدامMIT App Inventor . يتيح هذا التطبيق استقبال البيانات في الزمن الحقيقي، وتخزينها محلياً، وعرضها على شكل جداول ومنحنيات الخصائص I–V(التيار–الجهد) و P–V(القدرة–الجهد). كما يوفر واجهة بسيطة وسهلة الاستخدام لمراقبة أداء النظام الكهروضوئي وتحليل نتائجه.

أظهرت النتائج المتحصل عليها فعالية الحل المقترح في توصيف ومراقبة الألواح الكهروضوئية وتسجيل بياناتها، مع ضمان سهولة الاستخدام، وقابلية النقل، وإمكانية عرض القياسات وتحليلها بشكل فوري.

الكلمات المفتاحية : تطبيق هاتف محمول, MIT App Inventor , النظام الكهروضوئي، ESP32، منحنى التيار–الجهد(I–V) ، منحنى القدرة–الجهد(P–V) ، اقتناء البيانات، الاتصال عبر البلوتوث، المراقبة في الزمن الحقيقي، الطاقة المتجددة.

List of abbreviations

Pv: photovoltaic

V: Voltage

I: Current Intensity

P: Power

$V_{oc:}$ Open-Circuit Voltage

$I_{sc:}$ Short-Circuit Current

P-N junction: Positive-Negative Junction

EHP: Electron-Hole Pair

R_s: resistance series

$R_{sh:}$ resistance shunt

Amps: Amperes

Volts: Volts

V_{mp}: Voltage at Maximum Power

I_{mp}: Current at Maximum Power

P_{max}: Maximum Power

MW: Megawatts

GW: Gigawatt

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

General Introduction

The rapid technological development and the continuous expansion of industrial activities have led to a significant increase in electrical energy demand, especially during peak consumption periods. Many industrial sectors face serious challenges related to high electricity consumption, electrical network instability, and increasing energy costs. In addition, the excessive dependence on conventional energy sources such as fossil fuels has caused major environmental problems, including pollution and greenhouse gas emissions. Therefore, renewable energy sources have become an essential solution for ensuring sustainable development and reducing dependence on traditional energy resources.

Among the various renewable energy technologies, photovoltaic energy has become one of the most widely used solutions due to its ability to convert solar radiation directly into electrical energy in a clean and efficient manner. However, the performance of photovoltaic modules is strongly influenced by environmental conditions such as solar irradiance and temperature. Consequently, studying and analyzing the electrical characteristics of photovoltaic panels is essential for evaluating their efficiency and optimizing their performance.

For this purpose, the analysis of I–V and P–V characteristic curves plays an important role in understanding the electrical behavior of photovoltaic modules. These curves provide essential information about the operating conditions and performance of solar panels. Therefore, photovoltaic curve tracers are commonly used to measure and analyze the electrical parameters of PV modules under different operating conditions.

Nevertheless, traditional photovoltaic measurement systems often suffer from several limitations, including limited portability, lack of real-time monitoring, difficulty in data storage, and complicated visualization of measurement results. Furthermore, many conventional systems depend on wired communication and external computers, which reduces flexibility and usability in industrial and experimental environments.

In order to overcome these limitations, this work proposes the development of an intelligent photovoltaic tracing system based on the ESP32. The developed system

ensures real-time acquisition of photovoltaic measurements, data processing, and wireless transmission through Bluetooth communication.

Moreover, a mobile application was developed using MIT App Inventor to simplify user interaction with the system and improve data exploitation. The application allows wireless communication with the ESP32, real-time reception of photovoltaic measurements, local data storage, table visualization, and graphical representation of I–V and P–V curves directly on a smartphone.

The importance of this application lies in its ability to provide a simple and user-friendly interface for monitoring photovoltaic system performance, storing historical measurements, and facilitating graphical analysis of photovoltaic behavior in real time.

This master thesis is organized into Four main chapters:

- **Chapter 1** presents the general principles of photovoltaic systems, including photovoltaic module models, series and parallel connections, and the main electrical characteristics of PV systems.
- **Chapter 2** focuses on the principles of I–V and P–V curve tracing, the importance of photovoltaic characteristic curves, and the different methods used for curve plotting and photovoltaic characterization.
- **Chapter 3** presents the data storage framework and the development of the mobile application, including the ESP32-based acquisition system, Bluetooth communication, real-time data acquisition, local storage, and graphical visualization of photovoltaic measurements.
- **Chapter 4** presented the results of the developed mobile application for photovoltaic monitoring. The tests confirmed the proper operation of Bluetooth communication, data storage, and data visualization. The application successfully displayed photovoltaic measurements in tables and graphs, demonstrating its reliability for monitoring system performance.

Finally, this work aims to provide an intelligent, portable, and efficient solution for photovoltaic monitoring and characterization in industrial and experimental applications

CHAPTER 1: General Principles About Photovoltaic Modules

1.1. Introduction:

Photovoltaic (PV) systems use the photovoltaic effect to transform sunlight into electrical energy. Electric current is produced by electron–hole pairs created when sunlight strikes a solar cell. Electrical models like the single-diode and two-diode models can be used to simulate PV systems. The way solar panels are connected in parallel or series influences voltage and current, which in turn affects a PV system's performance. Designing effective solar energy systems requires an understanding of these concepts.

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 used technology, 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

1.3. Models of The Photovoltaic Array:

The primary energy source for the entire PV system is the solar panel. He sets up a series of connected photovoltaic cells in parallel with ports for extra security. The fundamental concept will be predicated on an examination of the photovoltaic cell, which is the hard core of the light-to-electricity converter. Numerous models of photovoltaic cells have been offered in literature

reviews; of these mathematical models, the diode model is typically kept as the best appropriate model for solar cells operating normally [4].

a) Single Diode Model:

This photovoltaic cell is distinguished by its equivalent plan (figure 1.1), which comprises a diode that represents the cell's junction and an electric current source that simulates the conversion of light flow into electrical energy. Two resistances, series R_S and shunt R_{sh}, are added to the model as the corresponding electric plan in order to account for physical occurrences at the cell level. The basic resistances, the junction's front, and the contacts' front and rear faces all contribute to the serial resistance. Following the penetration of the metallic impurities in the junction, the resistance shunt is caused by recombination losses that are primarily due to thickness [4]. The equivalent circuit of a photovoltaic cell is represented by the figure (1.1):

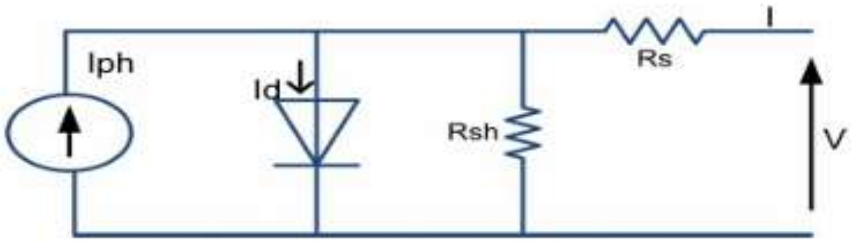

Figure 1.2: Conventional single diode model [4]

The following equation represents this concept, where I and V stand for the current and tension of a photovoltaic cell, respectively [4].

$$I = I_{ph} - I_s\left(e^{\frac{V+R_SI}{aV_1}} - 1\right) - \frac{V+R_SI}{R_{sh}} \qquad (1.1)$$

It is a not linear equation with two unknowns (I and V) and five parameters to be determined. These parameters are [4]:

- I_{ph}: photo-current, proportional equivalent current in the period of sunshine received by the cell.
- I_s: is the reverse saturation current.
- a: is the diode ideality factor.

• R_s: is the equivalent series Resistance.

•R_{sh}: is the parallel Resistance.

b) Two Diodes Model:

This time, we have two diodes to demonstrate the p-n junction polarization phenomenon. These diodes represent the minority carriers' recombination both on the material's surface and within its volume. In this instance [4], the solar generator's design is represented by figure (1.2):

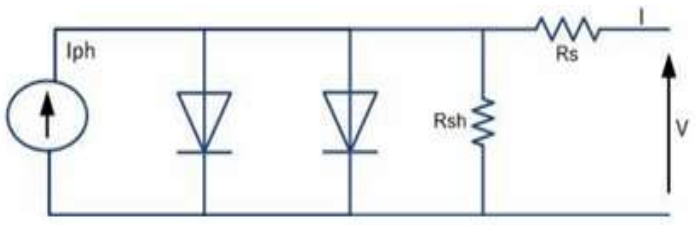

Figure 1.3: Conventional two diodes model [4]

The I-V characteristic of the two-diode model is described by this equation: [4]

$$I = I_{ph} - I_{s1}\left(e^{\frac{V+IR_S}{a_1 V_{t1}}} - 1\right) - I_{s2}\left(e^{\frac{V+IR_S}{a_2 V_{t2}}} - 1\right) - \left(\frac{V+IR_s}{R_{sh}}\right) \qquad (1.2)$$

Where V_{t1} and V_{t2} are the corresponding diodes' thermal voltages, and Is1 and Is2 are the reverse saturation currents of the first and second diodes, respectively. The diode ideality constants are denoted by a_1 and a_2 [4].

1.4. Solar Panels in Series or in Parallel :

Connecting panels one after the other, from the positive borne of one panel to the negative borne of the next, is known as branching. The overall tension increases while the intensity stays constant. Conversely, a parallel branching relates all positive and negative bonds collectively; the intensity increases but the tension stays constant [5].

1.4.1. Series Connection:

Solar panels feature two terminals, one positive and one negative, just like a battery. A series connection is made when the positive terminal of one panel is connected to the negative terminal of another panel. A PV source circuit is created when two or more solar panels are connected in this manner. When solar panels are connected in series, the amperage stays constant as the voltage of the panels increases. Therefore, the voltage of the series would be 80

volts and the amperage would stay at 5 amps if two solar panels with a rated voltage of 40 volts and a rated amperage of 5 amps were connected in series.

When panels are connected in series, the array's voltage rises. This is significant because the inverter in a solar power system requires a specific voltage to function. In order to satisfy your inverter's working voltage window requirements, you connect your solar panels in series [6].

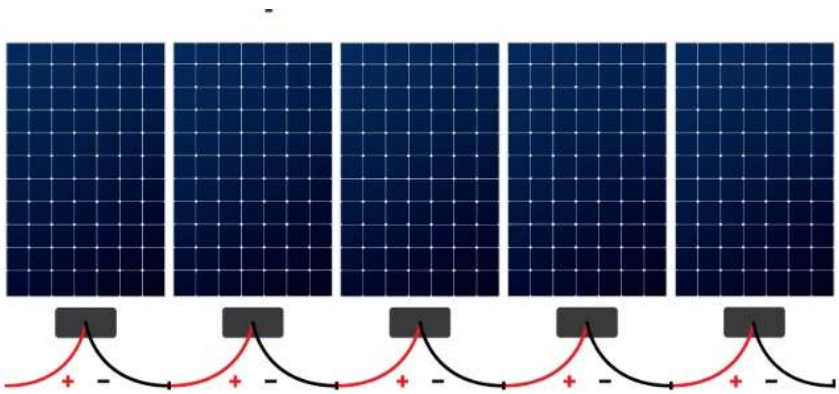

Figure 1.4: Connecting panels in series. [6]

a) Electrical Characteristics of a Serie Connection:

From a principle of operation standpoint, the electrical characteristics of panels connected in series follow specific rules. Take voltage, for example: the voltages of each panel are directly added together. For example, if two 12V solar panels are connected in series, the total voltage can reach 24V. This voltage increase helps to meet the operating voltage requirements of some inverters or to compensate for the voltage drop generated during transmission over long cable distances [7].

b) Advantages :

Higher voltage: Series connections allow for higher voltage outputs, which can be beneficial for matching inverter requirements and reducing power loss over long cable runs.

Less wiring: Generally, series connections require less wiring, which can reduce installation complexity and cost.

Better for low light conditions: In low light, series-connected panels are better adapted to produce enough voltage to charge batteries or run inverters.

Cable efficiency: Series connections allow for the use of lighter, less expensive cables due to lower amps [8].

c) Disadvantages :

Vulnerability to shading: If one panel in a series string is shaded or not working properly for whatever reason, it can significantly reduce the output of the entire string.

Limited flexibility: It's more challenging to add panels to a series-connected system after the initial installation, which might be problematic if you're eventually planning on increasing your solar panel system size.

Higher voltage: The higher voltages produced by series connections require more careful handling and may necessitate additional safety measures [8].

1.4.2. Parallel Connection:

When solar panels are connected in parallel, their negative terminals are linked together and their positive terminals are connected to each other. In a combiner box, the negative wires are connected to the negative connector and the positive wires to the positive connector. A PV output circuit is created when several panels are connected in parallel. When solar panels are wired in parallel, the voltage stays constant but the amperage increases. Therefore, the system's voltage would stay at 40 volts if the identical panels were wired in parallel, but the amperage would rise to 10 amps.

You can have more solar panels that generate energy without going over your inverter's working voltage restrictions by wiring them in parallel. You can overcome the amperage restrictions of inverters by connecting your solar panels in parallel [6].

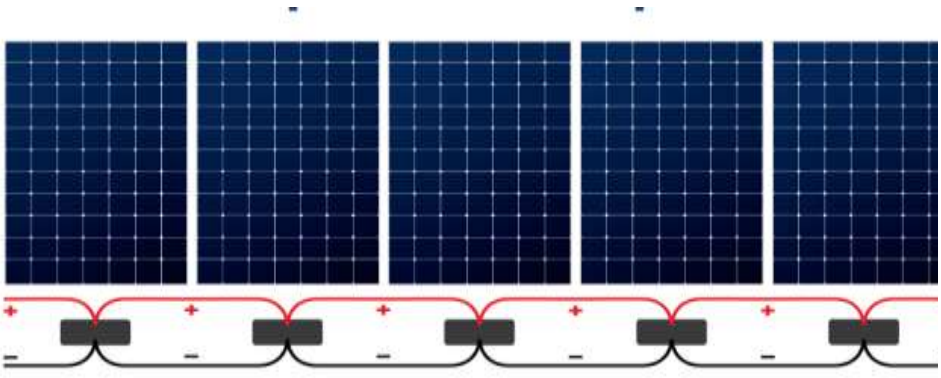

Figure 1.5: Connecting panels in parallel. [6]

a) Electrical Characteristics of a Parallel Connection:

When solar panels are connected in parallel, their voltage and current exhibit unique characteristics. In terms of voltage, the total voltage after parallel connection is the same as that of a single panel. For example, if two 12V panels are connected in parallel, the total voltage remains 12V. This stable voltage output is one of the important differences between parallel and series configurations [7].

b) Advantages:

Good resilience: Parallel connections maintain a more consistent current output, even if one panel is shaded or not performing optimally.

Easier to expand: Adding new panels to a parallel system is generally simpler than adding to a series system.

Lower voltage: The lower voltage output can be safer to work with and may be preferable in some residential settings [8].

c) Disavantages:

More complex wiring: Parallel connections often require more wiring and more expensive cables, which can increase installation complexity and cost.

Larger cables: The higher amps in parallel systems often need heavier, more expensive cables.

Limited distance: Lower voltages in parallel systems may limit the distance between the panels and the inverter or battery storage systems due to voltage drop over long cable runs [8].

1.5. Photovoltaic Capacities:

Photovoltaic solar energy remains the primary source of electricity production from renewable energies in Algeria, with a total capacity of 436.8 MW, of which 388.95 MW (82.4%) are connected to the grid and 47.85 MW (10.1%) are off-grid. Thanks to several large-scale calls for tenders launched in recent months, the country hopes to soon exceed the 4 GW mark [9].

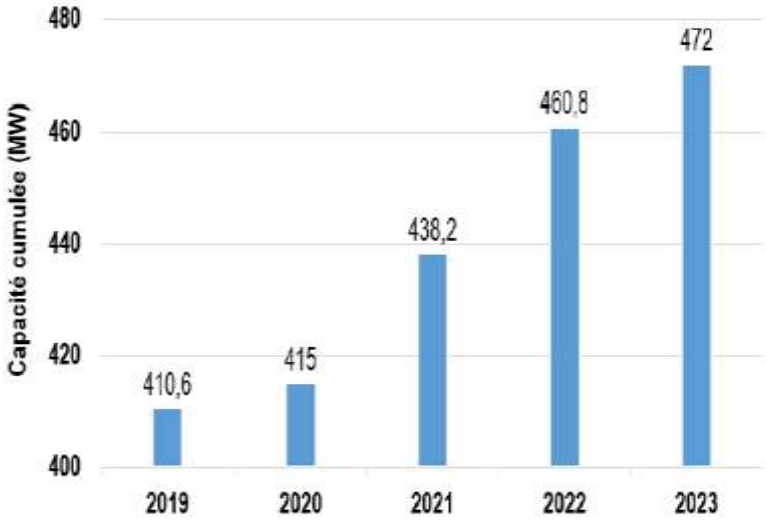

Figure 1.6: Evaluation of cumulative installed renewable energy capacity (excluding hydropower) up to the end of 2023. [9]

1.6. Conclusion:

In summary, solar energy may be efficiently converted into clean power using photovoltaic systems. Their performance is dependent on whether solar panels are connected in parallel or series, and their behavior may be explained by basic electrical theories. Improving the efficiency and design of solar energy systems requires a solid grasp of these ideas.

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 photovoltaic (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 [10].

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 [11].

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 photovoltaic (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 [12].

By measuring these parameters, the I-V curve tracer provides crucial details about the PV system's electrical performance, including the maximum power point, open-circuit voltage (V_{oc}), and short-circuit current (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 [13].

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 [14].

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 [14]

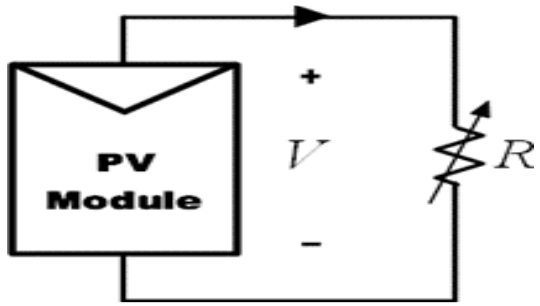

Figure 2.1: Variable Resistance Curve Tracing Method. [14]

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 [15].

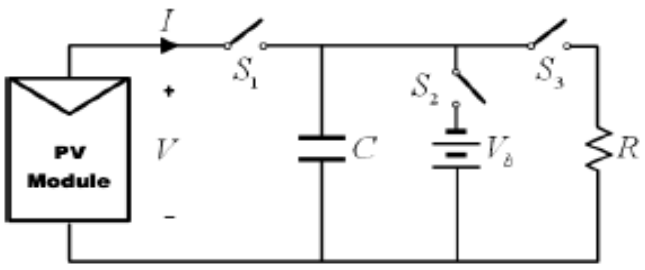

Figure 2.0: Capacitive Load Curve Tracing Method. [15]

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 [16].

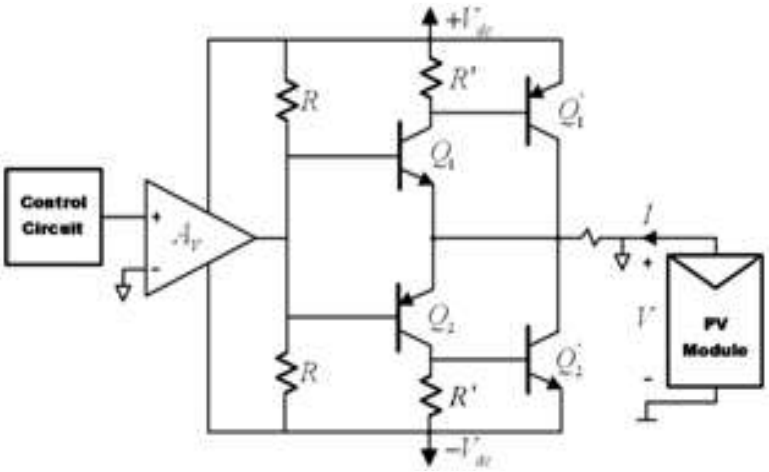

Figure 2.2.4.3: Bipolar Power Amplifier–Based Curve Tracing Method. [16]

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, analyzing 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 [16].

A four-quadrant power supply 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.

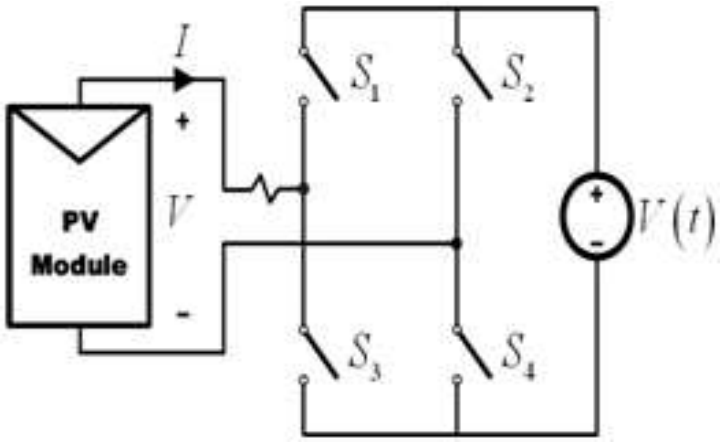

Figure 2.2.4.4: Four-Quadrant Power Amplifier–Based Curve Tracing Method. [16]

2.4.5. Chopper-based method:

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

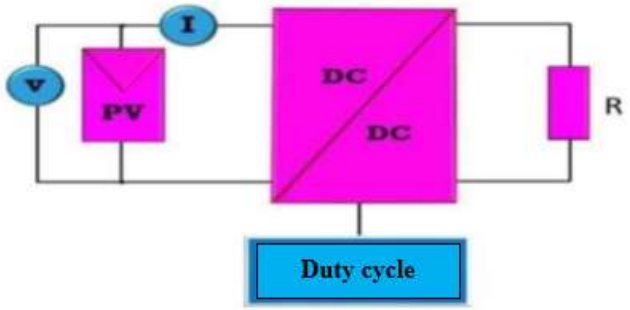

Figure 2.2.4.5: Chopper-Based Curve Tracing Method. [17]

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.

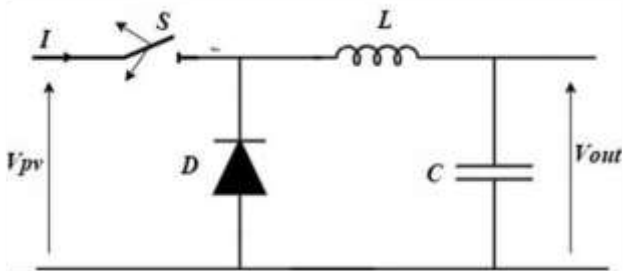

Figure 2.6: Step-Down Converter. [17]

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.

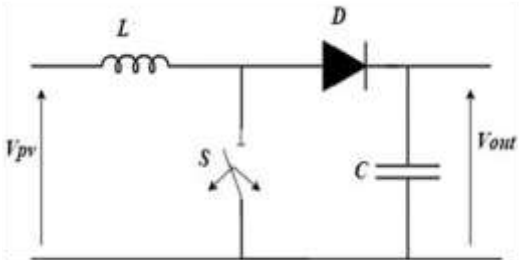

Figure 2.7: Step-Up Converter. [17]

c) Buck-Boost converter:

The buck-boost converter is a dual-function DC-DC converter 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.

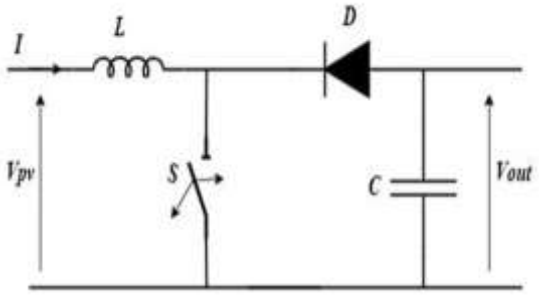

Figure 2.8 : Buck–Boost Converter. [17]

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, 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 [18].

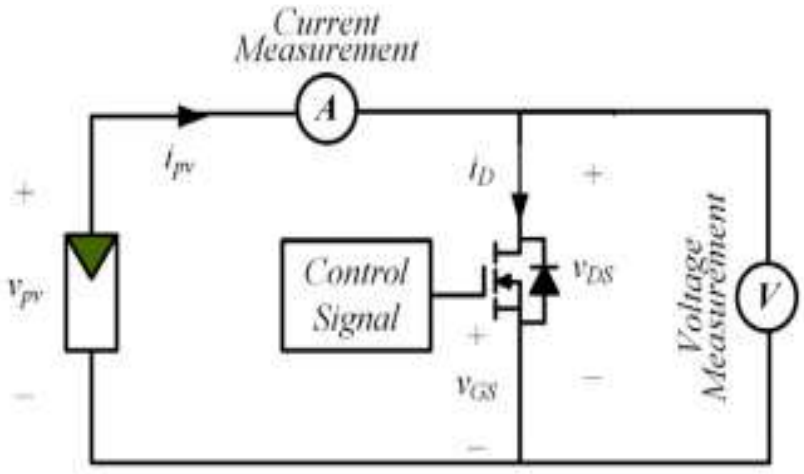

Figure 2.9: Electronic Load–Based Curve Tracing Method. [18]

2-1. 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 and 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: Data storage framework

3.1. Introduction:

In order to improve the monitoring and usability of the photovoltaic tracing system, a mobile application was developed using MIT App Inventor. The main objective of this application is to establish wireless communication with the ESP32 acquisition system, receive real-time photovoltaic measurements, process and store the acquired data, and provide an intuitive interface for visualization and analysis.

The application was designed as a complete monitoring platform composed of multiple interfaces, each performing a specific function such as Bluetooth communication, data acquisition, measurement storage, historical consultation, and graphical visualization. This chapter presents the development process of the mobile application, the programming logic of each interface, and the implementation of the different functionalities used for photovoltaic data monitoring and analysis

3.2. Mobile Application Development Using MIT App Inventor:

To improve the usability of the photovoltaic tracing system, a mobile application was developed using MIT App Inventor [19]. The main objective of this application is to establish wireless communication with the ESP32 [20] acquisition system, receive photovoltaic measurement data, process the received information, store it locally, and display it in an organized and user-friendly format.

The application is composed of four main interfaces:

- Screen1 : Bluetooth Connection Interface
- Screen2 : Data Acquisition Interface
- Screen3 : Mesurement History Interface
- Screen4 : Graphical Visualization Interface

3.3. Screen1 : Bluetooth Connection Interface :

Screen1 is the main interface of the application. It allows the user to establish Bluetooth communication with the ESP32 module.

3.3.1. User Interface Components:

The interface contains the following components:

a) Project Logo

The NEXVOLT logo is displayed at the top of the interface to provide a professional visual identity.

b) Connection Status Label

A status label was implemented in the application interface to continuously indicate the Bluetooth communication state between the smartphone and the ESP32 acquisition system. This label plays an important role in informing the user about the current connection status in real time. When the Bluetooth communication is established successfully, the label automatically displays the message “ESP32 Connected” and its text color changes to green, indicating that the communication channel is active and that the application is ready to receive photovoltaic measurement data. On the other hand, if the connection is not established or if the communication fails, the label displays the message “ESP32 Not Connected” in red. This situation may occur when Bluetooth is disabled on the smartphone, when the ESP32 module is powered off, when the device is outside the communication range, or when the connection is interrupted unexpectedly. This dynamic status indication improves the usability of the application and allows the user to monitor the communication state easily before starting the photovoltaic data acquisition process.

c) Connection Button

The Connection button allows the user to search for nearby Bluetooth devices and connect to the ESP32.

d) START Button

After successful Bluetooth connection, the START button redirects the user to Screen2 for data acquisition.

3.3.2. Screen Initialization

When the application starts, the Screen1.Initializeblock is executed automatically.

The application checks :

- whether Bluetooth is enabled.
- whether the ESP32 is already connected.

This initialization allows the user to know the communication status immediately after opening the application.

3.3.3. Bluetooth Connection Process:

When the user presses the Connection button:

1. the application scans nearby Bluetooth devices.
2. the user selects the ESP32 device.
3. the application attempts to establish communication.

If the connection succeeds :

- The status becomes “Connected”.

- The interface confirms successful communication.
- Figure 3.1: Bluetooth Connection Interface Confirming the Communication Between the Mobile Application and the ESP32.

Figure 3.1: Bluetooth Connection Interface

3.4. Screen2: Electrical Parameters Acquisition Interface:

After establishing Bluetooth communication with the ESP32, the application opens Screen2, which is dedicated to the acquisition and display of the main electrical parameters of the photovoltaic module. This interface mainly focuses on displaying the instantaneous photovoltaic characteristics such as short-circuit current, open-circuit voltage, and maximum power.

3.4.1. Display of Electrical Parameters:

When Screen2 is initialized, the current date and time are displayed automatically using the Clock component. The interface contains a measurement table including the following parameters:

- **Date and Time**
- **Isc (Short-Circuit Current)**
- **Voc (Open-Circuit Voltage)**
- **Pmax (Maximum Power)**

These parameters are received from the ESP32 through Bluetooth communication and displayed inside the ListView component in table format. This organization allows the user to

observe the main electrical characteristics of the photovoltaic panel during the acquisition process.

3.4.2. Bluetooth Communication and Data Reception:

When the user presses the Connection button, the application reconnects to the ESP32 acquisition system. If the communication is established successfully, the Bluetooth status becomes active and the application starts receiving real-time photovoltaic measurements [21]. The received data contains the measured electrical parameters transmitted by the ESP32, including voltage, current, and maximum power values.

3.4.3. Data Storage:

After receiving the measurements, the application stores the electrical parameters locally using TinyDB [22]. This storage operation creates a local database containing all acquisition sessions, allowing future consultation and comparison of photovoltaic measurements.

This interface represents the first level of photovoltaic data visualization focused on the fundamental electrical parameters of the PV module. Figure 3.2: Electrical Parameters Acquisition Interface Showing the Real-Time Visualization and Local Storage of PV Electrical Parameters for Future Analysis and Comparison

Figure 3.2 : Electrical Parameters Acquisition Interface

3.5. Screen3: Photovoltaic Performance Parameters Interface:

Screen3 is dedicated to displaying the photovoltaic performance parameters calculated from the acquired measurements. Unlike Screen2, which focuses on basic electrical quantities, this interface focuses on photovoltaic performance analysis.

3.5.1. Display of Performance Parameters:

When Screen3 is opened, the current date and time are displayed automatically using the Clock component. The interface contains a second table including the following calculated parameters:

- Date and Time
- MPP (Maximum Power Point)
- FF (Fill Factor)
- η (%) (Efficiency)

These parameters are loaded from TinyDB and displayed inside the ListView component. This separation between Screen2 and Screen3 improves data organization and simplifies the interpretation of photovoltaic measurements.

3.5.2. Measurement History Visualization:

The stored photovoltaic performance data is displayed in table format, allowing the user to compare the evolution of MPP, Fill Factor, and efficiency values over time [23]. This functionality helps evaluate the operating condition and performance stability of the photovoltaic module.

3.5.3. Bluetooth Reconnection:

A Connection button was implemented to allow the user to reconnect to the ESP32 acquisition system whenever necessary. If the communication is established successfully, the connection status becomes active. Otherwise, the application indicates a communication failure.

3.5.4. Data Management and Navigation:

Additional navigation buttons were added to improve accessibility between interfaces:

- Home → returns to Screen1
- Table1 → returns to Screen2
- Graphs → opens Screen4
- Delete → removes stored performance history

This interface represents the second level of photovoltaic data analysis, where the user can evaluate the performance indicators of the photovoltaic system in a more detailed manner. Figure 3.3: Photovoltaic Performance Interface Providing a Detailed Analysis of the Performance Indicators of the Photovoltaic System.

Figure 3.3 : Photovoltaic Performance

3.6. Screen 4: Graphical Visualization Interface:

Screen4 is dedicated to graphical visualization and analysis of photovoltaic measurements.

3.6.1. Loading Measurement Data:

When Screen4 is initialized:

- the application retrieves stored photovoltaic measurements from TinyDB [22];
- the data is loaded into lists for graphical processing.

3.6.2. Graph Generation:

The application uses Canvas components to draw [24]:

- Coordinate axes.
- I–V characteristic curves.
- P–V characteristic curves.

Two graphical areas are displayed:

a) I–V Curve Area

This section displays the relationship between:

- Current (I);
- Voltage (V).

It allows analysis of :

- Short-circuit current.
- Open-circuit voltage.
- PV operating region.

b) P–V Curve Area

This section displays the relationship between:

- Power (P).
- Voltage (V).

This graph is used to identify the Maximum Power Point (MPP).

3.6.3. Real-Time Curve Plotting:

During acquisition:

- The ESP32 continuously transmits voltage, current, and power measurements;
- The application receives the data through Bluetooth.

This enables real-time visualization of photovoltaic behavior [25].

3.6.4. Saving Graphical Results:

After completing an acquisition cycle:

- The I–V curve is saved as an image.
- The P–V curve is saved as an image.
- A measurement report is generated.

All generated files are stored locally using TinyDB.

This functionality supports :

- Long-term monitoring.
- Historical comparison.
- Future analysis.

3.6.5. Sharing Graphical Results:

Two sharing buttons were implemented:

- Share → shares the I–V curve;
- Share2 → shares the P–V curve.

The application uses the Sharing1.ShareFilefunction to export image files through the smartphone sharing system.

This allows :

- Report generation.
- Result sharing;
- External storage of graphical data.

3.6.6. Navigation Control:

A Back button was added to simplify interface navigation.

When pressed :

- The current screen closes automatically.
- The application returns to the previous interface.

Figure 4.1: Graphical Visualization Interface

3.7. Global Relationship Between Screen2, Screen3, and Screen4:

The three interfaces (Screen2, Screen3, and Screen4) form a complete photovoltaic monitoring and analysis system that transforms raw electrical measurements into meaningful information.

- **Screen2** is responsible for the acquisition and display of basic electrical parameters. It represents the real-time data collection stage from the photovoltaic system via ESP32 and Bluetooth communication.
- **Screen3** focuses on performance analysis. It processes the acquired data to calculate key photovoltaic indicators. This screen provides a deeper understanding of the system's performance over time.
- **Screen4** provides graphical visualization of the same data through I–V and P–V characteristic curves. It allows the user to visually interpret the behavior of the photovoltaic module, identify the MPP, and analyze the relationship between voltage, current, and power.

Overall, these three screens are strongly interconnected:

- Screen2 → data acquisition
- Screen3 → numerical performance analysis
- Screen4 → graphical analysis and visualization

This integration ensures a complete monitoring system that combines real-time measurement, analytical processing, and graphical interpretation, providing a comprehensive evaluation of photovoltaic system performance.

3.8. Conclusion:

In this chapter, the development of the mobile application for the photovoltaic tracing system was successfully presented. Using MIT App Inventor, an interactive and user-friendly application was designed to ensure wireless communication with the ESP32, real-time acquisition of photovoltaic measurements, local data storage, historical management, and graphical visualization of system performance.

The implementation of multiple interfaces allowed the integration of several important functionalities, including Bluetooth connection management, real-time data processing, measurement validation, local database storage, and curve generation for performance analysis. The developed application provides an efficient monitoring solution that improves data accessibility, simplifies system analysis, and enhances the overall usability of the photovoltaic tracing platform.

CHAPTER 4: Results And Discussion

4.1. Introduction:

This chapter presents the results obtained from the Andriod mobile App developed as part of this project. The app, designed with MIT App Inventor, serves as the user interface for the photovoltaic tracking system. It handles the wireless reception of data measured by the ESP32 board, stores it locally in a TinyDB database, and displays it in an organized way using tables and graphs.

Three measurement sessions were conducted on June 11, 2026, at 11:04 AM, 12:14 AM, and 2:08 PM. The aim of this chapter is to validate that the entire software chain works properly: Bluetooth connection, parameter reception, database storage, and visual feedback to the user.

4.2. App's General Architecture:

- Communication layer: handles the Bluetooth connection on the ESP32 board, and deals 0with receiving and decoding data frames
- Storage layer: saves received data locally in a TinyDB database inside MIT App Inventor, organized by session with automatic timestamps.
- Presentation layer: shows historical data in two separate tables and graphs the I-V and P-V curves.

The app's different screens are shown in the following sections, depending on the flow used during a measurement session.

4.3. Bluetooth Connection with the ESP32:

The first step in the app flow is to establish a Bluetooth connection between the smartphone and the ESP32 board. The app offers a dedicated screen for this operation, allowing the user to search for paired devices and select one.

During the three sessions conducted on June 11, 2026, the connection was successfully established each time. The connection status is visually indicated in the interface (status indicator), confirming the communication channel is available before any data is received.

Figure 01: Bluetooth pairing and data communication between the ESP32 acquisition system and the Android mobile application.

4.4. Data Reception, Storage, and Visualization:

After the Bluetooth connection is successfully established between the mobile application and the ESP32, the system becomes ready to receive measurement data transmitted by the acquisition board. The ESP32 sends a structured data frame containing the main electrical parameters obtained from the photovoltaic module, including (Voc), (Isc), (Vmp and Imp), (Pmax), Fill Factor (FF), and energy conversion efficiency (η).

Upon receiving each data frame, the application decodes and processes the information to make it available for both storage and visualization. An automatic timestamp is generated for each record, allowing the measurements to be organized chronologically and ensuring accurate tracking of each acquisition session.

To validate the correct operation of the system, three experimental tests were conducted using the photovoltaic tracer prototype. In each test, the application successfully established communication with the ESP32, received the transmitted data without loss or corruption, and processed it correctly. The recorded data was then automatically stored within the application and displayed through the user interface.

The results were organized into two historical tables: the first one presenting the basic electrical parameters, and the second one displaying the calculated performance indicators. In addition, the application generated graphical representations of the acquired data, enabling clear visualization of the I–V and P–V characteristics in a user-friendly format. These results confirm the proper functioning of the complete data flow, from acquisition and transmission to storage and visualization within the mobile application.

4.5. Display of Historical Tables:

The data presented in these two tables correspond to the measurements obtained from the three test sessions carried out using the prototype. They illustrate how the values are automatically displayed in the application interface after each data reception via Bluetooth

4.5.1. Table 1: Measurement History

The data presented in Table 1 correspond to the results of the three experimental test sessions carried out using the developed prototype. During the first test at 11:04 AM, the measured values were (Isc) of 1.97 A, (Voc) of 19.62 V, (Pmax) of 15.8 W. In the second session at 12:14 AM, the system recorded an increase in performance with Isc reaching 2.66 A, Voc of 20.32 V, and Pmax of 25.2 W. Finally, during the third test at 2:08 PM, the highest values were obtained, with Isc equal to 3.47 A, Voc of 20.40 V, and Pmax of 42.1 W. These results illustrate the evolution of the photovoltaic module output across the three test sessions.

Figure 4.1: Historical measurement data of the photovoltaic system displayed in Table 1 of the application

4.5.2. Table 2: Performance indicators

The data presented in Table 2 correspond to the performance indicators recorded during the three experimental test sessions carried out using the prototype. At 11:04, the system displays A maximum power point (MPP) of 15.79 W, A Fill Factor (FF) of 40.77%, and An efficiency (η) of 2.63%. During the second session at 12:14, the values increased to An MPP of 20.25 W, An FF of 46.20%, and An efficiency of 4.20%. Finally, at 14:08, the highest values are observed, with An MPP of 42.12 W, A Fill Factor of 59.41%, and An efficiency of 7.01%. These results represent the recorded outputs of the three test sessions stored and displayed within the application interface.

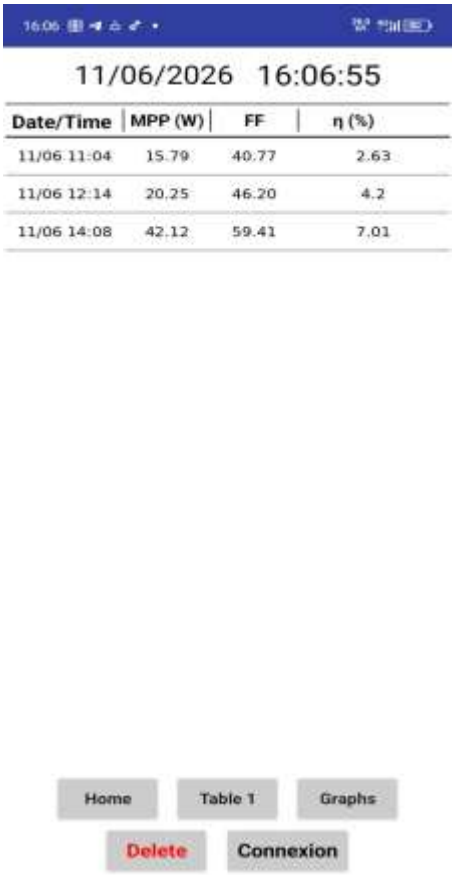

Figure 4.2: Historical measurement data of the photovoltaic system displayed in Table 2 of the application

4.6. Graphic visualization:

The figures below illustrate the successful visualization of the photovoltaic I–V and P–V curves obtained during the experimental validation phase of the developed mobile application. Despite the numerous technical challenges encountered throughout the implementation process and the several attempts made to optimize the graphical interface, the application was ultimately able to generate and display the characteristic curves correctly under testing conditions. This achievement demonstrates the capability of the proposed system to represent photovoltaic measurement data in a graphical form, thereby facilitating a more intuitive interpretation of the acquired information. The obtained results confirm the feasibility of integrating data visualization functionalities into the developed platform and constitute an important step toward the enhancement of photovoltaic monitoring and analysis tools. Furthermore, the successful display of these curves validates the effectiveness of the communication, data acquisition, and processing stages implemented within the overall system architecture

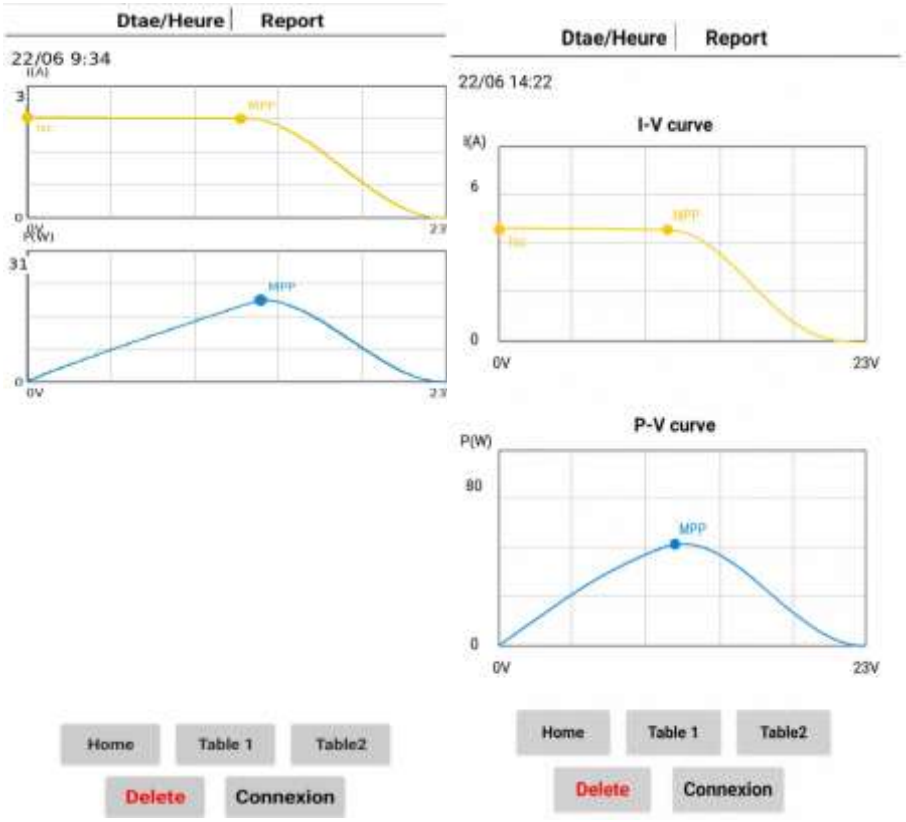

Figure 4.3: Graphical visualization of the photovoltaic module behavior through I–V and P–V curves based on stored measurement data

4.7. Conclusion:

This chapter presented the results of the mobile app developed with MIT App Inventor for monitoring the photovoltaic tracking system. The app was tested with three measurement sessions conducted on June 11, 2026, to validate its various features. The results show that the whole system works well, including the Bluetooth connection with the ESP32, data reception and processing, automatic timestamping, storage via TinyDB, as well as displaying the data in tables and I–V and P–V curves. The app proved to be reliable and functional, offering a complete interface for monitoring and viewing data both in real-time and historically.

General Conclusion:

As part of this project, a mobile application was developed using the MIT App Inventor platform to monitor and analyze the performance of photovoltaic panels through Bluetooth communication with an ESP32 microcontroller. The application enables the real-time reception, processing, and visualization of electrical parameters while providing a simple and user-friendly interface.

A key feature of the application is its ability to store measurement data locally, allowing users to access previous records, compare results, and monitor the evolution of photovoltaic system performance over time. This functionality enhances the application's usefulness for both monitoring and analysis purposes.

The developed system demonstrated satisfactory performance in data acquisition, storage, and visualization. It provides an integrated solution for photovoltaic performance monitoring and can serve as a foundation for future developments. Thanks to the flexibility of the MIT App Inventor platform, additional features and improvements can be easily implemented to meet future user needs and technological advancements..

Although the developed application achieved its intended objectives, several improvements can be considered in the future to enhance its capabilities, increase its efficiency, and extend its range of applications.

• Implementing an intelligent alert system capable of notifying users whenever abnormal operating conditions or unexpected performance reductions are detected, thereby facilitating faster intervention and maintenance actions.

• Integrating environmental parameters such as solar irradiance and temperature into the monitoring process to provide more accurate performance analysis and a better understanding of the operating conditions affecting photovoltaic modules.

• Adding an automatic PDF report generation feature that compiles measurement results, graphical representations, and performance indicators into structured documents that can be easily stored, printed, or shared with researchers and professionals.

• Developing more advanced and interactive graphical user interfaces that provide additional visualization and analysis tools, helping users interpret collected data more effectively and efficiently.

• Extending the application to support the simultaneous monitoring of multiple photovoltaic panels within the same platform, enabling the supervision of larger photovoltaic installations and facilitating panel-to-panel performance comparisons.

• Implementing comparison functionalities between current and previous measurement sessions in order to monitor the long-term evolution of photovoltaic panel performance and identify possible trends or degradations.

• Enhancing data management and storage mechanisms to handle larger quantities of measurements while improving data organization, retrieval, and historical analysis capabilities.

These potential improvements would significantly increase the effectiveness and versatility of the application, making it a more comprehensive tool for photovoltaic system monitoring and performance analysis. Furthermore, such developments could contribute to meeting the evolving needs of users and researchers while opening new opportunities for the creation of more advanced mobile solutions dedicated to renewable energy monitoring and management.

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Appendix

1. MIT App Inventor:

is a development platform that makes it easy to create mobile apps without having to code in complex languages.

This makes it very accessible to beginners, students, and anyone who wants to learn programming.

Figure: Application Logo

1.1. Designer interface:

In MIT App Inventor, the Designer interface is where you visually build your app (buttons, screens, sensors, etc.). It's organized into several categories of components. Here's a simple explanation:

User Interface :

This is everything the user sees and interacts with in the app, exemple: a button to click, displayed text, display an image…….

1.1.1. Layout :

Allows you to arrange elements on the screen, Examples:

Horizontal Arrangement, Vertical Arrangement, Table Arrangement

1.1.2. Sensors:

Allows you to use the phone's sensors, Example: Location Sensor (GPS), phone orientation

1.1.3. Social :

To communicate with others. Examples: select a contact, send a text message

1.1.4. Storage:

Allows you to save data. Examples: TinyDB (local storage on the phone), read/write files

Connectivity:

Allows the app to communicate with other devices or the internet. Examples:

Web (send/receive data from a website).

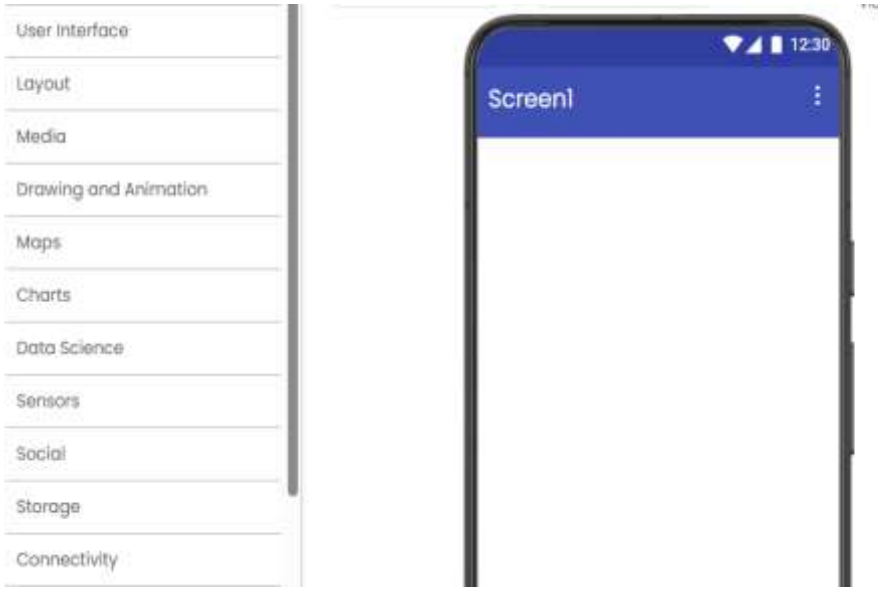


Figure: Designer

1.2. the Blocks interface:

In MIT App Inventor, the Blocks interface is where you program your app's behavior using blocks (like a puzzle). Each category has a specific role:

1.2.1 Control:

Used to manage the program flow (conditions, loops, etc.). Examples:

if / else, for each / while, open screen / close screen…….

1.2.2 Logic:

Used for true or false conditions. Examples: true / false, and / or / not, comparisons ……

1.2.3 Math:

Allows you to perform calculations. Examples: Plus, square root, power ……

1.2.4 Text:

For manipulating strings. Examples: text length, convert text vers number

1.2.5 Lists

Allows you to manage data sets. Examples: create a list, add / remove an element

In conclusion, MIT App Inventor is a simple and effective tool for creating mobile apps. The Designer interface is used to design the app's appearance, while Blocks is used to program its functionality.

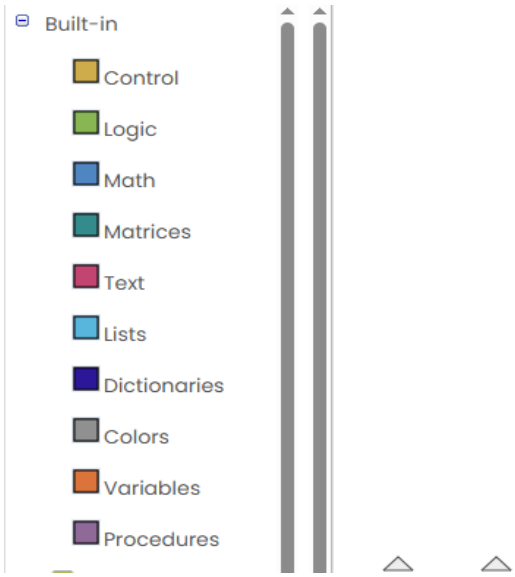
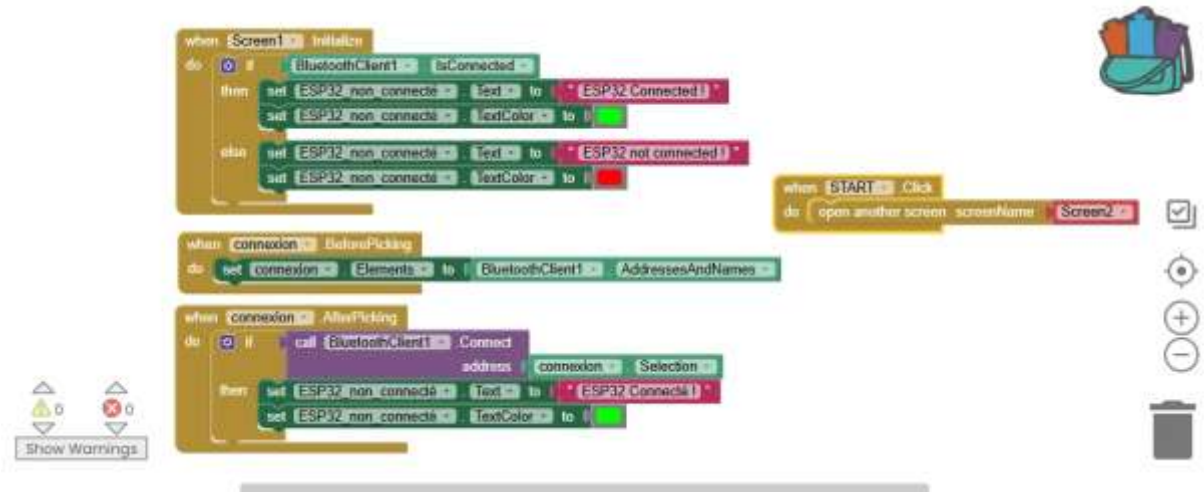
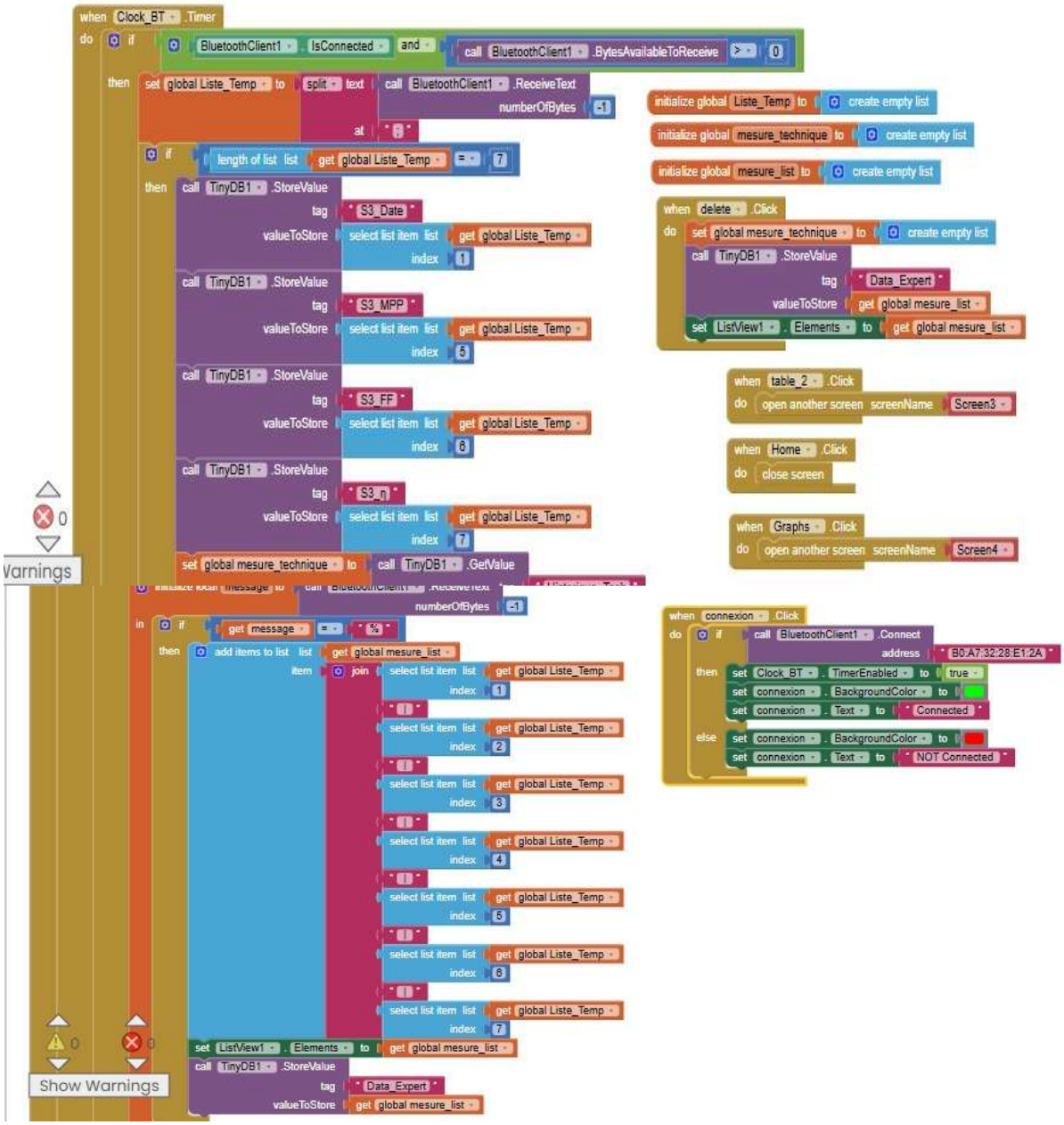
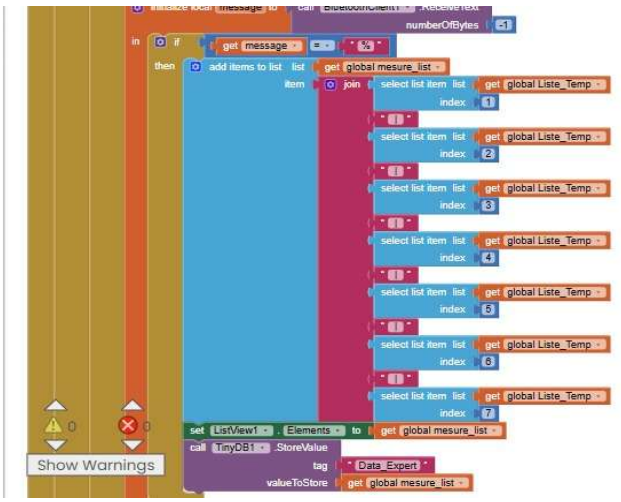


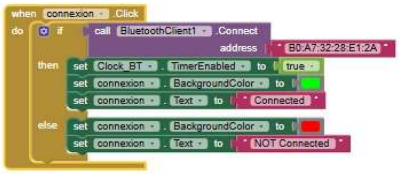
Figure: Blocks

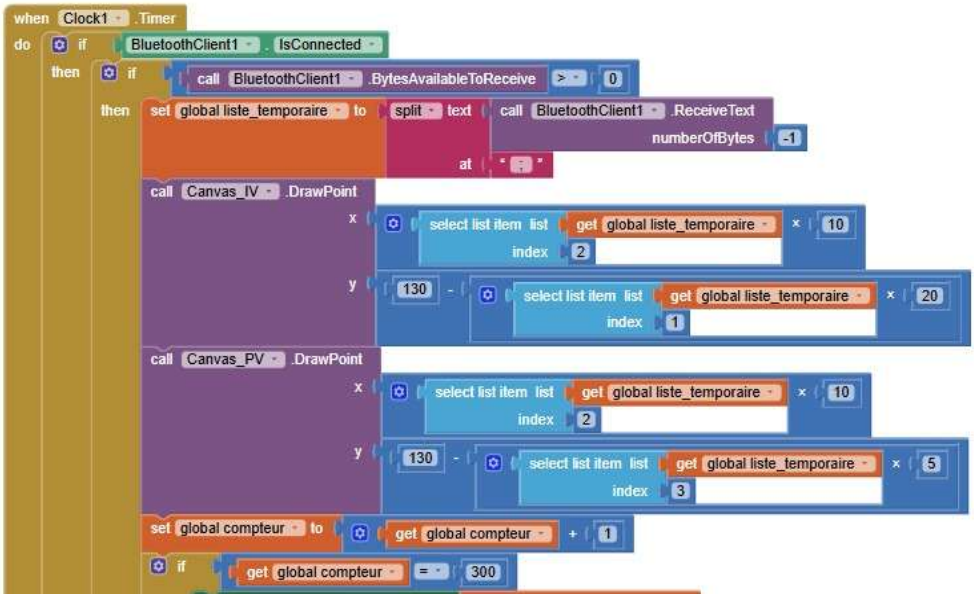
The following screenshots present the code used in the development of the application:



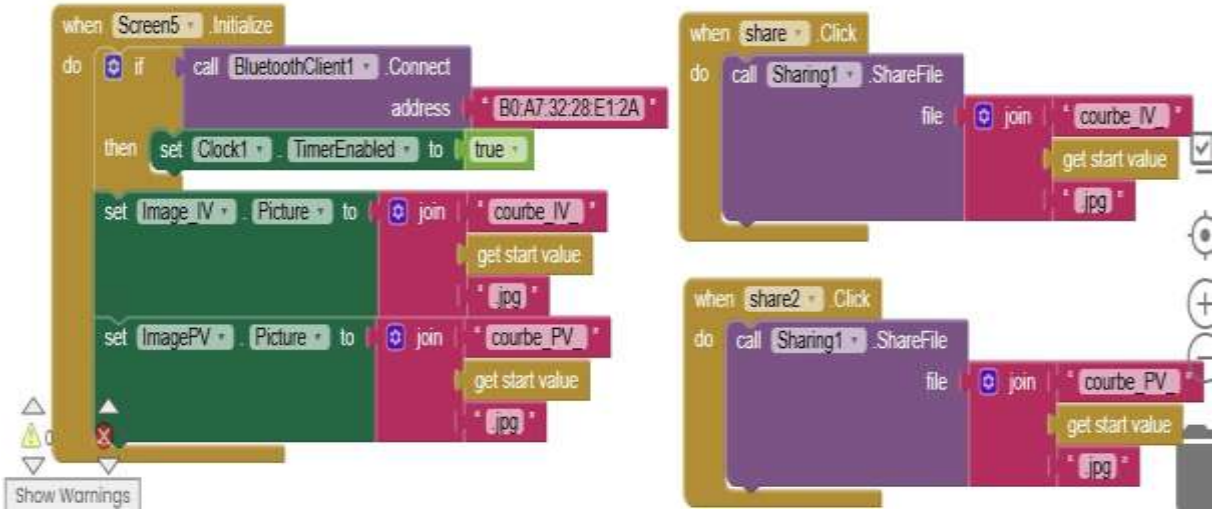


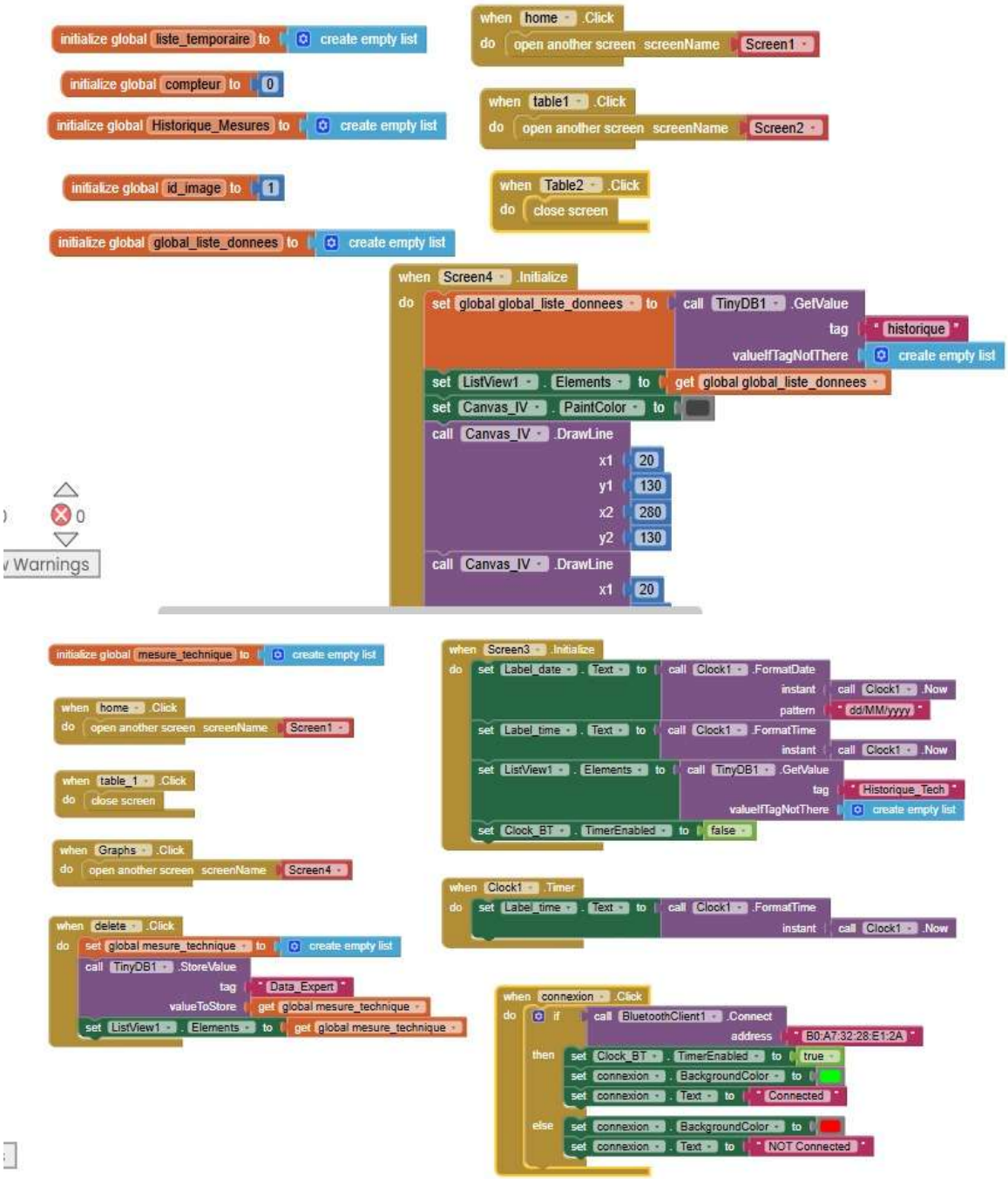

numberOfBytes
-1
get message
%
add items to list list
get global mesure_list
item
join
select list item list
get global Liste_Temp
index
1
2
3
4
5
6
7
set ListView1 . Elements to
call TinyDB1 .StoreValue
tag
Data_Expert
valueToStore
get global mesure_list
Show Warnings


when connexion .Click
do
if
call BluetoothClient1 .Connect
address
B0:A7:32:28:E1:2A
then
set Clock_BT . TimerEnabled to true
set connexion . BackgroundColor to
set connexion . Text to
Connected
else
set connexion . BackgroundColor to
set connexion . Text to
NOT Connected


when Clock1 .Timer
do
if
BluetoothClient1 . IsConnected
then
if
call BluetoothClient1 .BytesAvailableToReceive
>
0
then
set global liste_temporaire to
split
text
call BluetoothClient1 .ReceiveText
numberOfBytes
-1
at
:
call Canvas_IV .DrawPoint
x
select list item list
get global liste_temporaire
index
2
10
y
130
-
select list item list
get global liste_temporaire
index
1
20
call Canvas_PV .DrawPoint
x
select list item list
get global liste_temporaire
index
2
10
y
130
-
select list item list
get global liste_temporaire
index
3
5
set global compteur to
get global compteur
+
1
if
get global compteur
=
300

when Back .Click
do close screen


when Screen5 .Initialize
do
if
call BluetoothClient1 .Connect
address
B0:A7:32:28:E1:2A
then
set Clock1 . TimerEnabled to true
set Image_IV . Picture to
join
courbe_IV_
get start value
.jpg
set ImagePV . Picture to
join
courbe_PV_
get start value
.jpg
Show Warnings
when share .Click
do
call Sharing1 .ShareFile
file
join
courbe_IV_
get start value
.jpg
when share2 .Click
do
call Sharing1 .ShareFile
file
join
courbe_PV_
get start value
.jpg


initialize global liste_temporaire to create empty list
initialize global compteur to 0
initialize global Historique_Mesures to create empty list
initialize global id_image to 1
initialize global global_liste_donnees to create empty list
when home .Click
do open another screen screenName Screen1
when table1 .Click
do open another screen screenName Screen2
when Table2 .Click
do close screen
when Screen4 .Initialize
do set global global_liste_donnees to call TinyDB1 .GetValue
tag historique
valueIfTagNotThere create empty list
set ListView1 . Elements to get global global_liste_donnees
set Canvas_IV . PaintColor to
call Canvas_IV .DrawLine
x1 20
y1 130
x2 260
y2 130
call Canvas_IV .DrawLine
x1 20
0
Warnings
initialize global mesure_technique to create empty list
when home .Click
do open another screen screenName Screen1
when table_1 .Click
do close screen
when Graphs .Click
do open another screen screenName Screen4
when delete .Click
do set global mesure_technique to create empty list
call TinyDB1 .StoreValue
tag Data_Expert
valueToStore get global mesure_technique
set ListView1 . Elements to get global mesure_technique
when Screen3 .Initialize
do set Label_date . Text to call Clock1 .FormatDate
instant call Clock1 .Now
pattern dd/MM/yyyy
set Label_time . Text to call Clock1 .FormatTime
instant call Clock1 .Now
set ListView1 . Elements to call TinyDB1 .GetValue
tag Historique_Tech
valueIfTagNotThere create empty list
set Clock_BT . TimerEnabled to false
when Clock1 .Timer
do set Label_time . Text to call Clock1 .FormatTime
instant call Clock1 .Now
when connexion .Click
do if call BluetoothClient1 .Connect
address B0:A7:32:28:E1:2A
then set Clock_BT . TimerEnabled to true
set connexion . BackgroundColor to
set connexion . Text to Connected
else set connexion . BackgroundColor to
set connexion . Text to NOT Connected